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PROBLEMS OF AMERICAN GEOLOGY

A SERIES OF LECTURES DELIVERED WITH SOME OF THE
PROBLEMS OF THE CANADIAN TERRITORIES AND OF THE CON-
TINENTAL DIVISIONS AT THE UNIVERSITY OF THE
SOUTHERN PROVINCES IN TORONTO, 1913

BY
WILLIAM NORTH RICE
FRANK W. WILSON
JAMES DWIGHT JONES
AT THE AGE OF EIGHTY-TWO FROM A PHOTOGRAPH
TAKEN IN 1907
UNIVERSITY OF TORONTO
WILLIAM NORTH RICE

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JAMES DWIGHT DANA

AT THE AGE OF EIGHTY-TWO. FROM A PHOTOGRAPH
TAKEN IN 1895

PROBLEMS OF AMERICAN GEOLOGY

A SERIES OF LECTURES DEALING WITH SOME OF THE
PROBLEMS OF THE CANADIAN SHIELD AND OF THE COR-
DILLERAS, DELIVERED AT YALE UNIVERSITY ON THE
SILLIMAN FOUNDATION IN DECEMBER, 1913

By

WILLIAM NORTH RICE

FRANK D. ADAMS

ARTHUR P. COLEMAN

CHARLES D. WALCOTT

WALDEMAR LINDGREN

FREDERICK L. RANSOME

WILLIAM DILLER MATTHEW

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THE SILLIMAN FOUNDATION

In the year 1883 a legacy of eighty thousand dollars was left to the President and Fellows of Yale College in the city of New Haven, to be held in trust, as a gift from her children, in memory of their beloved and honored mother, Mrs. Hepsa Ely Silliman.

On this foundation Yale College was requested and directed to establish an annual course of lectures designed to illustrate the presence and providence, the wisdom and goodness of God, as manifested in the natural and moral world. These were to be designated as the Mrs. Hepsa Ely Silliman Memorial Lectures. It was the belief of the testator that any orderly presentation of the facts of nature or history contributed to the end of this foundation more effectively than any attempt to emphasize the elements of doctrine or of creed; and he therefore provided that lectures on dogmatic or polemical theology should be excluded from the scope of this foundation, and that the subjects should be selected rather from the domains of natural science and history, giving special prominence to astronomy, chemistry, geology, and anatomy.

It was further directed that each annual course should be made the basis of a volume to form part of a series constituting a memorial to Mrs. Silliman. The memorial fund came into the possession of the Corporation of Yale University in the year 1901; and the present volume constitutes the eleventh of the series of memorial lectures.

Paul

PREFACE

James Dwight Dana was born at Utica, New York, February 12, 1813, and died at New Haven, Connecticut, April 14, 1895. His long life was exceptionally fruitful in the geological sciences, so much so that the great paleontologist Von Zittel said of him: "He was incontestably the first geologist of North America, and, especially by his epoch-making *Manual of Geology*, he exerted a decisive influence upon geological study."

Dana's *Manual of Geology* first appeared in 1863, when he was fifty years of age. In view of the fiftieth anniversary of its publication and the one hundredth anniversary of Dana's birth, the Geological Department of Yale University desired to commemorate these dates in connection with the meeting at New Haven in December, 1912, of the Geological Society of America, the Association of American Geographers and the Paleontological Society. This wish was laid before the first-named society, and the following program was decided upon:

MEETING COMMEMORATIVE OF THE
APPROACHING CENTENARY
OF
JAMES DWIGHT DANA

FEBRUARY 12, 1813—FEBRUARY 12, 1913

LAMPSON LYCEUM, YALE UNIVERSITY, DECEMBER 29, 1912

8 P.M.

PROGRAM

Introductory Remarks

President Hadley

Dana the Man

William North Rice

Professor of Geology, Wesleyan University

Dana the Teacher

Edmund Otis Hovey

Secretary, Geological Society of America

Dana the Geologist

George Perkins Merrill

Head Curator of Geology, United States National Museum

Dana the Zoölogist

John Mason Clarke

Director, Science Division,
Department of Education, New York State*The Geological Society of America*

In the following year, a series of ten commemorative lectures was arranged for on the foundation of the Mrs. Hepsa Ely Silliman Memorial Fund, and of this course the present volume is the outcome. As Dana was so eminent a geologist, the Geological Department of the University desired that the lectures and especially the memorial volume should be of high scientific attainment. It was at first thought that a limited number of lecturers could cover the entire field of work in which Dana labored, and restudy his results in the light of present knowledge. On consideration of such a scheme, however, it was soon seen that it would grow to such proportions as to become impracticable and undesirable if given on the Silliman Foundation, and it was, therefore, decided to limit the scope of the lectures.

To give unity to the plan and to make the volume a real contribution to geologic science, the course was restricted to two fields whose problems are those of early and late geologic time respectively—the Canadian Shield and the Cordilleras. Within these limits the lecturers were asked to deal with subjects which are of present vital interest rather than to make a mere review of past accomplishments.

The contributions included in the volume are of a broad character and presented by men who have become personally familiar with their respective problems. It is thought that the subjects chosen have not heretofore been fully developed or clearly presented to geologists in general. Each subject is presented from the broader and more philosophic side, the

aspect of most interest to the geologist and the teacher, and leads to general conclusions and correlations.

The program of the lectures as given at Yale University during December, 1913, was as follows:

PROBLEMS OF AMERICAN GEOLOGY

Introduction

The Geology of James Dwight Dana, Tuesday, December 2, Professor William North Rice, LL.D., Wesleyan University.

I. Problems of the Canadian Shield

The Archæozoic and its Problems, Thursday and Friday, December 4 and 5, Professor Frank Dawson Adams, Sc.D., Dean of the Faculty of Applied Science, McGill University.

The Proterozoic and its Problems, Wednesday and Thursday, December 10 and 11, Professor Arthur Philemon Coleman, University of Toronto.

II. Problems of the Cordilleras

The Cambrian and its Problems, Monday, December 15, Doctor Charles Doolittle Walcott, Sc.D., LL.D., Secretary of the Smithsonian Institution.

The Igneous Geology and its Problems, Tuesday, December 16, Professor Waldemar Lindgren, Massachusetts Institute of Technology.

The Tertiary Structural Evolution and its Problems, Wednesday, December 17, Doctor Frederick Leslie Ransome, United States Geological Survey.

The Tertiary Sedimentary Record and its Problems, Thursday and Friday, December 18 and 19, Doctor William Diller Matthew, American Museum of Natural History.

The Geological Department of Yale University wishes to express its appreciation of the labors of the various Silliman lecturers for this Dana Commemorative Course and of their coöperation in its twofold purpose of advancing the sciences of geology and paleontology and honoring the great name of Dana.

"The life of James Dwight Dana," said Major Powell, "exhibits a well-rounded half-century of scientific investigation. For more than fifty years he was actively engaged in research, and for more than fifty years a stream of contributions to science issued from the well-spring of his genius. Dana was

preëminently the philosopher. He was the man who formulated definitions, axioms and laws which are the fundamental elements of scientific philosophy.”

CHARLES SCHUCHERT, *Chairman*,
for the Geological Department of Yale
University

June, 1914

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PROBLEMS OF AMERICAN GEOLOGY

CHAPTER I

THE GEOLOGY OF JAMES DWIGHT DANA

WILLIAM NORTH RICE

James Dwight Dana was born February 12, 1813, and died April 14, 1895. His first geological paper was published in 1835,¹ his last in 1895,² only a few weeks before his death—his contributions to geology ranging thus over a period of three-score years. The first edition of his *Manual of Geology* was published in 1863;³ the last, embodying the results of his long life of earnest thought and study, in 1895. That book was the Bible whose teaching was recognized as authoritative by American students for more than four decades. The great ability of the man, and the great duration of productive life which he enjoyed, combined to make him the most influential personage in the history of American geology.

Professor Dana was not exclusively a geologist. The earliest years of his productive scientific career were devoted chiefly to mineralogy. The first edition of his *System of Mineralogy* was published in 1837, and the fifth, which was the last edition edited by his own hand, in 1868. His earliest contribution to mineralogy was published in 1835,⁴ and his last, the fourth

¹ On the Condition of Vesuvius in 1834: *Am. Jour. Sci.*, (1), XXVII, pp. 281-288.

² Daimonelix of the Lacustrine Miocene of Nebraska: *Ibid.*, (3), XLIX, pp. 239-240.

³ This is the date given by J. D. Dana in article entitled A Brief History of Taconic Ideas: *Ibid.*, (3), XXXVI, p. 421. In E. S. Dana's biographical sketch, *Ibid.*, (3), XLIX, pp. 329-356, the first edition of the *Manual* is said to have been published in 1862. The preface of the book is dated November 1, 1862; and the date of the copyright is 1862.

⁴ A New System of Crystallographic Symbols: *Am. Jour. Sci.*, (1), XXVIII, pp. 250-262.

edition of the *Manual of Mineralogy*, in 1887. In the period from 1842 to 1854, his time was very largely given to zoölogy. His earliest zoölogical paper was published in 1836,¹ his last in 1894.² The last three decades of his life, however, were given almost exclusively to geology. He gave very little study to any other subject than geology after the publication of the fifth edition of the *System of Mineralogy*, in 1868.

MINERALOGY

The *System of Mineralogy* appeared when Dana was only twenty-four years of age and only four years out of college. It is certainly remarkable that a book representing so large an amount of research should have been produced by one so young. The book took rank at once as a standard treatise of the science. In the first two editions of the *System*, Dana followed the so-called "natural classification" of Mohs, and he proposed an original Latin nomenclature similar to that used in botany and zoölogy. In the third edition, 1850, the "natural classification" was abandoned, with the frank statement that it was "false to nature in its most essential points," and Dana's own Latin nomenclature was not even mentioned in the synonymy. It had become obvious that the primary basis of mineralogical classification must be found in chemistry, while, within the groups established on chemical grounds, subdivisions must be based largely on crystalline form. It was further recognized that the more comprehensive groups must be founded, not on the metallic or electro-positive constituents, but rather on the non-metallic or electro-negative constituents, and especially on the type of the chemical formula. A system of classification based primarily on chemical principles as now understood, with subdivisions characterized by crystalline form, recognizes all the true relations which were expressed in the so-called "natural

¹ Two American Species of the Genus *Hydrachna*: Am. Jour. Sci., (1), XXX, pp. 354-359.

² Observations on the Derivation and Homologies of some Articulates: *Ibid.*, (3), XLVII, pp. 325-329.

classification," and which the earlier forms of chemical classification failed to recognize. In his third edition, Dana outlined the chemico-crystallographic classification, whose general plan has been almost universally adopted, though the progress of mineral chemistry has led to great improvement in the details. A classification essentially similar to Dana's was proposed independently two years later by Gustav Rose in his *Krystallo-chemisches Mineralsystem*. To Dana, therefore, belongs the merit of originating a truly natural classification of minerals. The fact is worthy of incidental mention that Dana constructed hollow glass models of crystalline forms as early as 1835, probably the earliest models of this kind.

ZOÖLOGY

Dana's reputation as a zoölogist rests chiefly upon the Reports on the Zoöphytes and on the Crustacea of the United States Exploring Expedition. More than two hundred new species of coral animals and more than five hundred new species of Crustacea were described in these Reports; but far more important than the description of seven hundred species was the advance made by these investigations in the general classification.

The Report on Zoöphytes, especially, was an epoch-making work in that department of science. Dana divided the Zoöphytes into two groups which he called orders, the Actinoidea and the Hydroidea, and the former of these orders was divided into two suborders, Actinaria and Aleyonaria. The order Actinoidea, as defined by Dana, is equivalent to the class Anthozoa or Actinozoa, as generally recognized by zoölogists today; and his two suborders of Actinoidea exactly represent the two orders, known under various names, into which most zoölogists divide the class. To Dana, then, we owe the first correct delimitation of the class of Anthozoa and the first clear discrimination of its two main divisions. In its broad outlines, the classification first given to the world in Dana's Report on Zoöphytes has stood the test of time.

The study of the Crustacea was in a more advanced state than that of the corals before Dana's work. There was, therefore, no opportunity for such an epoch-making discovery in regard to the relations of the group as Dana made in regard to the Zoöphytes.

The study of the Crustacea suggested to Dana a striking generalization, which was first enunciated in his Report, but which was later discussed more fully in a number of papers published mostly in the *Journal of Science* between 1863 and 1866—the principle of Cephalization.¹ In the highest Crustacea (Decapoda), the eight anterior pairs of appendages are cephalic (*i.e.*, sensory or oral in function); namely, two pairs of antennæ, one pair of mandibles, two pairs of maxillæ, three pairs of accessory mouth-organs (maxillipeds); while the next five segments bear the principal locomotive appendages. In a lower group (Arthrostraca), the second and third pairs of maxillipeds are represented by legs, so that these creatures have only six cephalic (sensory or oral) segments, and seven, instead of five, locomotive segments. In still lower crustacea (Entomostraca), the number of functionally cephalic appendages is still less, even the antennæ becoming sometimes organs of locomotion or adhesion. Moreover, in the Brachyura, which form the highest division of the Decapoda, the posterior part of the body is greatly reduced in size, and most of its segments are destitute of appendages. The whole body seems almost, so to speak, absorbed into the head. It was natural that the contemplation of facts like these should suggest to a mind so fond of generalization as was that of Dana the broad principle that, as “antero-posterior polarity” characterizes animals in distinction from plants, so the grade of different animal forms in comparison with each other is shown by the “degree of structural subordination to the head and of concentration headward in body structure.”

¹ *Am. Jour. Sci.*, (2), XXII, pp. 14-29; XXXV, 65-71; XXXVI, 1-10, 233-235, 315-321, 321-352, 440-442; XXXVII, 10-33, 157-183, 184-186; XLI, 163-174; (3), XII, 245-251; *New Englander*, XXII, pp. 495-506.

The principle is, doubtless, an important and valuable one. Certainly, as we pass from the lower, and in general the earlier, types of animal life, to the higher, and in general the later, types, there is a tremendous advance in cephalization. From a protozoan, destitute even of a mouth, the earliest cephalic feature to be developed, or from a sea-anemone, whose symmetry is radial rather than bilateral, and in which, therefore, there is but faint indication of an anteroposterior axis, to man, with his immense brain, and his skillful hands employed in the service of the brain, there is a tremendous advance in the degree of structural subordination to the head. Dana's development of the principle of cephalization was ingenious and interesting; but it cannot be denied that he was sometimes led by mere analogies into fanciful conclusions. In general, in his discussion of animals as high or low in the system of classification, he made the mistake which was natural in pre-Darwinian days, of failing to distinguish between the lack of organs and functions in primitive forms that have never acquired them, and the lack of organs and functions in degenerate forms that have lost them by retrograde evolution. To the evolutionary zoölogist, the distinction of high and low becomes relatively unimportant and in some cases almost meaningless. The important distinction comes to be that between primitive and generalized forms on one hand and highly specialized forms on the other; and it is recognized that the specialization of later forms may involve either advancement or degradation—either increase or decrease in complexity of structure and variety of function.

EVOLUTION

In connection with this brief notice of Dana's zoölogical work, it is natural to speak of his attitude toward that theory of evolution which in the last half of the nineteenth century filled so large a space in the thought of biologists and geologists, and which has so profoundly affected the intellectual life of mankind. The reputation Dana had won as a zoölogist gave greater significance and wider influence to the assertion of the doctrine

of evolution in the later editions of the *Manual* and the *Text-book of Geology*.

Dana was not an early convert to the theory of evolution. In common with the great majority of naturalists and geologists about the middle of the nineteenth century, he regarded the theory of evolution in any form as dead beyond hope of resurrection. The general conception of transmutation of species was supposed to have been buried in the same grave with the crudities of Lamarek and the *Vestiges of Creation*. Weismann says, "We who were then the younger men studying in the fifties, had no idea that a theory of evolution had ever been put forward, for no one spoke of it to us, and it was never mentioned in a lecture."¹ The date of the publication of the *Origin of Species* approximately coincided with the date of the breakdown of Dana's health. It was, doubtless, in part at least, for that reason that he did not read Darwin's book for several years after its publication. We know from the correspondence between Dana and Darwin, that Dana did not read the *Origin of Species* until some time after February, 1863.² Naturally, therefore, he failed to appreciate the difference between the strong foundation on which Darwin's edifice was built and Lamarek's cloud castle of speculation.

Dana himself, in his *Thoughts on Species*,³ had formulated the somewhat metaphysical doctrine that "a species corresponds to a specific amount or condition of concentrated force defined in the act or law of creation."⁴ This formula was supposed to apply alike to chemical elements and compounds, the species of the inorganic world, and to the species of plants and animals. Dana was also disinclined to the theory of evolution on theological grounds, since he was under the influence of a phase of natural theology then prevalent, which found the most convincing evidence of the personality of God in the supposed breaks in the continuity of nature.

¹ Weismann, *The Evolution Theory*, vol. I, p. 28.

² Gilman, *Life of James Dwight Dana*, p. 313.

³ Am. Jour. Sci., (2), XXIV, pp. 305-316.

⁴ *Op. cit.*, p. 306.

Altogether apart from philosophical or theological opinions, Dana regarded the facts of palæontology as affording a conclusive disproof of evolution. In his presidential address on American Geological History before the American Association for the Advancement of Science, in 1855,¹ he declares that "through the periods of the Silurian and Devonian, at twelve distinct epochs at least, the seas over this American continent were swept of all or nearly all existing life, and as many times they were repeopled";² and from this supposed fact he draws an obvious argument against the theory of evolution in its Lamareckian form. In those days Dana's geological views were decidedly more catastrophic than in his later life. The progress of his thinking is strikingly shown by the contrast between the statement just cited from his address of 1855, and the declaration in the last edition of the *Manual of Geology*, that "probably not a tenth part of the animal species of the world disappeared, and far less of the vegetable life," in the immense geographic changes which marked the close of Mesozoic time.³ He had come to feel that the apparent exterminations mean only gaps in the record.

In the second edition of the *Manual of Geology* (1871), Dana still maintained the permanence of species. "Geology," he declared, "has brought to light no facts sustaining a theory that derives species from others."⁴ But in the second edition of the *Text-book of Geology*, published in 1874, he took a somewhat qualified evolutionary position, in the following statements: "The evolution of the system of life went forward through the derivation of species from species, according to natural methods not yet clearly understood, and with few occasions for supernatural intervention. The method of evolution admitted of abrupt transitions between species. For the development of man there was required, as Wallace has urged,

¹ Am. Jour. Sci., (2), XXII, pp. 305-334.

² *Op. cit.*, p. 318.

³ *Op. cit.*, p. 876.

⁴ *Op. cit.*, p. 602.

the special act of a Being above nature.”¹ In the two remaining decades of Professor Dana’s life, his faith in evolution became somewhat more decided. In the last edition of the *Manual of Geology*,² he gave much fuller recognition than before to Darwin’s principle of natural selection, though holding more nearly a neo-Lamareckian than a strictly Darwinian view of the method of evolution. He still maintained that “the intervention of a Power above nature was at the basis of man’s development.”³ In the same paragraph he declared that “nature exists through the will and ever-acting power of the Divine Being,” and that “the whole universe is not merely dependent on, but actually is, the will of one Supreme Intelligence.” One is tempted to ask why, if all nature is thus divine, we need to assume for man a supernatural origin. A truer evolutionary theistic philosophy recognizes so fully an immanent God in the continuity of nature that it seeks no apparent breaks of continuity wherein to find him.

Though Dana’s faith in the doctrine of evolution was, even to the end, a little hesitant, it must be recognized as a remarkable proof of his open-mindedness and candor that, at an age when most men’s opinions are already petrified, he was able to make so radical a change, and frankly to adopt the views he had so long and so ably opposed. In 1863, Darwin wrote to Dana as follows: “Pray do not suppose that I think for one instant that, with your strong and slowly acquired convictions and immense knowledge, you could have been converted. The utmost that I could have hoped would have been that you might possibly have been here or there staggered.”⁴ But the unexpected happened; and in the course of the next decade Darwin could rejoice over his friend’s conversion. The accession to the ranks of the evolutionists of one whose learning was so vast and varied, whose thinking was so conservative, and

¹ *Op. cit.*, p. 263.

² *Op. cit.*, pp. 1029-1036.

³ *Op. cit.*, p. 1036.

⁴ Gilman, *Life of James Dwight Dana*, p. 315.

whose spirit was so devout, was a very potent factor in promoting the acceptance of the doctrine among thinkers outside the ranks of scientific specialists.

THE MANUAL OF GEOLOGY

It is rather noteworthy that Dana's geological work was in no sense closely related with the work on mineralogy and zoölogy to which the earlier years of his scientific career were largely devoted. It might naturally have been expected that a mineralogist turning his attention to geology would be specially interested in lithology, and that a zoölogist would be specially interested in palæontology. Darwin turned from the study of recent barnacles to the study of allied fossil forms; and Cuvier, the great comparative anatomist, became the founder of palæontology. Among Dana's publications, however, there are very few papers which can be classed as lithological, and still fewer which can be classed as palæontological. He did no special work in palæontology, and he never manifested much interest in the new methods of research which have transformed lithology. As a geologist, Dana was chiefly interested in broad views of the cosmic processes which have shaped the history of the earth. "Geology," he declared, "is all the sciences combined into one." The instinct of generalization was Dana's most striking mental characteristic, and it was the opportunity for vast generalization that made the science of geology supremely attractive to him.

The book which in its successive editions has more profoundly influenced scientific thought than anything else which Dana wrote, bore the title, *Manual of Geology, treating of the Principles of the Science with special reference to American Geological History*. Two words in this title are profoundly significant, and suggest in part the reason for the immense influence which the book was destined to exert—American, and History.

American. This was not the first text-book on geology published in America. A number of others more or less meritorious

and useful had already appeared,¹ but the spirit and method of Dana's book were more distinctly American than any of its predecessors. It was not an exotic transplanted from Europe, but was indigenous to the soil.

History. Never before had the conception of geology as a history of the globe found so clear expression. Le Conte, in his cordial and generous eulogy of Dana,² declared that "geology became one of the great departments of abstract science, with its own characteristic idea and its own distinctive method, under Dana."³ There is certainly somewhat of exaggeration in this commendation, yet the statement contains an important truth. More or less clearly, all geological investigators must have felt that the distinctive idea of geology is that the structures of the rocks of the earth's crust have their supreme significance as monumental inscriptions, the deciphering of which may reveal to us the history of the earth. Yet this conception was never before so clearly formulated, and the whole treatment of the subject so consistently adjusted thereto, as in the writings of Dana. The portion of previous manuals dealing with the local distribution of the series of strata had generally borne some such title as "Stratigraphical Geology"; and very commonly, as in the well-known works of Lyell and De la Beche, the series had been traced backward, beginning with the most recent strata. In Edward Hitchcock's *Elementary Geology*, with which, in my boyhood, I commenced the study of the science, the stratigraphic chapter bears the title, "Lithological Characters of the Stratified Rocks." It occupies only twenty pages in a book of more than four hundred pages. It traces the formations backward in Lyellian fashion. Separate from the stratigraphic chapter is another and longer chapter on palæontology, which is arranged botanically and zoölogically, and not chronologically. The phrase, "Historical Geology," which forms the title of the largest section of Dana's

¹ As those of Cleaveland, Amos Eaton, Edward Hitchcock, Gray and Adams, and Ebenezer Emmons.

² Bull. Geol. Soc. America, VII, pp. 461-479.

³ *Op. cit.*, p. 463.

Manual, involves a distinct clarification of the general view of the science. Starting with this conception, he, of course, dealt with the earliest formations first. In the treatment of each era he endeavored to reconstruct, from the evidence afforded by the kinds and distribution of the rocks, the physical geography of the time. The subdivisions treated in that chapter of the *Manual* are characterized, not as series, systems, and groups of strata, but as eras, periods, and epochs of time. The common use, in recent geological writings, of such phrases as "Silurian era," rather than "Silurian system," etc., is a testimony to the influence of Dana's mode of treatment.

American Geological History. There was then an American Geological History. America was not a transient event dating from the last catastrophic upheaval, but North and South America had been geographical units through all geological time. In the preface to the *Manual*, Dana tells us that the plan of the book was adopted, not only "to adapt it to the wants of American students," but because he believed "that, on account of a peculiar simplicity and unity, American Geological History affords the best basis for a text-book of the science." By reason of their complete isolation from other great land masses, the two continents of North and South America exhibit most fully the typical process of continental evolution, as the laws of crystalline form can exhibit themselves in perfection only where a single crystal in a solution or magma is allowed to grow without interference from other growing crystals. The point of view which thus characterized the *Manual* was already taken in the presidential address before the American Association for the Advancement of Science, in 1855.

THE PERMANENCE OF CONTINENTS AND OCEANS

The doctrine of the permanence of continents and oceans—the gradual emergence of continental lands and the withdrawal of the waters into the deepening ocean basins—was first enunciated by Dana in 1846.¹ He had just returned from his

¹ On the Volcanoes of the Moon: *Am. Jour. Sci.*, (2), II, pp. 335-355. In this article, pages 352-355 treat of the origin of continents on the earth.

voyage around the world in Wilkes's exploring expedition. In that voyage he had studied the phenomena of barrier reefs and atolls, had adopted Darwin's theory of their origin by subsidence, and had defended and illustrated the theory by a far greater wealth of observation than Darwin's route had afforded him the opportunity to make. It was, apparently, the thought of the subsiding ocean bottom, rather than the thought of the emerging land, by which Dana was first led to the doctrine of the permanence of continent and ocean; but, in studying the stratigraphy of North America and the geological history therein revealed, Dana was profoundly impressed by the orderly succession of the Palæozoic formations along the southern margin of the great Archæan nucleus of the continent. Particularly suggestive of the gradual emergence of the continent from the sea is the arrangement of Palæozoic formations in approximately parallel east and west bands across the state of New York; and those facts and the inference which they suggest are strongly emphasized in the pages of the *Manual*.

The doctrine of the permanence of continents, when announced by Dana, was essentially a new one. Geologists and pseudo-geologists of all classes had felt at liberty to redistribute continents and oceans according to their own sweet will. After the biblical pseudo-geologists had become convinced of the impossibility of the deposition of the whole series of fossiliferous strata in the Noachian deluge, their next shift was the supposition that the fossiliferous strata were deposited in the ocean in the interval between the creation and the deluge, and that at the time of the latter event continent and ocean were reversed.¹ Hutton believed that the débris of the continents was carried far out to sea by means of ocean currents, and was deposited over substantially the whole floor of the ocean; and, when one continent was worn away, another might be uplifted in some other part of the world.² Lyell eliminated the catastrophic element of Hutton's theorizing; but, like his predecessor, Lyell

¹ Granville Penn, *Comparative Estimate of the Mineral and Mosaical Geologies*, London, 1825.

² Playfair, *Illustrations of the Huttonian Theory*, note 19.

believed in an indefinite amount of change in the distribution of continent and ocean. In attempting to find an explanation for changes of climate in geological time, he felt at liberty to speculate on a series of changes in the distribution of continent and ocean which would sometimes bunch the continents around the poles, and at other times girdle the earth with an equatorial belt of land.¹ The readers of Darwin's *Letters* will remember his half-comic, half-pathetic protest, in a letter to Lyell, that the disciples of the great geologist "in a slow and creeping manner beat all the old catastrophists who ever lived."²

The doctrine of the substantial permanence of continent and ocean has been very generally accepted by American geologists, though it has not met the same degree of favor in Europe. Some of the leading European geologists still feel at liberty to postulate extensive continental areas where now are found abysses of ocean, in order to give opportunity for migrations to account for the distribution of life in successive geological periods. It seems altogether probable that Dana was right in his general conception. The greater density of the suboceanic masses in comparison with the subcontinental masses, as shown by pendulum observations, indicates that the distinction between continent and ocean has its basis in the heterogeneity of the material in the interior of the earth; and the determining conditions must, therefore, have had their origin in the initial aggregation of that part of the primitive nebula which formed the earth, or, perhaps, as suggested by Chamberlin and Salisbury, in changes attendant upon the beginning of the formation of the ocean.³ The study of the sedimentary rocks which cover our existing continents shows that almost all of them were deposited in shallow waters; many of the strata, indeed, in waters so shallow that the layers of mud and sand were from time to time exposed by the receding tide or the subsiding freshet, to dry and crack in the sun or to be pitted by raindrops.

¹ *Principles of Geology*, 11th ed., New York, 1872, vol. I, p. 271.

² *Life and Letters*, New York, 1888, vol. I, p. 431.

³ *Geology*, vol. II, pp. 106-111.

None of the sedimentary deposits seem to have been formed in waters of truly oceanic depth.

Certain it is, however, that Dana made the evolution of the continents too simple an affair. He recognized, indeed, that the progressive emergence of the continental lands was attended by continual oscillation; yet, even in the last edition of his *Manual*, it is obvious that he did not duly appreciate the magnitude of those oscillations. The studies of the last few decades have shown that the history of North America has been no substantially continuous emergence of the continental area, but a long series of alternations of dry land and continental seas, the amount of dry land varying from less than half the present area in the climax of the Ordovician transgression, to somewhat more than the present area in the emergence at the time of the Appalachian Revolution. We have made a long journey from the simplicity of the continental emergence pictured in the first edition of Dana's *Manual* to the complex history represented in Schuchert's more than fourscore palæogeographic maps.¹

It is noteworthy that in the first edition of Dana's *Manual* there were three palæogeographic maps, bearing respectively the legends, "Azoic Map of North America," "North America in the Cretaceous Period," and "North America in the Period of the Early Tertiary." These must have been among the earliest attempts to represent by that method the evolution of a continent.² A number of other such maps were added in later editions of the *Manual* and the *Text-book*.

While Dana was in error in his notion of a substantially continuous emergence of the continent, he was probably right in conceiving of continental evolution as dynamically related to the subsidence of the ocean bottom. It is probable that the

¹ Palæogeography of North America: Bull. Geol. Soc. America, XX, pp. 427-606, pls. 50-101. The Delimitation of Geological Periods illustrated by the Palæogeography of North America: Congrès Géologique International, 12e Session, 1914.

² Probably the earliest palæogeographical maps were the work of Élie de Beaumont.

contraction of the interior of the earth tends to produce a continuous subsidence of the ocean bottom and emergence of the continents; but the rigidity of the earth's mass makes the effect intermittent, though the cause is constant. After each epoch of deepening of the ocean and emergence of the land, comes a period in which the land is lowered by denudation, the continental shelf is built outward, and the ocean, which is raised by sedimentation to a higher level, gradually overflows the areas degraded to base-level or depressed by warping of the crust.¹

MOUNTAIN-MAKING

The idea of oceanic subsidence and continental emergence is naturally connected with the contractional theory of mountain-making. There is little doubt that in some form the contractional theory is true. The alternating anticlines and synclines of the Appalachian Mountains and the Jura, the gigantic thrust faults of the Alps, the Scotch Highlands, and the Cordillera, the frequent development of slaty cleavage and schistosity in planes whose strike is parallel to the axis of the mountain range—all bear witness in unmistakable language to the fact of compression of the earth's crust, which must mean contraction of its interior.

The cause of contraction may admit of question. The commonly received form of the nebular theory, with its conception of a globe originally gaseous or liquid from intense heat and gradually cooling, affords a very simple and obvious explanation for contraction of the interior of the globe. On the planetesimal theory of Chamberlin and Moulton, which does not postulate an extremely high initial temperature, the explanation is not quite so obvious, but may perhaps be no less satisfactory. It has been shown that the distribution of heat in the interior of a planet formed by the aggregation of innumerable planetesimals would give so steep a thermal gradient at a depth of about one-third of the radius that heat would naturally pass

¹ Chamberlin, *The Ulterior Basis of Time Divisions and the Classification of Geologic History*: Jour. Geology, VI, pp. 449-462.

from the central portions of the sphere to those more superficial. Thus, while the central parts were cooling, the more superficial parts of the sphere might be rising in temperature. Both the cooling of the central parts and the warming of the more superficial parts would concur to produce a compressive force in the more superficial parts of the sphere. Moreover, it is by no means certain that thermal changes are the sole cause of contraction. It is altogether probable that chemical changes are in progress, resulting continually in the formation of molecules of higher specific gravity. But the evidence of internal contraction and consequent crustal wrinkling seems independent of any uncertainty in regard to the cause of contraction.

The conception of the contractional origin of mountains was not original with Dana. A glimmer of the idea appears in the writings of Leibnitz. Constant Prévost appears to have first developed the idea into a truly scientific theory;¹ but the elaboration of the theory into its present form is very largely the work of Dana.² The views of Le Conte on the subject of mountain-making were on most points similar to those of Dana; but, while Le Conte's discussions were ingenious and valuable, the priority in the general development of the theory belongs to Dana. "To the North American geologists," says von Zittel, "undoubtedly belongs the credit of founding the theory of horizontally acting forces and rock-folding upon an ample basis of observation."³

Dana's discussion of the subject began in the *Journal of Science* in 1846, with the paper entitled, *On the Volcanoes of the Moon*.⁴ In later years he returned to the subject again and again, and the theory as shaped by his maturest thought appears

¹ Dana quotes Prévost in his first article, and remarks on the similarity of their views, though he says that his own conclusions had been formed before he saw Prévost's memoir. *Am. Jour. Sci.*, (2), II, p. 355.

² "Professor Dana was the geologist who first gave clear expression to the theory of horizontal compression in explanation of the origin of mountains." Von Zittel, *History of Geology and Palæontology*, p. 304.

³ *Ibid.*, p. 307.

⁴ *Am. Jour. Sci.*, (2), II, pp. 335-355.

in the last edition of the *Manual*. In his earlier writings his speculations on the origin of continents and mountains were based on the assumption of a liquid globe, and some of his views seem rather crude in the light of our present knowledge and beliefs regarding the physics of the globe. Thus, in the article above cited, he says: "It is therefore a just conclusion that the areas of the surface constituting the continents were first free from eruptive fires. These portions cooled first, and consequently the contraction in progress affected most the other parts. The great depressions occupied by the oceans thus began."¹ One cannot help asking what conceivable force held up the continental crust floating on a universal molten interior, while the parts of the surface still liquid or more thinly crusted gradually settled down to a lower level. In Dana's later writings, his reasonings were more soundly based on the conception of a substantially solid globe.²

In the first edition of the *Manual*, the subject of mountain-making was discussed with special reference to the Appalachian Range, whose structure had been so beautifully worked out by Henry D. Rogers in the First Geological Survey of Pennsylvania, and which Dana took as a typical example of orogenic processes. In later editions he availed himself of the knowledge accumulated by geological work in the Cordillera to give to the subject more varied illustration.

¹ *Op. cit.*, p. 353.

² Dana's articles bearing on the theory of mountain-making, in the *American Journal of Science*, belong to four groups, separated by intervals of several years, as follows—1846-1847: (2), II, pp. 335-355; III, 94-100, 176-188, 381-398; IV, 88-92. 1856: XXII, 305-334, 335-349. 1866: XLII, 205-211, 252-253. 1873: (3), V, 347-350, 423-443; VI, 6-14, 104-115, 161-172. In the last group (1873), he accepts the doctrine of an essentially solid globe, though still holding to a subcrustal liquid layer. In the last edition of the *Manual*, he holds the globe to be solid throughout (p. 376), though recognizing the probable existence of a zone of potential liquidity not far below the surface (p. 304). The mobility of the crust required for the movements of which we have geological evidence, he attributes largely to the flowing of solids as shown by the experiments of Tresca and others (p. 351).

His conception of the origin of what he considered a typical mountain range (synclinorium) may be summarized as follows: In the contraction of the earth's interior the suboceanic crust is the chief seat of subsidence. As the suboceanic crust in its subsidence necessarily flattens, so that its profile continuously approaches the chord of the arc, it exerts a tangential thrust toward the continental areas. The rather abrupt change in the radius of curvature in passing from the oceanic to the continental areas determines lines of weakness along the continental borders which mark in general the location of the great wrinkles of the crust resulting from the tangential thrust. These great wrinkles Dana called geanticlines and geosynclines, in distinction from simple anticlines and synclines, which are foldings of strata on a much smaller scale both in breadth and depth. In the gradual subsidence of a geosynclinal trough along the border of a continent, the trough may naturally be kept full of sediment deposited *pari passu* with the subsidence. Thus sediments may accumulate in long and narrow tracts to immense thickness, as in the case of the six miles or more of the Appalachian Palæozoic. In the progressive subsidence, the isogeotherms rise into the masses of strata, keeping ever approximately parallel with the surface. The water-loaded sediments are softened by the high temperature which invades them, in much greater degree than the nearly anhydrous crystalline rocks which they have displaced. The geosynclinal trough at last becomes so weak that the ever persistent tangential pressure crushes it together. Thus may be formed the alternating anticlines and synclines of the Appalachian or the Jura. Thus, under somewhat different conditions, may be formed great thrust faults; or weak shales may mash into slates, or sediments may be transformed into intensely metamorphic schists, and igneous rocks involved in the folded mass may be squeezed into well-foliated gneisses. A mountain range formed thus by the compression of a geosynclinal trough, Dana called a synclinorium.

But Dana recognized that a geanticlinal fold may result in

permanent elevation, and thus constitute a mountain range of a different type. A mountain range formed by a geanticline he proposed to call an anticlinorium.¹ As examples of such geanticlinal elevations he referred to the Cincinnati uplift in Palæozoic time, and the upswelling of the Rocky Mountain region at the close of the Cretaceous. In the latter case, there is much folding of the strata in parts of the uplifted mass, but this folding belongs to an earlier date than the geanticlinal movement. Dana points out the fact that the area of a synclinorium may be subsequently uplifted by geanticlinal movement.² The same mountain region may thus exemplify the two types of the synclinorium and the anticlinorium. The Appalachian Range, Dana's typical example of a synclinorium, was reduced substantially to a peneplain in the course of Mesozoic time, and its present elevation is due to a geanticlinal movement. I think the structure of the Great Basin, with its ranges formed of faulted blocks, is most plausibly explained by the conception of a vast geanticlinal arch extending from the Sierra Nevada to the Wahsatch, whose broken fragments have settled by gravitational readjustment to form the present Basin Ranges. In like manner, the eastward tilting of the Connecticut Trias, and the faults with upthrow mostly to the east, and, in contrast therewith, the westerly dip of the New Jersey Trias, and the faults with upthrow mostly to the west, find their explanation in a similar geanticlinal arch fractured and settling into gravitational adjustment.

It has always seemed to me that Dana himself did not fully appreciate the importance of his own conception of the anticlinorium as a distinct type of mountain structure. In the last edition of the *Manual*, the word anticlinorium does not appear. The contractional theory of mountain-making gains completeness by the recognition of these two contrasted types of orogenic movement, both resulting from contraction of the interior and tangential thrust in the crust. In the synclinorium we have

¹ Am. Jour. Sci., (3), V, p. 432.

² *Ibid.*, pp. 432, 437, 440.

close folding and thrust faults; in the anticlinorium we have broad arches with no close folding contemporaneous with the uplift, and normal faults. Dana's names for the two types, synclinorium and anticlinorium, are classically correct and elegantly appropriate. It has been a distinct loss to science that most recent writers have carelessly or willfully ignored Dana's discussion, and used the words synclinorium and anticlinorium as equivalent respectively to compound synclines and compound anticlines—a sense in which the words are etymologically inappropriate, and in which they are not needed.¹

In the typical development of a synclinorium, the subsidence of the geosynclinal trough and the accumulation of sediment go on slowly for indefinite ages. The crushing of the geosyncline is a movement relatively rapid. To these epochs of comparatively rapid geographic change Dana appropriately gave the name of revolutions. In geological history, as in human history, there are long ages of tranquillity with only gradual changes, alternating with comparatively brief epochs of revolutionary change. These revolutions are time boundaries in geological history. The Appalachian revolution forms the boundary between the Palæozoic and the Mesozoic, and the Laramide revolution forms the boundary between the Mesozoic and the Cenozoic. In the recognition of such revolutions we perceive the truth which was imaged in distorted form in the old Catastrophism; for the evolutionary geology of today is, as Huxley asserted many years ago, the heir of both Catastrophism and Uniformitarianism.²

The importance of the conception of revolutionary periods in geology, particularly in connection with the history of life, was clearly recognized by Le Conte in his paper *On Critical Periods in the History of the Earth, and their Relation to*

¹ *Am. Jour. Sci.*, (4), II, pp. 168-169; *Proc. Am. Assoc. Adv. Sci.*, LV, pp. 375-376.

² Evolution "embraces all that is sound in both Catastrophism and Uniformitarianism." *Lay Sermons, Addresses, and Reviews*, article on Geological Reform, p. 243.

Evolution.¹ The epochs of rapid geographical change are also the times of rapid biological change, marked by the extinction of species not in harmony with the new environment, and the rapid evolution of new forms adapted for new conditions. Chamberlin has shown that these geographical revolutions are accompanied by great climatic changes. The critical periods of extinction of species and rapid evolution of new forms are the times when the rigidity of the earth's crust yields to the accumulating strain, when the ocean bottom subsides, when continents emerge into larger area and higher altitude, when more or less of mountain-making takes place along the continental borders, and when these geographical changes bring in their train the diminution of the quota of carbon dioxide in the atmosphere and the tendency to cold and arid climates. In alternation with these revolutions or critical periods come the long ages in which the continents are slowly denuded, the continental shelves are extended landward by encroachment of the sea and seaward by sedimentation, the quota of carbon dioxide is replenished, the climate grows warm and humid, and the fauna and flora which had been impoverished gradually expand to their former luxuriance.² Darwin's doctrine of "the Imperfection of the Geological Record,"³ which affords the only reconciliation between the facts of palæontology and the theory of evolution, is immensely reinforced by the fact that these critical periods are the very points where the sedimentary record fails us. The times of rapid evolutionary change are marked only by unconformability in the stratification. Darwin's classical comparison of the geological record to a historical volume most of whose chapters have been torn out, gains vastly in force when we perceive that the chapters which are missing are precisely the ones in which the story of evolutionary change should have been recorded.

¹ Am. Jour. Sci., (3), XIV, pp. 99-114.

² Chamberlin, The Utterior Basis of Time Divisions and the Classification of Geologic History: Jour. Geology, VI, pp. 449-462.

³ *Origin of Species*, ch. IX in the earlier editions, ch. X in the later editions.

CORAL ISLANDS

It was apparently by the study of the coral formations of the Pacific that Dana was led to the conception of oceanic subsidence and continental emergence which was the dominant idea of his whole theory of the physical history of the world. This study of coral formations was doubtless the most important geological work which he accomplished in the Exploring Expedition. Dana's first introduction to the problem of barrier reefs and atolls was at the Paumotu Islands in 1839. When he arrived at Sydney, his mind was full of the problem—a problem which for him was still unsolved. But Darwin had been at work at the problem three years earlier, and at Sydney Dana learned of Darwin's theory. It seemed to him then to explain the phenomena he had studied in the regions of barrier reefs and atolls which he had already visited; and the larger acquaintance with coral formations which he gained in the course of the next two years seemed to him only to bring ampler evidence of its truth. Although the original conception was Darwin's, Dana had the opportunity to study a vastly greater number and variety of coral formations than Darwin had ever seen, so that he was able to support the theory with a greater wealth of evidence than Darwin himself. Darwin welcomed most cordially so powerful an ally. Writing to Lyell, after receiving a copy of the Report on the Geology of the Exploring Expedition, he refers to the substantial agreement of Dana's views with his own, and adds, "Considering how infinitely more he saw of coral reefs than I did, this is wonderfully satisfactory to me. He treats me most courteously."¹

The theory of Darwin and Dana may be summed up in a single word—subsidence. If there occurs, along a coast of continent or island bordered by a fringing reef, a subsidence not more rapid than the upward growth of the reef, the coral growth and consequent reef formation will be most rapid on the outer margin of the reef, where the water is purest, and the supply of oxygen and of floating life available for food is

¹ *Life and Letters*, vol. I, p. 342.

greatest; and the channel between the reef and the shore will consequently become wider and deeper. Thus the fringing reef becomes a barrier reef. If an island is girt with a coral reef, the ultimate effect of a progressive subsidence will be to carry the original island entirely under water, leaving an atoll as a monument to mark its place of burial. The most important difference between Darwin's own conception of the theory and that of Dana, was that Darwin, in the spirit of the Lyellian geology, thought of the Pacific area of coral islands as probably marking the site of a drowned continent;¹ while Dana, in accordance with his own doctrine of the essential permanence of continent and ocean, conceived the drowned lands to be only volcanic peaks, such as may be formed by submarine volcanic action in regions remote from continental land.²

The history of the Darwinian theory has been a singular one. When first announced, it produced on most scientific minds the same impression of complete satisfaction that it produced upon the mind of Dana. The subsidence of large areas of the ocean bottom which it postulates is sufficiently probable *a priori*; and the theory possesses that same charm of simplicity which characterizes Newton's conception of gravitation and Darwin's own theory of natural selection. Very naturally, therefore, for three or four decades, it was generally accepted as the one complete theory of barriers and atolls. Later researches, however, have shown conclusively that both barrier reefs and atolls may be formed without subsidence. At the southern extremity of Florida, three successive barrier reefs have been formed, all of which now have their crests almost at the same level, showing that there has been no crustal movement of any consequence.³ Chamisso long ago showed that an atoll might be formed on a submarine volcano, or on a shoal of any other origin, simply by the more luxuriant growth of corals on the margin than in the

¹ *Structure and Distribution of Coral Reefs*, London, 1842, p. 145.

² *Corals and Coral Islands*, 3d ed., p. 409.

³ Le Conte, On the Agency of the Gulf Stream in the Formation of the Peninsula and the Keys of Florida: *Am. Jour. Sci.*, (2), XXIII, pp. 46-60.

middle. Of course it was impossible to believe that several hundred submarine volcanoes had been raised to within about a hundred feet of the same level; but Murray showed that no such assumption of coincidence was necessary. A submarine volcano that did not rise into the zone of coral growth could be built up by the accumulation of skeletons of other kinds of marine life until it reached that zone; while a volcano that rose a little above the sea level might be degraded to a shoal by wave action.

But, while it is certain that both barrier reefs and atolls can be formed without subsidence, it still seems probable that there has been within late geological time a very extensive subsidence in the central part of the Pacific Ocean, and that this subsidence has been an important factor in the origin of the numerous atolls and barrier reefs of that region. In going northeastward from the zone of fringing reefs of the New Hebrides and Solomon Islands, one would traverse successively zones of barrier reefs, large atolls, small atolls, and blank ocean—an arrangement which is strongly suggestive of a subsidence progressively increasing towards the middle of the ocean. The association of fringing reefs with active volcanoes and of barrier reefs with extinct volcanoes, as pointed out by Darwin,¹ indicates that in some way the different kinds of coral formations are correlated with hypogene actions; and the explanation of that relation lies perhaps in the theory that crustal elevation in any region diminishes the pressure on the rock masses in a condition of potential liquidity a few miles below the surface, thus lowering the melting-point, so that actual liquefaction takes place, and the molten materials find their way to the surface. The active volcanoes should, therefore, be in regions where the crust has been recently undergoing elevation, while in subsiding areas the volcanoes should be extinct. The lagoons in the larger atolls often show a depth much greater than the limiting depth of coral growth. This is probably evidence of subsidence, since there are very strong objections to Murray's notion that the lagoons are extensively widened and deepened by the solvent

¹ *Structure and Distribution of Coral Reefs*, London, 1842, p. 140.

action of the sea water. "The existence of deep fiord-like indentations in the rocky coasts of islands inside of barriers," as noticed by Dana in various island groups in the Pacific, is conclusive proof of subsidence. Those bays can be nothing but drowned valleys.¹ The Funafuti core, brought up from a bore eleven hundred feet deep, is said to show no important change of character through its entire length. It appears, therefore, probable that a true coral reef rock extends down to the bottom of the bore and we know not how much farther. Such a thickness of reef could of course be formed only by subsidence. It seems probable, therefore, that Darwin and Dana were right in believing that the multitudinous barriers and atolls of the Pacific are evidence of the subsidence of a vast area.

THE HAWAIIAN VOLCANOES

Next to the study of the coral formations, the most important geological work done in the Exploring Expedition was in the study of volcanoes. Dana's study of the Hawaiian volcanoes contributed effectively, with the work of Poulett-Scrope, Lyell, and Prévost, to the demolition of von Buch's theory of craters of elevation and the establishment of a true theory of the origin of volcanic cones.² In another way, Dana's work on the Hawaiian volcanoes was important, as making known a type of volcano very different from Vesuvius and other volcanoes which had been most studied, in the almost complete absence of explosive action, and the tranquil outpouring of vast floods of highly fluid lava.

When more than threescore and ten years of age, Dana revisited the Hawaiian volcanoes which he had studied so well

¹ This important argument is one of Dana's own contributions to the theory of coral islands. *Am. Jour. Sci.*, (3), XXX, p. 92.

² "Ein klassisches Gebiet für Vulkanforschung ist der Insel Hawaii mit den beiden Riesenkegeln Mauna Loa und Mauna Kea die schon 1840 von J. Dana in meisterhafter Weise untersucht und beschrieben wurden." Von Zittel, *Geschichte der Geologie und Paläontologie*, p. 409. See also p. 397.

almost a half-century before. The results of observations old and new—the old observations viewed through the half-century of geological study—were given to the world in his *Characteristics of Volcanoes*.

THE GEOLOGY OF NEW ENGLAND

Dana made special studies of three phases of the local geology of New England and the adjacent territory: the so-called “Taconic system” of western New England and eastern New York; the trap rocks of the Connecticut Triassic; and the Glacial and post-Glacial history of New England, especially of the Connecticut Valley.

The Taconic System. A great series of schists, quartzites, and crystalline limestones extending from Canada, through western Vermont, Massachusetts, and Connecticut, into southeastern New York, was described by Ebenezer Emmons in 1842 as the “Taconic system,”¹ and by him and his followers was claimed to be older than the Champlain group of the New York geologists (now classified as Cambrian and Ordovician). The views of Emmons were by no means universally accepted when first set forth. Dissent was expressed in the discussions of the time in the Society of American Geologists and Naturalists by Edward Hitchcock, Henry D. Rogers, Mather, and James Hall. They regarded the rocks in question as folded and metamorphosed Palæozoic strata. Dana referred to the question in 1855, in his address before the American Association for the Advancement of Science, accepting then the views of the opponents of the Taconic system, though at that time he had himself given no study to these rocks in the field.² In process of time the Taconic of Emmons underwent some modifications. Emmons regarded the general structure of the Taconic rocks in western Massachusetts and eastern New York as essentially monoclinal,

¹ *Natural History of New York: Geology of New York: Part II, comprising the Survey of the Second Geological District*, pp. 135-164.

² *Am. Jour. Sci.*, (2), XXII, p. 331.

modified in detail by some folding and faulting. In 1842, therefore, he was naturally led by the prevalent easterly dip to consider the western beds of the series to be the oldest. The discovery of two trilobites and several other fossils in the "Black slate" and "Taconic slate," which he had considered the lowest members of the series, apparently convinced him that these must be the highest, instead of the lowest, strata. Accordingly, in the second version of the system, in 1844,¹ he reversed the order of the strata, however difficult it might be to give any dynamic explanation of such an inverted monoclinal series. This reversal was accompanied by a transposition of the Stockbridge limestone and the "Granular quartz" at the east end of the series, and the annexation at the west end of an extensive group of rocks, which in 1842 had been called Hudson River shales and alleged to overlie the "Taconic slate" unconformably. In 1855, Emmons divided the Taconic system into Lower and Upper Taconic.² In the illustrative sections the continuous monoclinal arrangement of the strata as figured in former publications gives place to a more complicated arrangement, in which the structure of the Greylock region is represented as synclinal. The Upper Taconic is recognized as a fossiliferous formation, though held to be older than the Potsdam sandstone, which was the oldest formation then recognized in the New York Palæozoic. The Lower Taconic was asserted to be non-fossiliferous in the Taconic region, though it was stated that in rocks supposed to be of the same age in North Carolina numerous specimens were found of one or two species of coral of the genus *Palæotrochis*—a genus which has been relegated to the limbo of pseudo-fossils.

Dana took up the investigation of the subject in the field in 1871, and the results of his work were presented in a series of papers mostly published in the *American Journal of Science*

¹ First published in pamphlet form; included in 1846 in the *Agriculture of New York*, vol. I, as chapter V.

² *American Geology*, vol. I, part II, pp. 1-122. Substantially the same view is presented in his *Manual of Geology*, pp. 81-89.

from 1872 to 1888.¹ In the course of these years he made a thorough study of the rocks in question in many localities ranging from Vermont to Manhattan Island. In 1875 he had as his companion on one of his excursions Rev. Augustus Wing, who had then been studying the Taconic rocks for ten years, though he had been too modest to give his work to the public. With the generous appreciation of the labors of others which always characterized Professor Dana, he availed himself of the opportunity to rescue from undeserved oblivion the discoveries of a patient and conscientious investigator. Only after the death of Mr. Wing in 1876, a letter came to light which he had written to Professor Dana in 1872, but which his extreme modesty had prevented him from ever sending. The contents of that letter Dana published with annotations.² In 1870 Wing had discovered Ordovician fossils in the Eolian limestone of Vermont, the equivalent of the Stockbridge limestone of Massachusetts, which formed a part of Emmons's Lower Taconic. As years passed on, numerous fossils were discovered by Dale, Dwight, and others in various localities and at various horizons of the Taconic system. In 1886 and 1887 the number of known fossils from the Taconic was greatly augmented by the discoveries of Walcott, and the stratigraphy of the rocks was studied with his usual thoroughness. The independent work of Walcott completely confirmed the conclusions already reached by Dana.³ The investigations of Dana and others showed clearly that no part of the Taconic system was pre-Cambrian, and that the whole series was made up of alternations of Cambrian and Ordovician strata. Dana was truly justified in closing his final

¹ Am. Jour. Sci., (3), III, pp. 179-186, 250-256, 468-471; IV, 362-370, 450-453; V, 47-53, 84-91; VI, 257-278; XIII, 332-347, 405-419; XIV, 36-37, 37-48, 132-140, 202-207, 257-264; XVII, 375-388; XVIII, 61-64; XX, 21-32, 194-220, 359-375, 450-456; XXI, 425-443; XXII, 103-119, 313-315, 327-335; XXVIII, 268-275; XXIX, 205-222, 437-443; XXXI, 241-248, 399-401; XXXII, 236-239; XXXIII, 270-276, 393-419; XXXVI, 410-427; Am. Nat., VI, 197-199; VII, 708-710; Proc. Am. Assoc. Adv. Sci., XXII, pt. 2, pp. 27-29; Quart. Jour. Geol. Soc., XXXVIII, pp. 397-408.

² Am. Jour. Sci., (3), XIII, pp. 332-347, 405-419.

³ *Ibid.*, (3), XXXV, pp. 229-242, 307-327, 394-401.

article, entitled *A Brief History of Taconic Ideas*, with the simple monumental inscription, "1842-1888."

The Taconic question was primarily a question of local stratigraphy. It was, however, very much more than this. The settlement of the age of the Taconic rocks fixed the date of the first important epoch of orogenic disturbance in the post-Archæan history of North America. As the Appalachian revolution forms the boundary between Palæozoic and Mesozoic time, and the Laramide revolution the boundary between Mesozoic and Cenozoic time, so the Taconic revolution stands as a boundary between Ordovician and Silurian time. There is good reason to believe that the orogenic disturbance at this date extended southward as far as Virginia, though whatever mountains of Taconic date were formed south of New York have disappeared in the process of degradation. The Taconic Mountains on the western boundary of New England stand as a topographic monument of the Taconic revolution.

The settlement of the age of the Taconic rocks was important also as establishing a perfectly clear case of somewhat highly crystalline rocks of Palæozoic age. It thus contributed, with other similar discoveries in various parts of the world, to afford conclusive proof that highly crystalline rocks are not necessarily pre-Cambrian; that metamorphism, resulting in the production of highly crystalline schists, may have taken place at any age in the earth's history; and that a crystalline terrain is known to be pre-Cambrian only when overlain by strata of Lower Cambrian age. The work of Dana thus effectually antagonized a neo-Wernerian school of geologists, now happily extinct or nearly so, who fancied that crystalline minerals might serve, like fossils, for the determination of geological age.¹

¹ "Repeated examples have shown that the most skillful stratigraphists may be misled in studying the structure of a disturbed region where there are no organic remains to guide them, or where unexpected faults and over-slides may deceive even the most sagacious. I am convinced that in the study of the crystalline schists, the persistence of certain mineral characters must be relied upon as a guide, and that the language used by Delesse, in 1847, will be found susceptible of a wide application to crystalline strata:

While Dana's work on the Taconic question contributed very largely to the prevalence of sound views in regard to the occurrence of metamorphism at various geological periods, it must be recognized that in some respects his views on the subject of metamorphism were peculiar, and have not won their way to general acceptance. It is interesting to note an extraordinary article which he published in 1843,¹ showing his opinions in relation to metamorphism at that stage of his career. In that article he proposed to establish three propositions:²

"1st, That the schistose structure of gneiss and mica schist is no satisfactory evidence of a sedimentary origin;

"2d, That some granites with no trace of a schistose structure may have had a sedimentary origin;

"3d, That heat producing the changes that are termed metamorphic was not applied from beneath by conduction from some internal source of heat; on the contrary it was applied through the waters of the ocean, covering and permeating the deposits

'Rocks of the same age have most generally the same chemical and mineralogical composition, and, reciprocally, rocks having the same chemical composition and the same minerals, associated in the same manner, are of the same age.' In this connection the testimony of Professor James Hall is also to the point. Speaking of the crystalline schists of the White Mountain Series, he says: 'Every observing student of one or two years' experience in the collection of minerals in the New England States knows well that he may trace a mica schist of peculiar but varying character from Connecticut, through central Massachusetts, and thence into Vermont and New Hampshire, by the presence of staurolite and some other associated minerals, which mark with the same unerring certainty the geological relations of the rock as the presence of *Pentamerus oblongus*, *P. galeatus*, *Spirifer Niagarensis*, or *S. macropleura*, and their respectively associated fossils, do the relations of the several rocks in which they occur.' " Hunt, *Chemical and Geological Essays*, p. 271.

"It is only by bringing together observations, as I have done, that we can ever hope to determine the geological value of these mineral fossils. In no other way did William Smith prove, in Great Britain, the value of organic fossils, and thus lay the foundations of palæontological geology." *Ibid.*, p. 327.

¹ Am. Jour. Sci., (1), XLV, pp. 104-129.

² *Op. cit.*, p. 105.

which received their high temperature from the eruption itself. In other words, the metamorphic rocks so-called are not *hypogene*, as explained by Mr. Lyell, but—to use corresponding phraseology—*epigene*.”

The third of these propositions seems hardly better than a vagary. Of course Dana soon escaped from that delusion, and recognized metamorphism as a hypogene process.

The first proposition he never categorically contradicted, but in later years he was disposed greatly to limit the range of its application. In 1884, while admitting the possibility of the development of schistosity by pressure, he declares, “I have never yet examined any gneiss without finding good evidence that it was part of a stratified series.”¹

The second proposition he maintained to the end of his life, insisting that granite and allied plutonic rocks are, at least in many cases, altered sediments. In the first two editions of the *Manual of Geology*, a section of the chapter on lithology bears the title, “Metamorphic or Crystalline Rocks.” In these editions the statement appears, “These rocks are sometimes called plutonic rocks, to distinguish them from the true igneous rocks.” The term “igneous rocks” seems here to be substantially synonymous with volcanic rocks. Not until the third edition of the *Manual* (1880) do we find granite included in both the metamorphic and the igneous rocks. This is especially remarkable in connection with the fact that in 1843 Dana distinctly recognized both igneous and metamorphic granites. In the cases so frequently occurring of a crystalline terrain which in one part is massive and in another part more or less distinctly foliated, as where a granite grades into a gneiss, or where a gabbro grades into a hornblende gneiss or hornblende schist, Dana held that the rock was originally stratified, and that the massive phase marked a more extreme metamorphism than the foliated. It is certain he never came to any adequate appreciation of the power of dynamic metamorphism to transform plutonic rocks into gneisses and schists.

¹ Am. Jour. Sci., (3), XXVIII, p. 396.

The Trap Rocks of the Connecticut Triassic. Surely no resident of New Haven could fail to have his attention attracted by East and West Rock. The careful study which Dana gave to "the Four Rocks" of the New Haven region showed unmistakably that the trap of these picturesque hills forms intrusions in the Triassic sandstones. It was a hasty but not unnatural generalization which led Dana to assert that the same structure extends through the long series of ranges of trap hills from Saltonstall Ridge to Mount Holyoke. The substantial identity in chemical and mineralogical constitution of all of the traps of the Connecticut Valley naturally suggested that they all belong to one epoch of vulcanism. But a single epoch of vulcanism may afford both extrusions on the surface and intrusions in underlying rocks; and, when stratified rocks with interbedded sheets of igneous rock are tilted and extensively eroded, the topographic forms resulting from extrusive and intrusive sheets may be substantially the same. The general form of West Rock is the same as that of the Meriden Hills, but the topography is due simply to the resistance which the trap offers to erosion, and is independent of the question whether it is contemporaneous or intrusive. The clear proof of the extrusive character of the trap sheet in the Meriden Hills and Mount Holyoke presented by Davis, Emerson, and others, failed to convince Dana of the error of his generalization. Had their work come earlier, one cannot help thinking that his candid spirit would have recognized the force of the evidence.

Glacial and Post-Glacial History of New England. When the first edition of the *Manual of Geology* was published, opinion was still divided in regard to the origin of the heterogeneous mantle of clay, gravel, and boulders covering much of the area of Canada and the northeastern United States, as well as northwestern Europe, and commonly called "drift." In opposition to the earlier diluvial theories, Agassiz had advocated the doctrine that the drift was due to the action of a glacier of continental extent. Dana clearly indicated his sympathy with the views of Agassiz in his address before the American Asso-

ciation in 1855, and in the first edition of the *Manual of Geology* the glacier theory of drift was unqualifiedly adopted. Thenceforward the great influence of the *Manual of Geology* was unquestionably an important factor in the rapid progress of the glacier theory to substantially unanimous acceptance. When we remember that in 1865 Lyell still maintained the submergence of the plain of northern Europe and of the glaciated region of North America,¹ and that it was not until 1875 that Torell convinced the German geologists that the drift of northern Germany was transported by an ice sheet whose centre was in the mountains of Scandinavia,² we shall appreciate the importance of Dana's influence in gaining for the glacier theory the general acceptance of American geologists. In 1873 Dana recognized the terminal moraine of the great ice sheet forming the crest of the Backbone of Long Island.³

While Dana was thus one of the most influential defenders of the glacier theory of the drift, he failed to keep pace with the development of glacial geology in the later decades of his life. He had studied drift only in New England, where the ice sheet of the Wisconsin epoch has pretty thoroughly obliterated the traces of earlier ice invasions; and he was slow to appreciate the abundant evidence of the complexity of the Glacial period accumulated by the glacialists of the Mississippi basin.

The cause of the glacial climate Dana held to be the elevation of northern lands. Even in the last edition of the *Manual* he asserts that the direct effect of elevation of land supplemented by the effect of consequent changes in the course of ocean currents would be a sufficient cause for the glacial climate.⁴ At the date of the publication of the last edition of the *Manual*, most geologists were very skeptical as to the adequacy of that explanation, though perhaps at that time there was nothing better available. Dana refers to the theory of Croll, and justly, I think, finds it unsatisfactory. That a high eccentricity

¹ *Elements of Geology*, 6th English ed., pp. 149, 164.

² Von Zittel, *History of Geology and Palæontology*, p. 539.

³ *Am. Jour. Sci.*, (3), V, p. 210.

⁴ *Op. cit.*, p. 978.

of the earth's orbit would produce some climatic change seems probable; but whether it would produce any decided effect in the direction of glaciation, and, if so, whether the tendency to glaciation would be manifest in the hemisphere with aphelion winter or in the hemisphere with aphelion summer, is altogether uncertain. Tyndall had noticed, some decades previously, the important influence of absorption of heat by carbon dioxide, and suggested the possibility that fluctuations in the amount of carbon dioxide might have been a cause of climatic changes in geological time; but the development of that suggestion into a definite theory of the cause of glacial climate, by Arrhenius and Chamberlin, is subsequent to the completion of Dana's life work.

In the period from 1870 to 1883 Dana made considerable study of river terraces, and published a number of papers on the effects of the melting of the great ice sheet.¹ Unhappily, this part of his work was vitiated by a totally wrong conception of the dynamics of river action. He believed that the upper terraces were built up by the river while it kept open a deep and broad channel whose bottom was not much if at all above the present bottom of the river. He was inclined to think that the lowest terrace, which in the upper Connecticut has usually an altitude of from sixty to eighty feet above the present river bed, may have extended across the river at the time of the post-Glacial flood, and may have constituted then the bottom of the river.² This supposition, of course, leads to the conclusion that the melting of the ice sheet was so rapid as to produce perfectly enormous floods in the rivers. He concluded that the Connecticut River was, at the maximum of the flood, 185 feet deep at Haverhill, New Hampshire, and 125 feet deep at Hartford.³

¹ Trans. Conn. Acad., II, pp. 45-112; Am. Jour. Sci., (3), I, pp. 1-5, 125-126; II, 233-243, 324-330; V, 198-211; X, 168-183, 280-282, 353-357, 409-438, 497-508; XI, 178-180; XII, 125-128; XXII, 451-468; XXIII, 87-97, 179-202, 360-373; XXIV, 98-104; XXV, 440-448; XXVI, 341-361; XXVII, 113-130.

² Am. Jour. Sci., (3), XXIII, p. 187.

³ *Ibid.*, p. 188.

For a good deal of the distance the channel between the upper terraces had a breadth of more than a mile at the top and more than a half-mile at the bottom. Dana noticed, only to reject, the view of Warren Upham that "the filling up of the Connecticut Valley with stratified drift took place in the era of the melting, or the Champlain period, and the excavation of the channel and the making of the terraces in a later era." "This hypothesis," says Dana, "makes two great floods necessary to the results, one for transportation and deposition, and another for abrasion, when, in fact, one may have done both."¹ On the supposition that no crustal movements intervened between the date of the post-Glacial flood and the present time, Dana reckoned that the slope of the river from Haverhill to Long Island Sound must have been more than three feet per mile, which would give for different sections of the river velocities ranging from ten to sixteen miles per hour. He recognized, of course, that such a velocity is obviously inconsistent with the fact that vast masses of fine sands and clays have been left all along the Connecticut Valley. He speculated, therefore, on the possibility of the velocity in some places having been diminished by dams of ice. He believed in 1882 that the only place where the formation of such a dam seemed probable was at Middletown, where the river passes from its broad valley in the Triassic to its narrow gorge in the crystallines;² though he later adopted the view that another dam existed between Mount Tom and Mount Holyoke.³ A dam at Middletown might account for clay deposits near Hartford; but a dam at Middletown or even one near Northampton would not account for deposits of fine material along the upper course of the Connecticut. He then considered the possibility of a tilting of the land. The elevated beaches near the mouth of the St. Lawrence show that probably the level of the land in New Hampshire and Vermont was lower at the time of the melting of the ice sheet than now, but he found it difficult to postulate any probable

¹ *Am. Jour. Sci.*, (3), XXIII, p. 92.

² *Ibid.*, p. 195.

³ *Manual of Geology*, 4th ed., p. 992.

attitude of the Connecticut Valley which would reduce the slope sufficiently to account for the fine sediments which have been left even far up the valley. There is something rather pathetic in the dilemma in which Dana found himself, as witnessed by the following sentences: "It is quite certain that the slope must have been much less than that which corresponds to a height of water-surface at Haverhill of 387 feet, or a pitch in the valley to Springfield of twenty-one inches a mile. But it is not so evident what slope would harmonize the facts; that is, would cause a velocity sufficient to make or leave coarse valley deposits near and at flood level, such as might be made by a current of four to six miles an hour, and, at the same time, leave almost undisturbed beds of sand or of fine pebbles along its bottom."¹

Of course, the problem proposed in these sentences is insoluble. Under no conditions could a river produce effects which are essentially irreconcilable with each other. The view of Upham, which Dana considered and rejected, is substantially true. If the material of which the terraces are composed was deposited by the river, it must have been deposited at a time when, by diminished slope or by overloading, its capacity for erosion and transportation was made vastly less than when the present deep channel was carved. So far from Upham's supposition requiring two floods, one for deposition and one for erosion, it does not necessarily require any flood at all. A river whose volume was not very different from that of the Connecticut at the present time could, under one set of conditions of slope and load, have filled its valley and formed a wide drift plain over which it meandered, and, under other conditions, could have carved the present channel, leaving remnants of the old drift plain as terraces. The brief but wonderfully clear and incisive discussion which Gilbert has given in his *Report on the Geology of the Henry Mountains*² illuminates the whole subject of river terraces. The truer interpretation of the terraces would abolish the necessity for any enormous flood, and enable us to hold, what

¹ Am. Jour. Sci., (3), XXIII, p. 200.

² *Op. cit.*, p. 132.

is certainly more probable, that the melting away of the great ice sheet was a slow process extending over a long period of time.

It may be remarked that it is highly probable that, in some cases, the deposits now forming the highest terraces were not formed by the river at all, but were rather in the nature of deltas from the melting ice, formed at a time when local glacial tongues still occupied the central parts of the valley. This view has been adopted by Woodworth in regard to the terraces of the Hudson estuary,¹ and by Gulliver in regard to the terraces of the estuarine portions of the Thames² and the Connecticut. The truth of this view in regard to the terraces of the Connecticut just below Middletown seems to me unquestionable. Moreover, the question raised by Professor Fairchild demands serious consideration—How far up the valley of the Connecticut did estuarine conditions exist at a time when the Hudson-Champlain Valley was a strait?³

DANA'S WORK AND CHARACTER

So long as science is progressive, the study of the works even of the greatest scientists must be largely a study of errors. The great minds to whom it is given to see visions of new truth, almost always first see the truth dimly and imperfectly. Like the blind man in the Gospel, when first they see, they "see men as trees walking." Already those who estimate most highly the teaching of Dana have abandoned some of the geological opinions which he held to the end of his life, and which find expression even in the latest edition of the *Manual*. The psychology of error is not always easily intelligible; and in the works of the greatest men we find errors of a sort which we are at a loss to account for. We wonder how they could have fallen into them. Reference has already been made to a few such errors in the work of Dana; as, for instance, the notion of metamorphism by

¹ Bull. N. Y. State Museum, No. 84, pp. 79-86.

² Bull. Geol. Soc. America, X, pp. 492-495.

³ Pleistocene Marine Submergence of the Connecticut and Hudson Valleys: Bull. Geol. Soc. America, XXV, pp. 219-242.

epigene action, the conception of the oceanic depressions as being due to the fact that the continents are the first areas of the crust that solidified, and the impossible process of formation of river terraces. Such was the strange piece of Paleyan natural theology which appeared in the earlier editions of both the *Manual* and the *Text-book of Geology*, in the statement that the North American continent was made humid and fertile by the felicitous placing of the Cordillera on the western border—a position which is in fact the cause of aridity and sterility to a vast area.¹

But oftentimes the errors of great men are closely connected with the very mental characteristics to which are due their great achievements. Their faults are "the defects of their qualities." Dana was preëminently a generalizer and a systematizer. Amid the multiplicity of phenomena, he looked for the unity of principle; and again and again he saw that unity where others had failed to find it. This was what made Dana one of the few great leaders in scientific thought. Facts may be, as Agassiz so nobly said, "the words of God"; but the words mean nothing to us until we can arrange them in sentences. From its first publication in 1863, the *Manual of Geology* has been, for every American geologist, the one supremely indispensable book for its encyclopedic array of facts; but the general conception of the meaning of geological fact, with which the whole book is luminous, is the greater glory. With his irrepressible instinct for systematization, generalization, and unification, it is no wonder that Dana sometimes mistook analogy for identity, and sometimes grouped facts in a pseudo-system. The only man who has made no unsound generalization is the man who has never generalized at all. An example of such unsound generalization is seen in his metaphysical dogma as to the meaning of species, in which he sought to extend one formula to things so entirely diverse as chemical elements and compounds on one hand and plants and animals on the other. In like manner, in

¹ He even speaks of "the drying Pacific winds." *Am. Jour. Sci.*, (2), III, p. 100.

the working out of his principle of cephalization, mere analogy was oftentimes treated as identity. His vision of the magnificent unity of continental evolution led him to picture the history as a substantially continuous emergence of the continents from the sea, with only trifling oscillations. The very clearness of his vision of the essential unity of the epoch of vulcanism in the Triassic of eastern North America prevented him from recognizing that, while the traps at New Haven were intrusive, the traps at Meriden were extrusive.

No just criticism of his errors can dim the glory which belongs to his unique achievements. His panoramic view of geological history gave dynamic unity to geology in general and to American geology in particular. When we consider how profound and far-reaching in modern geological thought is the influence of ideas of which we owe to Dana the origination or elaboration, we shall be in full accord with the estimate of von Zittel in his *Geschichte der Geologie und Paläontologie*: "He was incontestably the first geologist of North America, and, especially by his epoch-making *Manual of Geology*, he exerted a decisive influence upon geological study."¹ There will seem to be no exaggeration in the still stronger statement of Prof. John W. Judd, in a letter to Prof. Edward S. Dana on the occasion of his father's death: "Geologists and mineralogists all over the world will feel that the greatest of all the masters of our science has now passed away."

Our theme is Dana the Geologist, not Dana the Man. It would, therefore, be irrelevant to speak of those moral and social traits which commanded the respect and love of those who came into intimate relations with him. I must say nothing of his gentleness and courtesy, his courage amid perils, his patient cheerfulness under the restraints and burdens of ill health, his purity and conscientiousness in every relation in life, and the religious faith which, in his thought, sanctified all the work and

¹ "Er galt unbestritten für den ersten Geologen Nordamerikas, und übte namentlich durch sein epochemachendes *Lehrbuch der Geologie* einen entscheidenden Einfluss auf das geologische Studium aus." *Op. cit.*, p. 459.

all the experience of life. But there is one trait of his character which was both moral and intellectual—one virtue which he conspicuously exemplified which is intimately related to his intellectual achievements. The characteristic that most impressed all who came to know him, whether through personal intercourse or only through the reading of his works, was his profound sense of the sacredness of truth.

The ethical virtue of truthfulness is naturally associated with the intellectual power of clear thinking. The man who never knows exactly what he thinks, whose conceptions are all more or less nebulous, falls easily into the vice of saying something a little different from what he thinks. On the other hand, the man who thinks clearly and who has acquired the power of accurate expression is naturally truthful. The whole discipline of the man of science is an ethical training in the virtue of truthfulness. In some other intellectual professions, men speak and write primarily with the purpose of influencing the conduct of others. They deal with questions in which great interests are involved and strong passions are aroused. Under such conditions, even men of high moral character are tempted to make representations not quite true, in order to make the arguments for the course of conduct which they are advocating seem stronger than they really are. The work of the scientific man is largely detached from the sphere of practical life. The habit of investigating where there is no strong reason for desiring one conclusion rather than another, and the habit of speaking and writing where there is no motive for misrepresentation, strengthen day by day in the true scientific man the habit of truthfulness.

In this virtue, wherein scientific men as a class may justly claim preëminence, the great master of American Geology was an illustrious pattern. With absolute sincerity he sought to know the truth and to communicate to others the truth as it had revealed itself to him. No pride in what is wrongly called consistency wrought in him unwillingness to accept new light. He seemed to take pleasure in confessing ignorance or error. In the third edition of his *System of Mineralogy*, when he cast

aside the classification and the Latin binomial nomenclature of the former editions, he wrote in the preface: "To change is always seeming fickleness. But not to change with the advance of science is worse; it is persistence in error." He said to me, in speaking of the changes introduced in the third edition of the *Manual of Geology*, "When a man is too old to learn, he is ready to die; or at least he is not fit to live." The frankness with which he changed his opinions and his teachings on the subject of evolution, when past threescore years of age, is a striking illustration of his loyalty to truth, and of the perennial intellectual youth which is the reward that truth gives to her loyal worshippers. The same exquisitely delicate sense of truth which made him so ready to change opinions, made it easy for him to hold opinion in abeyance. He knew that he did not know some things, and he would not assert plausible conjectures as truths. Professor Farrington has preserved some of the aphorisms which he uttered from time to time, and which might well be adopted as maxims by all students of science.¹ "I think it better to doubt until you know. Too many people assert, and then let others doubt." "I have found it best to be always afloat in regard to opinions on geology." "I always like to change when I can make a change for the better."

His liberality in the treatment of difference of opinion was another phase of his devotion to truth. Sensible of the liability to error attending the beliefs of all men, he recognized that only by the criticism of opposing views could truth be reached. The pages of the *Journal of Science* were always freely open for the presentation of views most widely divergent from those of the editor. "More," he said, "could be learned by studying unconformities than conformities,"¹ and this he believed to be as true of unconformable opinions as of unconformable strata.

While we honor the insight of the geologic seer who gave to the world a new vision of the "one increasing purpose" which makes the unity of nature, it is meet that we should also pay the tribute of our reverence to that loyalty to truth which made the

¹ Jour. Geology, III, pp. 336, 339.

consistent unity of his own intellectual life. If we may not share "the vision and the faculty divine" which he possessed, the study of his work may give us a deeper sense of the sacredness of that quest of truth to which we too are called.

CHAPTER II

PROBLEMS OF THE CANADIAN SHIELD

I. THE ARCHÆOZOIC

FRANK DAWSON ADAMS, D.Sc., F.R.S.

INTRODUCTION

In the history of ancient peoples, in those gray beginnings of nations when the first movements of national life are commencing to be discernible, we find that all is indistinct and uncertain. A few of the greatest and most striking figures loom up like giants in the misty and often golden distance. This is the time of legends and of heroes.

With careful study, however, made fruitful by new methods of research, the light of knowledge penetrates ever farther backward into these abysses of past time. Aided by the pickaxe and the spade, we are now coming to understand many things with reference to the stories of Hercules and the Thracian Minotaur, of Helen and the siege of Troy, and even of the still earlier times before the age of bronze, concerning which it seemed at one time impossible that any certain knowledge could ever be secured.

It is to the elucidation of what I might call the heroic period of the history of our earth—so far as our study of the Canadian Shield has thrown gleams of light upon this ancient time—that I have been invited to address myself in these lectures. Let me, therefore, endeavor to outline in some general way our present knowledge of these dark places of the earth, indicating in so doing some of the still unsolved problems of the deeper portions of the Canadian Shield, the answers to which must be obtained—

if indeed they can be found—though not as in human history with the pick and shovel—at least with those tools which in geological investigations take their place, the compass and the hammer.

Here we are at once brought face to face with our first difficulty. I have been invited to speak to you first of the Archæozoic of the Canadian Shield, and my friend, Dr. Coleman, has been asked to follow me and to speak of the Canadian Shield in Proterozoic times. While, however, nearly the whole of the Canadian Shield lies within the bounds of the Dominion of Canada, the geologists of that country do not divide the pre-Cambrian in this manner; some of them do not think that these divisions can be recognized in Canada, and Dr. Coleman and I were unable to determine the limits of our respective fields.

With the full permission of the Dana Lecture Committee, therefore, and with their hearty approval, we have agreed upon a division of the subject whereby I am to touch upon certain facts concerning the form and topographic features of the shield and upon certain problems presented by its older or deeper lying parts, while Dr. Coleman will deal with the more recent pre-Cambrian times and the questions and problems presented by their strata.

And first—What is the Canadian Shield?

From beneath the broad table-land of horizontal Palæozoic rocks which occupies so large a part of northeastern North America, the underlying pre-Cambrian rocks emerge in its central portion like a flat shield. "It is to the exposed Archæan surface," says Suess in his great work, *Das Antlitz der Erde*, "that we give the name of the Canadian Shield." The ancient rocks composing it were folded and planated in pre-Cambrian times, while the Palæozoic strata now lie horizontally on their upturned edges. Except on the northeast, the shield is still encircled by the border of flat-lying Palæozoic strata, the contact being accentuated by a remarkable series of lakes—"glint lakes" Suess calls them, following a Russian usage derived from the corresponding (Baltic) shield in Europe—which are distributed along its margin.

The important rôle played by the Canadian Shield in the structure and development of the continent of North America was long since pointed out by Dana, who, in the second edition of his *Manual of Geology*, published in 1875, refers to it as the "Great Northern Nucleal Area of Archean Rocks," which, he says, has the shape of the letter V. By the time of the publication of the fourth edition of the *Manual* in 1895, exploration had materially extended our knowledge of the geology of northern Canada, and Dana in this edition refers to this area as being "approximately V-shaped in its southern part," the arms of the V closely following in direction the eastern and western coast lines of the present continent respectively. Further exploration in the north since that time shows that the Canadian Shield has a rudely circular outline, especially if Greenland be considered as a portion of the nucleus.

Where the northeastern boundary of the Canadian Shield should be drawn is still a matter of question; for while the pre-Cambrian rocks composing it extend uninterruptedly to Davis Strait and Baffin Bay and reappear again, forming the greater part of Greenland, the more or less level expanse of the shield is interrupted along the northeastern shore of North America by a tract of higher country, in places rising into mountain ranges which skirt the Atlantic coast from the Strait of Belle Isle to Cape Sabine in Smith Sound, a distance of nearly 2000 miles. These in places are known to have an elevation of 6000 feet, while some of the peaks near Eclipse Bay are estimated by Daly to be as much as 7500 feet high. This mountainous belt is considered by Suess to form the eastern border of the shield. If, however, the shield be conceived of as extending to the easterly margin of the Archæan exposures, and the ranges in question be regarded as elevations traversing it, thrown up possibly by more recent faulting, the Canadian Shield would embrace not only the ranges in question but a large part, if not the whole, of Greenland. Confining our attention, however, to that part of the shield which lies within the confines of North America proper, and which is situated to the west of the belt of mountainous country referred to above, the Canadian

Plate I

Shield is found to possess a very uniform and well-marked physiographic character.

THE PHYSIOGRAPHIC CHARACTER OF THE CANADIAN SHIELD

It forms a great expanse of country, having an area of about 2,000,000 square miles and an average elevation of about 1500 feet above sea-level. It seldom reaches an elevation of over 2000 feet, the highest portion being found in Central Labrador, which is approximately 2400 feet above the sea. It is interesting to note that the physiographic features of the Canadian Shield as a whole, as above outlined, namely, a great plateau nearly uniform in elevation, but rising to a somewhat greater height near its eastern margin and bounded on the east by a range of mountains, are to a certain extent repeated in that relatively small outlying portion of the shield which is situated in the state of New York and which is known as the Adirondack Mountain region. As stated in a recent paper by W. J. Miller,¹ "this is roughest along the northeastern and eastern sides, less rough along the southeastern and southern sides, and very smooth along the southwestern side." The mountains in the eastern Adirondacks, some of them rising to elevations of 5000 feet or more, present some of the highest land in the whole Canadian Shield, elevations which are comparable only to those of the mountain range facing the Atlantic coast in Labrador, to which reference has been made.

The accentuation of the great plateau-like expanse of country forming the Canadian Shield is remarkably low. The surface has a hummocky or gently undulating character. Over great tracts an elevation 150 feet above the general surface forms a marked topographic feature, a hill 300 feet high is rarely seen, while a hill rising to a height of 500 feet above the general level can hardly be found anywhere except perhaps in the Adirondack district where faulting has developed a more rugged topography.

When standing on the summit of any of the higher elevations,

¹ Early Palæozoic Physiography of the Southern Adirondacks: Bull. N. Y. State Museum, No. 164, 1913, p. 81.

Plate II. View of the Canadian Shield from the south end of Lake Michikama, Labrador. This is the largest lake in Eastern Labrador.

an uninterrupted view of the country for long distances is obtained, and its character as a vast peneplain is displayed in a striking manner. The horizon is a level line broken only by a very few monadnocks formed by harder masses. On the surface of this peneplain the forces of erosion have etched a very shallow pattern whose depressions are occupied by the lakes and rivers forming the drainage system of the country. In designating this surface as a peneplain it must be mentioned that the term is here employed as descriptive of the nearly level character of the country without the implication of any definite origin for this remarkable land form.

As is well known, the central portion of the shield is depressed slightly below sea-level and there rests upon it here the shallow body of water known as Hudson Bay, which has a depth of about seventy fathoms. The great peneplain of the Canadian Shield also carries upon its surface thousands of lakes, great and small, occupying slight depressions in its surface. These are connected by a maze of streams. In this respect it finds an exact counterpart in the Baltic Shield. These lakes and the streams connecting them form a remarkable series of waterways for canoe travel, by which it is possible to pass from any one part of the shield to any other if the path is known, and it was by these lines of water travel that the Indians, the French voyageurs, and the traders of the Hudson Bay Company penetrated the country to its most remote recesses. When a careful study is made of any area, it is found that this maze of lakes and streams, etched out of the surface of the country, often brings out with remarkable fidelity the details of its geological structure, the courses of the rivers tending for long distances to follow the strike of the foliation of the gneisses, and the lakes being frequently hollowed out of belts of softer rock enclosed in the harder and more resistant gneisses which underlie the greater portion of the area.

Another interesting fact in connection with this drainage system is the existence of a number of deep cañons radiating out from the interior of the peneplain toward its circumference. Among these may be mentioned that occupied by the Saguenay

River from Ha-Ha Bay to the St. Lawrence River. The sheer grim walls of this cañon, composed of bare granite or gneiss, rise on either side of the river to a height of 1000 feet or more. At Cape Eternity the cliff is 1500 feet high, while the Admiralty soundings show that the river is here 876 feet deep, giving a total height to the cañon wall of 2376 feet. Having passed the bar at its mouth, there is not a shoal or rock, and the river is navigable for the largest ship afloat as far as Point Roches, a distance of fifty-seven miles from the point where it enters the St. Lawrence, its depth averaging about 600 to 700 feet.

Another of these cañons is that through which flows the Cold-water branch of the Mingan River, which Baddeley describes as running through a cañon 2000 feet deep. Still another is occupied by the lower reaches of the Hamilton River, which enters the Atlantic Ocean on the coast of Labrador in about 54° North Latitude.

Lake Temiscaming, out of which flows the Ottawa River, occupies a similar cañon-like depression, the walls of which are from 800 to 1000 feet in height. The Ottawa flows through this cañon to the south as far as Mattawa. North of Lake Temiscaming the cañon is occupied by Wabi Creek; while still further to the north, I am informed by Dr. Barlow, it becomes filled up by horizontal strata of Niagara age, the relation of which to the pre-Cambrian is of such a character as to indicate that the cañon originated in pre-Niagara times. Many other similar cañons might be mentioned, occurring in widely separated portions of the shield.

The age of the peneplain is one of the unsolved problems of the Canadian Shield. Although its surface was undoubtedly modified by the great ice sheet of the Pleistocene, it long antedated this period. Along its margin in Ontario, the *roche moutonnée* surface can be seen to pass beneath the Palæozoic strata, here of Ordovician age. Sir Archibald Geikie has drawn attention to the same phenomenon in the case of the pre-Cambrian rock surface in the north of Scotland, where the *roche moutonnée* surface passes beneath the horizontal strata of the Torridon sandstone. It seems probable that the peneplain is

the result of long continued subaërial decay and of successive glaciations, the earliest of these possibly dating back to Huronian times, in whose conglomerates Dr. Coleman sees evidence of morainic origin and of the existence of widespread glacial conditions. Possibly marine denudation also may at some time during these past ages have played a part in this process of widespread denudation. The great cañons referred to above in all probability represent ancient river valleys deepened by subsequent glaciation, as the most recent investigations seem to show was the case in the development of the fjords of the Norwegian coast.

The average elevation of the peneplain being, as before stated, about 1500 feet, the rainfall over this vast area of two million square miles, passing outward, cascades down over the margin of the peneplain into the sea or on to the surface of the plain which bounds it on the north and west, giving rise to a great number of waterfalls, representing an immense water power, which is now being utilized at many points and made the basis for the development of a number of great industries.

The Canadian Shield is a region which has but very limited agricultural possibilities except where blanketed by lacustrine strata, as in the great clay belt of northern Ontario and north-western Quebec, which is crossed by the National Transcontinental Railway. Its southern portion, however, is covered with a forest of immense value, which, if properly husbanded by employing modern methods of conservation, will be a great and permanent source of wealth to the Dominion of Canada, while the northern portion of the area might be made a perpetual dwelling-place for the fur-bearing animals.

The fact that this great area of rough and broken country, which is not susceptible of continuous settlement, is as it were, driven down into southern Canada like a great wedge, separating the older provinces of eastern Canada from the great plain of western Canada and the province of the Pacific coast, develops certain social and political conditions which, although not coming within the purview of the science of geology, are none the less problems presented by the Canadian Shield.

GEOLOGICAL STRUCTURE OF THE CANADIAN SHIELD

The exploration carried on far and wide over the Canadian Shield shows that it is composed for the most part of gneisses and gneissic granite, most of which is of igneous origin. This is the Laurentian System. There are, however, distributed over the surface of the shield, chiefly in the form of long and relatively narrow belts, certain very ancient sediments, pre-Cambrian in age. These belts occupy the position of synclinal folds which have sagged down or have been forced down into the igneous rocks of the Laurentian which surround and underlie them. With each advance of exploration into the unsurveyed portions of the shield, additional occurrences of these ancient sediments are discovered. These belts in the southern half of the shield have a prevailing northeast and southwest strike, indicating the trend of ancient folds, which probably developed as mountain ranges in pre-Cambrian times, having a general direction parallel to the present course of the river and gulf of St. Lawrence. One of the longest, best defined, and most striking of these folds is the geosyncline, which, starting from the north shore of Lake Huron, extends past Lake Temiscaming, Lake Abatibbi, to Lake Mistassini, and thence on in a northeasterly direction till it is lost in the unexplored portion of Labrador peninsula. The original Huronian area of Logan lies in this belt, which also contains some of the greatest mineral deposits of the world, the nickel and copper ores of Sudbury, the silver ores of Cobalt, and the gold deposits of Porcupine.

Along the southeastern border of the Canadian Shield the ancient sediments are represented chiefly by limestones, while the northern and western synclines are occupied chiefly by sandstones, quartzites, and conglomerates with great outpourings of lava and associated ashes, etc., generally basic in character and all, of course, highly altered. These two developments of different petrographic character are separated by great upwelling bodies of the gneissic granite, so that they do not come in contact with one another, and therefore their relative stratigraphic position is still unknown.

In the northern and western belts referred to above, several formations are represented which differ among themselves in character and which are very irregular in distribution. As the different belts are isolated and often widely separated from one another, and are, with the exception of the limestone of Steep-rock Lake, unfossiliferous, no help can be obtained from palæontological studies, and correlation between the successions recognized in the several areas is always difficult and uncertain. It is only in those areas which have been made the subject of detailed mapping and very careful study that any basis for other than a purely speculative correlation exists. These latter areas represent only a relatively insignificant part of the whole development of the ancient rocks, and they all lie in the more accessible portions of the shield, that is, at or near its southern margin. It may thus easily happen that, even when these areas come to be thoroughly studied and known, the succession which is recognized in them may not be that which is presented by the remoter and inner parts of the shield or of the still more remote regions of the far north.

THE PRE-CAMBRIAN SUCCESSION IN THE REGION OF THE GREAT LAKES

The margin of the protaxis about Lakes Superior and Huron has been more carefully examined than any other portion of the shield in which the western synclines occur. The pre-Cambrian succession in this district has been studied for many years by the Geological Surveys of the United States and of Canada, as well as by the State and Provincial Surveys and by individual workers. The conclusions reached by the various investigators have not always been in close agreement, and the nomenclature employed has shown corresponding diversities. The mapping in the United States and Canada was in most cases begun in areas more or less remote from one another and from the international boundary line, but eventually the Geological Surveys of the two countries were extended to the boundary and it was then found that what proved to be identical formations had been designated by different names in

different parts of the region, and that in some cases there had been a diversity of interpretation as to the stratigraphical succession. It was, therefore, decided that an International Committee should be appointed jointly by the Federal Surveys of the United States and Canada, which Committee should visit the various pre-Cambrian areas in the Lake Superior and Lake Huron districts on both sides of the border, familiarize themselves with the work which had been carried out in them by the various workers, and ascertain in how far a comparative study of the different areas might afford a basis for harmonizing divergent views. The Committee was also to ascertain whether it might not be possible to suggest a common nomenclature which should express the facts so far as known and which might be adopted by all.

Such a Committee was appointed in 1905 and in the summer of that year visited the various areas referred to, examined the geological succession and made certain recommendations with reference to classification and nomenclature, which recommendations were subsequently accepted by the United States Geological Survey and by the Geological Survey of Canada.

The Committee found the pre-Cambrian succession in the region in question to be as follows, and suggested that the following nomenclature be adopted to designate the respective formations:

CLASSIFICATION OF THE PRE-CAMBRIAN OF THE REGION ABOUT LAKE SUPERIOR
AND LAKE HURON, PROPOSED BY THE INTERNATIONAL COMMITTEE

Cambrian—	Upper sandstones of Lake Superior
	<i>Unconformity</i>
Pre-Cambrian—	Keweenaw (Nipigon)
	<i>Unconformity</i>
Huronian—	{ Upper (Animikie)
	<i>Unconformity</i>
	{ Middle
	<i>Unconformity</i>
	{ Lower
	<i>Unconformity</i>
	Keewatin
	<i>Eruptive contact</i>
	Laurentian

The Committee further stated that each series in the pre-Cambrian succession was separated from that which followed it by an unconformity, but they refrained from expressing any opinion as to the relative values or importance of the several breaks, neither did they propose any classification of the succession into larger groups. These were matters which it was felt could best be decided when a more complete knowledge of the region had been obtained as a result of further investigation. The Report of the Committee and the classification set forth in it served to crystallize our knowledge of the pre-Cambrian succession in that region. It was not intended to be, and of course could not be, a final statement concerning the pre-Cambrian succession in this portion of the shield. Such a statement will only be possible after many years, and possibly many decades hence, when all the areas in this complex region have been mapped in detail and critically studied; but the scheme of classification proposed by the Committee embodied the results of the investigations up to that time and has served as an excellent basis for further studies.

Let us consider a few of the problems which are suggested by the Committee's Table of Classification and some of the advances in knowledge which have been made since it appeared.

Lawson, to whose epoch-making work we are still largely indebted for our knowledge of the geology of the Lake of the Woods and Rainy Lake region, had stated that another and enormously thick series of sediments, to which he gave the name Couthiching, lay beneath the Keewatin Series there, and represented the base of the whole sedimentary series. When the Committee visited this region, they examined by far the largest of the areas mapped by Lawson as typical Couthiching, designated as the Shoal Lake area. It was on his study of this area that Lawson based his figures of 23,760 feet to 28,754 feet as the thickness of the Couthiching, which is shown in one of the sections accompanying his map as having an anticlinal structure and as dipping beneath the Keewatin. The Committee found that the series in question lay on top of and not below the Keewatin. A second Couthiching area about Rat Root Bay

was examined with the same result. The Committee, therefore, stated that "In the Rainy Lake district the Huronian should include that part of the Couthiching of the south part of Rainy Lake which is limited by the basal conglomerate as shown at Shoal Lake," and Lawson's Couthiching was accordingly omitted in the scheme of classification submitted by the Committee. Lawson has, however, recently devoted some additional time to field work in this district, has revised his work, and proposed a new classification. He concedes that the Shoal Lake and Rat Root areas of the Couthiching overlies the Keewatin, assigning it to a new series which he designates as the Seine River Series and which probably belongs to the Middle Huronian of the Committee's classification. Lawson holds, however, that two other small areas of Couthiching shown on his map do represent a series which is older than the Keewatin and which distinctly underlies it. One of these areas, at Bear's Pass on Rainy Lake, was visited by a party of members of the Twelfth International Geological Congress last fall, and the stratigraphical evidence is clear that at this place these Couthiching rocks, which are feldspathic mica schists and fine-grained gneisses, do underlie the Keewatin of this district. There are, therefore, in this Rainy Lake district two small areas of sediments—that of the Rice Bay area being estimated by Lawson to have a thickness of about 4600 feet—which represent "the old sedimentary crust through which the Keewatin igneous rocks were erupted and on which they were poured out as flows." The two series, however, are conformable. If the Keewatin as developed in the various separate pre-Cambrian areas can be taken as equivalent to one another, these Couthiching rocks represent, so far as we are at present aware, the oldest sediments in the pre-Cambrian of the western portion of the Canadian Shield; but it is not clear whether they should be classed as a separate series or regarded as belonging to the base of the Keewatin.

As a result of his re-examination of the Rainy Lake region, Lawson has suggested that the following classification be

adopted for the pre-Cambrian succession of the Lake Superior region :

CLASSIFICATION OF THE PRE-CAMBRIAN OF THE LAKE SUPERIOR REGION
PROPOSED BY ANDREW C. LAWSON¹

Apart from the fact that the succession is thrown into the two major groups of Archæan and Algonkian, both terms being used in senses other than those in which these terms are now generally employed, this classification differs very little from that of the International Committee of 1905. The changes are three. *First*, the saving remnant of the Coutchiching rightly finds a place in the sequence. *Second*, the Animikie is separated in a more marked manner from the two lower members of the Huronian by emphasizing the relative importance of the unconformity beneath it. *Third*, the Laurentian is placed above the Keewatin and a body of intrusive granite is inserted in the

¹ A Standard Scale for the Pre-Cambrian Rocks of North America: Congrès Géologique International, 12e Session, Canada, 1913 (Advance Copy), p. 3.

stratigraphic succession below the Animikie. The two latter changes are worthy of consideration.

As has been mentioned, the question of the relative value of the several unconformities in the pre-Cambrian succession was one on which the International Committee expressed no opinion, since they considered that the evidence was not at that time sufficiently clear to enable them to do so. Lawson¹ in 1887 classed the Animikie as Huronian. In 1902,² he expressed the opinion that this series should not only be separated from the Huronian, but that it was so widely separated that it should be placed in the Palæozoic. The unconformity at the base of the Animikie—which represented what he termed the Eparchæan Interval—was considered by him to be immensely greater than any of the pre-Cambrian unconformities and to be one of the greatest breaks in the whole geological column. The studies of Van Hise and others, however, led them to express the opinion that “there is no evidence whatever that the unconformity at the base of the Animikie is more important than the one separating the middle and lower Huronian or that separating the Animikie and Keweenawan.”³

In his most recent paper, Lawson takes a middle course between his opinions as formerly expressed, and states that “it may be conceded without argument” that the break between the Keewatin and Huronian is as great as that in the base of the Animikie (the Eparchæan Interval) and is worthy of a similar emphasis, although he fails to give it this emphasis in his scheme of classification which is shown above. He suggests that it be designated as the Epi-Laurentian Interval.⁴

Lawson, therefore, now recognizes that, as pointed out by the

¹ *Geology of the Rainy Lake Region*: Am. Jour. Sci., (3), vol. 33, June, 1887, p. 479.

² *The Eparchæan Interval*: Bull. Dept. of Geol., University of California, vol. 3, 1902.

³ *Pre-Cambrian Geology of North America*: Bull. U. S. Geol. Surv., No. 360, 1909, p. 38.

⁴ *A Standard Scale for the pre-Cambrian rocks of North America*: Congrès Géologique International, 12e Session, Canada, 1913 (Advance Copy), p. 16.

writer¹ some years ago, the pre-Cambrian succession in the northern and western portions of the Canadian Shield appears to fall into three great subdivisions, the Eparchæan and Epi-Laurentian intervals forming the dividing lines.

THE TWO GREAT DIASTROPHIC BREAKS

As is generally recognized, in attempting to correlate the pre-Cambrian succession over great stretches of country such as those presented by the Canadian Shield, it is necessary in the absence of fossils to employ one of three criteria: (1) The tracing of a formation directly from one part of the area to the other. This is not possible when the correlation is to be effected in areas which are actually separated and remote from one another. (2) Similarity of petrographical character—which is often misleading. (3) Relation to widespread epochs of diastrophism.

In the paper referred to,³ the attempt was made to employ this third method in correlating the pre-Cambrian succession of the Canadian Shield, the diastrophic epochs which ushered in each of the two Intervals being employed as the basis for correlation. The line of argument was as follows: We know that the Canadian Shield has been a positive element throughout geological time. The diastrophic epochs with their development of schistose structures in the moving masses and the associated phenomena of igneous intrusion would be short as compared with the long intervening periods of planation and sedimentation. If, therefore, the shield moved as a whole, these diastrophic epochs might serve as a basis for correlation over the whole area.

The geological history of the pre-Cambrian times in the region of the Great Lakes is in outline as follows: Resting on the Laurentian, although penetrated by it, is the lowest and oldest sedimentary series. This is the widely extended Keewatin Series, with its lava flows and pyroclastic material stratiform

¹ The Basis of Pre-Cambrian Correlation: Jour. Geology, vol. 17, February-March, 1909, p. 115.

if not stratified, containing, according to Coleman, nearly as much material of sedimentary origin as material of volcanic derivation; which is believed by others to be composed almost exclusively of material of volcanic or at least of igneous origin. It in any event passes downward in one district into the undoubtedly sedimentary rocks of the Couthiching. This represents the first long and apparently widespread period of sedimentation in the shield. Then came an epoch of intense folding and metamorphism, accompanied by great batholithic granitic intrusions. The thrust which gave rise to the folding came from the southeast and was exerted against the ancient continent. The resulting folds were developed in a direction approximately parallel to the course of the present river and gulf of St. Lawrence. Along the axes of these folds great granite batholiths rose, disintegrating, fraying out, metamorphosing, and partly absorbing the lower surface of the invaded sediments. These movements can be traced over thousands of square miles. This epoch of diastrophism resulted in the elevation of great tracts of country and brought to a close the first clearly recognized chapter in the history of the Shield.

After prolonged and profound denudation—the Epi-Laurentian Interval—the sea again transgressed upon the Canadian Shield, and in this sea the Lower and Middle Huronian were laid down. This sea certainly covered the region of the Great Lakes and extended west as far as the head of Lake Winnipeg and as far north as Lake Mistassini, and in places at least as far north as Hudson Bay. This period of sedimentation was followed by another epoch of diastrophism. Again the thrust was from the southeast, resulting in widespread folding, and again it was accompanied by the intrusion of great batholiths of granite, this epoch of diastrophism marking the close of the second great chapter in the history of the region. This was succeeded by another period of long and deep erosion—the Eparchæan Interval—during which much of the ancient sedimentary deposit was swept away and the “roots of the mountains” were laid bare.

Then followed another widespread transgression of the sea,

in which the sediments of the Animikie-Nastopoka Series were laid down. These sediments present the same general character in very widely separated localities. They occur not only in the immediate vicinity of the Great Lakes, but rocks apparently of this age form chains of islands which extend for 300 miles along the east coast of Hudson Bay, attaining in places a thickness of 3000 feet. Strata apparently of this age are also found over large tracts in central Labrador and with the overlying Keweenaw-Athabasca rocks occupy large areas in the region about the Coppermine River. No pre-Cambrian series is exposed over so great an area in Laurentia. The positive movement which raised it above sea-level was chiefly epeirogenic and therefore over the greater part of the area the strata still retain their horizontal attitude.

The close of this time was also marked by an epoch of diastrophism—expressed by faults and overthrusts, the superficial manifestation of deep-seated intrusions. This epoch of mild diastrophism closed the third great period in the history of the pre-Cambrian in the Canadian Shield.

It is interesting to note that in the Siberian nucleus which belongs to the same North Polar region, our present information indicates that there is a similar threefold division in the pre-Cambrian succession. The succession in northern China was found by Bailey Willis to be as follows:¹

Hu-t'o system—Slate and quartzite

Unconformity

Wu-t'ai system—Quartzite, marble and schists

Unconformity

T'ai-Shan complex—Gneisses of varied character with younger intrusions.

“Applying therefore this criterion of diastrophic periods to the correlation of the pre-Cambrian succession of these widely separated portions of the great northern nucleus, we obtain an identical result in both cases—the diastrophic movements seem to have affected the nucleus as a whole.”²

¹ Research in China, vol. 2, 1907, p. 4.

² Frank D. Adams, *Op. cit.*, p. 117.

Diagram showing the Pre-Cambrian succession in the region of the Great Lakes.

In Lawson's classification, the insertion of the Laurentian above the Keewatin and the introduction of another body of granite—the Algonian granite—into the sequence below the Animikie is a procedure to which exception may properly be taken. The objection is based on the fact that these granites are not members of the stratigraphic succession—they are intrusions into certain portions of it. The Laurentian granite does not lie between the Keewatin and the Lower Huronian—it is an intrusive body penetrating the Keewatin and rising as far as the base of the Lower Huronian. In the same way the Algonian granite does not occur in the succession between the Animikie and the underlying portion of the Huronian—it is intruded through the whole series up to the base of the Animikie.

The introduction of irregular intrusive masses as elements of a sedimentary succession is never seen in vertical sections of strata of other ages, but has been recently employed by several writers on the pre-Cambrian of the Canadian Shield.

The actual relations are shown in the generalized diagram on page 62.

The succession is, using the terms in the sense employed by Lawson, properly set forth as follows:

Upper Cambrian
Unconformity
 Keweenawan
Unconformity
 Animikie
 — *Eparchæan Interval* —
 Upper Huronian—Cut by the Algonian granite.
Unconformity
 Lower Huronian—Cut by the Algonian granite.
 — *Epi-Laurentian Interval* —
 Keewatin—Cut by the Laurentian and newer granites.
 Coughtiching—Cut by the Laurentian and newer granites.
Intrusive contact
 Laurentian granite.

This shows the succession as it actually occurs. It seems evident that the Laurentian, forming as it does the base of the

whole succession—that on which the pre-Cambrian of the Canadian Shield everywhere rests—should, by virtue of its position, be given in any section in which it occurs the place which it actually occupies in nature—it is the “Fundamental Gneiss.”

In the Sudbury, Cobalt, Porcupine, and other areas which are situated on that great belt of pre-Cambrian rocks of which the “original Huronian area” forms a part, some detailed studies of the succession have been made by Coleman, Knight, Miller, Barlow, and others, as a result of the discovery of the enormous ore bodies which occur in this region.

The most prominent member of the stratigraphic succession at Cobalt consists of a series of heavily bedded conglomerates. From veins cutting this conglomerate series, 80 per cent or more of the silver ores of Cobalt has been won. This series is practically unmetamorphosed, but rests unconformably upon a complex which in part has been subjected to at least two periods of intense diastrophism. In the earlier descriptions of the Cobalt district, this conglomerate series—the Cobalt Series—was designated as Lower Huronian and the complex beneath was referred to the Keewatin. Within the last four or five years, more detailed work has revealed the presence of another series composed of slates, graywackes, and conglomerates, which occupy vertical or almost vertical attitudes. To this older series of sediments the name of Temiscaming Series has been given. The conglomerates of this series hold pebbles of true Keewatin and gneissoid granite. Moreover, the Temiscaming Series has been invaded by great volumes of what has been called the Lorrain granite. Though not yet found in immediate contact with the true Keewatin in this district, it has been inferred that the Temiscaming Series rests unconformably upon the Keewatin. It is evident that these older sediments were deposited subsequent to the period of diastrophism marked by the invasion of the Laurentian granites, and that they passed through a later period of diastrophism accompanied by the intrusion of the Lorrain granite and followed by a long period of erosion representing the great unconformity which separates them from

the so-called Lower Huronian Series, to which reference has been made.

This Temiscaming Series has been recognized in many areas adjacent to Cobalt. Thus, in the Porcupine district a series of slates, quartzites, and conglomerates, dipping at steep angles and schistose in character, rests unconformably upon the Keewatin greenstones. Though containing no pebbles of granite, there is evidence that granite intrusion followed the deposition of this series.

In northwestern Quebec a very heavy band of highly schistose conglomerates, graywackes, and arkose, called the Pontiac schists, has been traced by Wilson and Bancroft¹ from a few miles east of Larder Lake to the headwaters of the Bell River at Lake Match-Manitou, a distance of approximately 110 miles. To the westward this series passes unconformably beneath the equivalent of the so-called Lower Huronian of Cobalt. The conglomerate bands not only contain pebbles derived from the Keewatin greenstones, but also many pebbles of granite and gneiss. Occupying as it does a synclinal position and apparently resting unconformably upon the Keewatin, this series has been invaded by vast batholiths of granite and has been largely converted into quartzose, biotite, and hornblende schists.

Approximately 110 miles north of the point where the National Transcontinental Railway crosses the Bell River on Matagami Lake, a similar group of sediments—the Matagami Series—now converted into quartzose, biotite, and hornblende schists, the conglomerates of which enclose abundant squeezed pebbles not only of granite and allied rocks but also of Keewatin greenstone, are invaded by widespread batholiths of granite. Other localities in this region, as, for instance, Gowganda and the eastern shore of Lake Temiscaming, might be mentioned where a similar series of sediments, at the latter locality known as the Fabre Series, occur, which are older than the Cobalt

¹ J. A. Bancroft, A report on the Geology and Natural Resources of certain portions of the Drainage Basins of the Harricanaw and Nottaway Rivers: Report on Mining Operations in the Province of Quebec, Department of Mines, Quebec, 1912.

Series and which present evidence of having been subjected to two periods of diastrophism.

In a paper read before the International Geological Congress at Toronto last August, Collins¹ gives the following classification as representing the succession in the region just described:

	Silurian (Niagara)	
	<i>Unconformity</i>	
Huronian	{ Nipissing diabase }	Keweenawan
	{ Sudbury norite }	
	<i>Intrusive Contact</i>	
	{ Whitewater series }	
	{ Lorrain series }	
	<i>Local Unconformity</i>	
	{ Cobalt series }	
	<i>Great Unconformity</i>	
Pre-Huronian	{ Batholithic granite intrusives }	
	<i>Intrusive Contact</i>	
	{ Sudbury series }	
	{ Temiscaming series }	
	{ Fabre series, etc. }	
	<i>Unconformity</i>	
	{ Granite intrusives }	
	{ Keewatin group }	

It will be noted that in this classification also a whole series of igneous intrusions have been included with true sedimentary elements in the stratigraphic succession, and the Keweenawan has been included in the Huronian, which adds to the confusion. As a matter of fact, in the present state of our knowledge, all attempts to correlate this with the standard Lake Superior succession are based on conjecture. Not until the whole area down to the shores of Lake Huron has been carefully mapped, its complex structure unravelled, and the relations of its constituent members clearly understood, will it probably be possible to effect a definite correlation.

In the meantime it is interesting to ask the question, Where are to be found in this region the two great diastrophic breaks

¹ W. H. Collins, A Classification of the Pre-Cambrian Formations in Region East of Lake Superior: Congrès Géologique International, 12e Session, Canada, 1913 (Advance Copy), p. 5.

in the pre-Cambrian succession to which reference has been made?

One of them appears to be at the base of the Cobalt Series.

If this be the lower of the two, representing what Lawson has called the Epi-Laurentian Interval, the Temiscaming-Matagami Series is pre-Huronian, as believed by Collins and Bancroft, and represents a series of sediments which are absent in the Lake Superior region, and the upper or Eparchæan Interval is either at the base of the Whitewater Series or is unseen, the higher members of the series being here absent, having been removed by erosion.

If, on the other hand, the unconformity above mentioned is the upper one and represents the Eparchæan Interval, the Cobalt Series and the overlying Whitewater Series are Upper Huronian and the Epi-Laurentian Interval is at the base of Temiscaming-Matagami Series, which will be Middle or Lower Huronian. The existence of a marked unconformity at the horizon in question is indicated by the presence of a great abundance of pebbles of Keewatin rocks as well as of an earlier granite in the conglomerate beds of the series. Which of these correlations is correct is another of the problems of the Canadian Shield.

THE PRE-CAMBRIAN SUCCESSION IN THE REGION OF THE ST. LAWRENCE RIVER—THE GRENVILLE SERIES

But there is another facies of the pre-Cambrian rocks in the Canadian Shield, namely, that which, as already mentioned, is found in its typical development along the southeastern margin. This is known as the Grenville Series and it is characterized by the presence of large bodies of limestone, while the quartzites and conglomerates which form such an important element in the pre-Cambrian succession, which has just been described, are rarely seen.

This Grenville Series extends along the southern margin of the shield, from the east shore of the Georgian Bay on Lake Huron, across the Provinces of Ontario and Quebec, to a point

about halfway between the St. Maurice River and the city of Quebec. To the south it passes beneath the Palæozoic strata, but comes to the surface again in the Adirondack Mountains, over the whole area of which it is exposed at intervals. Bayley, who has recently studied the pre-Cambrian limestone series of the highlands of New Jersey, believes that this also is to be correlated with the Grenville Series. It is thus known to have extended over an area of *not less than 83,000 square miles*.¹

The limestones of the series are in many places represented by enormous bodies of nearly pure marble, but these elsewhere become impure through the presence of various silicates distributed through them, often in lines marking the plane of the original bedding. In its usual development the limestone is white, cream-colored or pinkish in color and coarse in grain. In many places this limestone is found to be regularly interstratified with bands of fine-grained paragneiss, or of fine-grained amphibolite. These rocks when subjected to orogenic movements are less plastic than the limestones, and on the face of high cliffs or on other large exposures the most striking display of autoclastic action can be seen; the interstratified bands of paragneiss or amphibolite being first thrown into a series of undulations which wind to and fro over the exposed surface and as the effect of pressure becomes more intense, these are folded back upon themselves or torn into fragments which move away from one another, the more plastic limestone flowing in between them, giving to the mass as a whole the appearance of a coarse conglomerate.

The paragneisses represent beds of highly altered, argillaceous sediments of varying degrees of purity, some of the sillimanitic varieties having exactly the composition of an ordinary clay slate, while other varieties are more siliceous. They are fine in grain and show no protoclastic or cataclastic structure. Their structure is allotriomorphic, the original material having been completely recrystallized, and they differ distinctly in appearance from the foliated granitic gneisses of

¹ Frank D. Adams, Recent Studies in the Grenville Series of Eastern North America: Jour. of Geology, vol. 16, October, 1908, pp. 632-633.

the batholithic intrusions resembling in many respects the hornstones found in granite contact zones, but they are usually more coarsely crystalline.

The amphibolites are, next to the limestones, the most abundant rocks in the Grenville Series. The question of their origin has been one of the most difficult problems which presented itself in the study of the Grenville Series. They are represented by a number of distinct varieties, some of which are intimately associated with the limestones and paragneisses, while others occur in association with the great masses of gabbro which are found so commonly as intrusions in the series; others again show no definite association with any particular petrographic type. Recent studies in the Haliburton district¹ of eastern Ontario have shown that in these amphibolites there are included rocks which have originated in three different ways, namely, (a) by the recrystallization of impure calcareous sediments; (b) by the alteration of basic dykes or other similar intrusions; (c) by the transfusion of limestones by material from the batholithic intrusions of granite.

The quartzites in the Grenville Series are distinctly subordinate and over the greater part of the area almost entirely absent. One of their most important developments is in the district about the Thousand Islands.

In most parts of the region occupied by the Grenville Series, the succession is so torn to pieces by igneous intrusions that it is impossible to obtain even an approximate measure of its thickness. In certain parts of eastern Ontario, however, there are lines of section where these intrusions are distinctly subordinate and where measurements can be made with the same degree of accuracy as in other developments of pre-Cambrian rocks. From a study of these, it may be stated that the Grenville Series is one of the thickest series of pre-Cambrian sediments in North America, and that it presents by far the thickest development of pre-Cambrian limestones on the continent.

The correlation of the Grenville Series with the succession

¹ Frank D. Adams, *The Origin of the Amphibolites of the Laurentian Area of Canada*: Jour. of Geology, January-February, 1909.

to the Ministry of Education and Science of the USSR. The Ministry of Education and Science of the USSR is the main body responsible for the implementation of the State Educational Standard for the subject of "History of the USSR" in the 10th grade of secondary schools.

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Plate III. Cliff of nearly horizontal strata of the Grenville Series. These strata consist of garnetiferous quartzite interstratified with a rusty weathering of garnetiferous gneiss. Near St. Jean de Matha, Province of Quebec.

already described in the Lake Superior and Lake Huron districts is another of the unsolved problems of the Canadian Shield. Between these two great pre-Cambrian facies there intervene everywhere great bodies of the intrusive granite-gneiss. On this account, no attempt was made by Adams and Barlow¹ to correlate the Grenville Series of the very extended area mapped by them in the Haliburton and Bancroft areas with the western succession. As exploration advances the two may somewhere be found together and their relations will then be determined.

In the Madoc area to the south of the Bancroft district, Miller and Knight² have recently been investigating the succession. Here they have found a series of greenstone schists which they correlate with the Keewatin, and overlying these a series composed of quartzite, graywacke, jaspilite, slate, and crystalline limestones which they correlate with the Grenville. These two series are invaded by granite intrusions which were succeeded by a prolonged period of erosion. After this another series of rocks was laid down which they have designated as the *Hastings* Series, using this term in a different sense from that proposed by Logan in the earlier years of the Canadian Survey and employed by the International Committee when they visited this district.

If this break at the top of what has been designated as the Grenville Series in this district is the Epi-Laurentian Interval, and the series in question proves on the areal extension of the mapping to be the true Grenville Series, this latter is pre-Huronian in age and is a series overlying the Keewatin in this part of the shield as the Couthiching underlies it in the Rainy Lake region. Whether this is the case or not is another problem of the Canadian Shield which can be solved only in the light of additional knowledge.

¹ Frank D. Adams and Alfred E. Barlow, *Geology of the Haliburton and Bancroft Areas, Province of Ontario: Geological Survey of Canada, Memoir, No. 6, Ottawa, 1910.*

² C. W. Knight, *The Madoc Area: Guide Book No. 6, Congrès Géologique International, 12e Session, Canada, 1913, pp. 56-58.*

THE BASE OF THE PRE-CAMBRIAN

The question as to the base on which this whole pre-Cambrian succession rests is one which is and must always be of very special interest, for its consideration carries us back to the beginning of the history of the earth, or at any rate to the beginning of the history of the earth as we know it, the earth on whose surface bodies of water could exist and on which processes of sedimentation began.

But in looking for this base in the Canadian Shield, we are brought face to face with one of the greatest of the unsolved problems which this great region presents. Whenever we search out the oldest beds of the series and examine them, whether it be in the Keewatin and Coutchiching in the west, or the Grenville Series in the east, we find that they rest upon enormous bodies of granite which break up through them, tearing them to pieces and sending great apophyses into them. These masses have the form of great batholiths which are at the present time the visible base of the whole succession. These ancient sediments, however, were not deposited upon the granite as we now see it, for the granite penetrates them and the contact is an intrusive one, the granite breaking up and tearing through the base of this great body of sediments which rests upon it. The granite therefore in its present form at least is later than the lowest sediments. Only two explanations of this fact are possible.

(a) Either the oldest sediments were deposited on a surface of granite, which granite was subsequently softened by being reheated through a rise of the geotherms in this portion of the earth's crust, thus taking upon itself again an intrusive character and breaking through the sediments which have been deposited upon it, destroying all evidence of the original contact. This was Lawson's explanation of the phenomenon in the Lake of the Woods region. He thought that there was evidence that the granitic magma had not only destroyed the original basement but had dissolved or incorporated it, so that

the granite represented in part the materials of the original basement.

(b) Or, the original basement on which the sediments were deposited now lies somewhere far below the surface and these great bodies of granite have been intruded within the series, so that while the visible succession rests upon them, the true basal beds of the whole succession lie somewhere beneath, within the earth's crust.

These granite batholiths have essentially the same character in all parts of the shield where they have been carefully studied. They have been most carefully mapped in the Lake Superior region in the west, where they rise through the Couthiching-Keewatin succession, and 900 miles further east in the Haliburton region, where they penetrate the Grenville Series. The area mapped in each case embraces several thousand square miles. Identical phenomena to those presented in these regions are seen in the original Grenville area and in that portion of the shield lying to the north of Montreal, although these areas have not been studied in the same detail.

It must be noted, however, that all these areas lie on the margin of the Canadian Shield, and it will be a matter of great interest to ascertain, as the mapping is carried further north, whether the interior portions of the country show the same phenomena of batholithic intrusion, or whether this is a phenomenon peculiar to the southern and marginal portion of the shield.

The whole phenomenon is excellently displayed in the maps of the Haliburton and Bancroft areas recently issued by the Geological Survey of Canada. In this region, on the margin of the shield the Grenville Series is widespread and is comparatively free from igneous intrusions. Going to the northwest, however, the granite in ever increasing amount wells up through this sedimentary series and gradually disintegrates it into a sort of breccia composed of shreds and patches of the invaded rock scattered through the invading granite, until eventually connected areas of the sedimentary series disappear entirely and over hundreds of square miles the granite and

granite-gneiss alone are seen, holding however in almost every exposure, inclusions which represent the last scattered remnants of the invaded rocks. The type of structure represented by the invading granite is that of a batholith, this term being used in the sense employed by Lawson in his classic work on the Lake of the Woods and Rainy Lake districts to designate great lenticular or rounded bosses of granite which are found arching up in the overlying strata, through which they penetrate, disintegrating the latter and displaying a more or less distinct foliation, which is seen to conform in general to the strike of the invaded rocks where these latter have not been removed by denudation. Within the batholiths themselves the strike of this foliation follows sweeping curves, which are usually closed and centred about a certain spot in the area where the foliation becomes so nearly horizontal that it is difficult to recognize its course in a level country. The foliation is not only so distinct that its strike can readily be mapped in all its windings, but its dip can also be recognized. This dip is outward in all directions from a central point or area in the intrusion where the foliation is—as above mentioned—practically horizontal. In some cases there are two separate centres about which the foliation respectively strikes in great concentric curves.

The strike of the invaded sediments also conforms to the windings of the margin of the batholiths and to their foliation, and dips away from the intrusion on all sides.

The batholiths are, therefore, undoubtedly formed by an uprising of the granite magma from below, and the foci indicate the axes of the greatest upward movement and those along which the granite magma was supplied most rapidly. It is evident from the structure that the granitic magma has risen slowly, arching up the strata into great domelike forms; and in many cases, from a detailed study of the phenomena presented, it can be clearly seen that the rise of the magma, beginning when it was in the earlier stages of crystallization, continued as crystallization proceeded, and while the magma was filled with the products of crystallization, and was brought to a close only when the magma had, so to speak, frozen into

solid rock. The foliation is of protoclastic origin and was developed by progressive movement during the successive stages of cooling.

The feldspar individuals developed during the crystallization of the magma were thus, as the crystallization proceeded in the slowly moving mass, crushed against one another and thus broken and granulated, the cores of the original individuals being frequently clearly discernible in the trail of granulated material. While this was taking place, that portion of the magma which eventually crystallized as quartz was still in a fluid or plastic form and eventually crystallized in sinuous lines of uncrushed material, completing the solidification of the rock and bringing the movement to a close.

A very interesting phenomenon which is displayed by the granite batholiths of the Haliburton and Bancroft areas is the development of belts of Nepheline Syenite along the border of these masses where they are intruded into the limestones of the Grenville Series. These belts of Nepheline Syenite, although not occurring continuously along the whole limestone contact, are found only in this position, and while varying considerably in width from place to place, they represent in the aggregate one of the largest occurrences of this rock hitherto discovered.

The Nepheline Syenite rocks composing these belts usually possess a distinctly foliated or banded structure and fade away into the limestones. Isolated grains, or aggregates of grains, of Calcite are found in the Nepheline Syenite at a very considerable distance from the contact and become relatively more numerous on approaching the latter, transitional rocks being found in which the constituent minerals of the Nepheline Syenite, and grains or masses of Calcite, are present in approximately equal amount. The foliation or banding of the Nepheline Syenites is a survival of the foliation or bedding of the limestone which in the original rock is frequently marked by lines of impurities.

These rocks while referred to as Nepheline Syenites, to which species for the most part they actually belong, display a very considerable variation in composition, ranging from nearly pure

nepheline rocks such as Congressite and Monmouthite through more felspathic varieties such as Raglanite and alkali Syenites, to Essexite or even more basic forms. In some localities furthermore these rocks are rich in Corundum and at Craigmont have been made the basis of an extensive industry for the production of this mineral. It seems probable that this series of Nepheline Syenites and allied alkali rocks have been produced by the permeation or transfusion of the limestones along the contacts by exhalations or solutions from the highly alkaline granitic magma forming the batholiths, which exhalations were fixed by the limestones and progressively replaced them, giving rise to the rocks in question and to the phenomenon described.¹

Frequently portions of the cover still remain in place upon the surface of the batholith; in other cases a number of batholiths are found arranged in linear series with the cover of sedimentary strata between them still in place.

Fragments which have sunk down into the magma from the roof of the batholiths are scattered throughout the mass, sometimes having a more or less angular form, but usually showing unmistakable evidences of having been softened and drawn out into elongated *Schlieren* by the slow movement of the magma in which they are enclosed. Passing from the immediate margin of the Grenville Series in Ontario, northward into the shield, these batholiths presenting the phenomena above described, coalesce into one enormous body of gneissic granite, whose strike can still be followed in great sweeping curves holding lines of fragments or *Schlieren* conforming in direction to the course of the strike and marking the undulations of the overlying cover of sediments which has long since been removed by erosion. On the other hand, over great areas of

¹ Frank D. Adams and Alfred E. Barlow, *Geology of the Haliburton and Bancroft Areas, Province of Ontario: Geological Survey of Canada, Memoir, No. 6, Ottawa, 1910.*

Frank D. Adams and Alfred E. Barlow, *The Nepheline and Associated Alkali Syenites of Eastern Ontario: Trans. Royal Society of Canada, (3), vol. 2, 1908-1909.*

the shield where the cover is still intact and the sediments forming the succession are still in place, these are seen to present an undulating character, with quaquaversal dips from many recurrent points, conveying an irresistible impression that the whole district was at one time floating on a great sea of magma which supported it, and which, now solidified, still underlies it at no great depth below the present surface, the whole mechanism of which would be revealed in the form of batholithic intrusions like those described above had the erosion been carried a little deeper.

Such an area is that which lies toward the margin of that portion of the shield which lies to the north of the St. Lawrence River between Montreal and Three Rivers.¹ Here over an area of about 750 square miles in extent there is a great development of gneisses with occasional bands of white crystalline limestone and quartzite through which the Mattawin River, the River du Loup, and other smaller streams cut their way in the nearly horizontal strata, affording good vertical sections of from one to two hundred feet. Over this tract of country the gneisses either lie quite flat, or display low dips seldom exceeding 30°. In several parts of the area, the direction of the dip varies rapidly from place to place, low undulations in the flat gneiss being observed running now in one direction and now in another, the whole giving the impression of a comparatively thin crust resting upon and sustained by an originally molten or fluid mass. That this was in all probability actually the case is shown by the appearance, in the district immediately to the south, of a great body of granite which comes from beneath the horizontal gneiss just described. A study of this batholithic structure suggests that we have here laid bare the deeply eroded basement of an ancient mountain range having a course parallel to that of the river and gulf of St. Lawrence. Here are seen the "Roots of the Mountains"; the uprising granite magma, forced in beneath

¹ Frank D. Adams, Report on the Geology of the Laurentian Area to the North of the Island of Montreal: Geological Survey of Canada-Ottawa, 1896.

Plate IV. Amphibolite invaded by granite. Loc. 8, Concession
VIII, Township of Matheson, Haliburton region, Province of
Ontario. (First stage.)

Plate IV. Amphibolite invaded by granite. Lot 9, Concession
VIII. Township of Methuen, Haliburton region, Province of
Ontario. (First stage.)

Plate V. Amphibolite invaded by granite, near Maynooth, Haliburton region, Province of Ontario. (Second stage.) The amphibolite inclusions have been drawn out by the movement of the flowing mass.

Plate V. Amphibolite invaded by granite, near Killaloe Railway Station, Haliburton region, Province of Ontario. (Third stage.) The movement here having been more intense has developed a well-marked banding in the rock, the amphibolite inclusions being now represented by the darker bands.

Plate VI. Amphibolite invaded by granite near Killbuck, Haliburton
 region, Province of Ontario. (Second stage). The amphibolite
 inclusions have been drawn out by the movement of the flowing
 mass.

Plate V. Amphibolite invaded by granite, near Killbuck, Haliburton
 region, Province of Ontario. (Third stage). The
 movement here having been more intense has developed a well-
 marked banding in the rock, the amphibolite inclusions being now
 represented by the darker bands.

this positive area from an adjacent one of negative movement to the south being the direct cause of elevation, or at least a very important contributory cause. It will be a matter of great interest to learn, with the advance of our knowledge of this great region, whether this structure persists in the inner parts of the shield, or whether it is there replaced by other forms and structures having a different origin.

Another problem which awaits its final solution is that of the origin of the dark basic streaks or bands found abundantly in the gneissic granite. As has been mentioned, the origin of these in the Haliburton region and elsewhere in the Laurentian has been clearly demonstrated; they are fragments of the walls and roof of the country rock penetrated by the granite, which have been carried away in the moving magma, being softened, deformed, and metamorphosed during the process. The contention put forward by Morley Wilson in an interesting paper which has recently appeared, that "this method alone cannot account for the banded structure of the Laurentian axial complex because the composition of the bands is for the most part wholly different from that of the rocks constituting the batholithic roof," is not conclusive, for it has been shown that basic rocks of igneous origin, as well as the calcareous rocks which form so large a part of the cover penetrated by the granites, are, by the action of the intrusive granitic magma, altered to amphibolitic rocks of the various types which form the dark bands in the granitic intrusions. It may well be, however, that future studies in other and wider areas of the Canadian Shield will show that the banded characters so widespread in the Laurentian may also in some cases originate from the movements of a magma which differentiates into more basic types, and even that the structure may be accentuated by movements which take place when this differentiated magma is already partially consolidated, and from which the still fluid portions are being squeezed out by the increasing pressure so as to take up new positions in the fast consolidating mass. Whether such be the case is another "problem of the Canadian Shield," which, like the others, will be solved in time, "*Mente et Malleo.*"

CHAPTER III

THE PROTEROZOIC OF THE CANADIAN SHIELD AND ITS PROBLEMS

A. P. COLEMAN

INTRODUCTION

One need not go far back in the history of geology as a science to find the rocks below the Cambrian neglected, looked upon as an incubus to be got rid of as quickly as possible. The rocks immediately under the Cambrian would perhaps some time furnish fossils and be annexed to the Cambrian, while the rocks below were a "basal complex" which no man could unravel, very likely parts of the original crust of the earth formed when the molten globe began to solidify on the surface. They were too different from the orderly fossiliferous rocks of later series to be easily fitted into the scheme of things, and time devoted to them was largely wasted.

At present no part of the earth's history is attracting more attention than the pre-Cambrian, and we are gradually disentangling obscure relationships and opening out a wonderful vista into the past which has already doubled the length of geological time and bids fair to make the post-Cambrian record only an appendage to the far more important pre-Cambrian story of the world.

In this development the Canadian Shield and its extensions into the United States have played a most important part, and a vast literature, not infrequently of a controversial nature, has grown up about it. Have not Van Hise and Leith compiled a volume of more than nine hundred pages in merely outlining

it? The history of the changing opinions of geologists in regard to this most difficult but most fascinating of subjects may be found in the excellent and impartial volume just mentioned, and need not be detailed here; yet certain stages of the development of Canadian pre-Cambrian geology, particularly in the last few years, require to be mentioned to make our present position intelligible.

Sir William Logan's first broad classification of the pre-fossiliferous rocks into the Laurentian, a highly crystalline older portion probably consisting of metamorphosed sediments, and the Huronian, a more distinctly sedimentary younger portion, was not improved upon for a long time. In field work this classification largely resolved itself into calling all green or gray rocks Huronian and all pink granitoid or gneissoid rocks Laurentian, until an iconoclastic young geologist named Lawson was sent thirty years ago to map the Lake of the Woods. Here he found puzzling features. The green rocks proved to be volcanic, old lava flows and ash rocks and agglomerates, not at all like the quartzites and conglomerates of Logan's Huronian; and worse still, they were not younger than the Laurentian on which they rested, but older. In fact, the Laurentian was not a series of metamorphosed sediments but consisted of batholithic masses of granite and gneiss heaving up and penetrating the overlying rocks, which were called the Keewatin.

From this time forward, geologists began to consider the Laurentian entirely eruptive and to divide the former Huronian into a lower volcanic group, the Keewatin, and an upper mainly sedimentary group, the Huronian. It was found, however, that the lower group usually included some sedimentary rocks as well as volcanics; and Lawson himself discovered on Rainy Lake a thick series of undoubted sediments, which he called the Couthiching and described as underlying the Keewatin. Later Adams and Barlow separated from the southeastern Laurentian a very thick series of limestones and other sedimentary rocks, similar in age to Logan's middle Laurentian, and known as the Grenville. In the meantime an influential group of American geologists working in the states adjoining Lake Superior had

replaced the terms Laurentian and Huronian by Archæan and Algonkian, the Archæan being defined as an eruptive complex made up of plutonic rocks invading Keewatin volcanics, while the Algonkian rested unconformably upon the Archæan and consisted mainly of sediments. The underlying idea seems to have been that of separating an early stage in the cooling of the earth, when all rocks were eruptive and neither water nor life existed, from a later oceanic stage of widespread sedimentation. The finding of water-formed sediments on a large scale in the lower series destroyed the foundation for this grouping of the pre-Cambrian, and more recently it has been admitted by all that water-formed rocks may occur at every horizon even to the lowest. It can hardly be doubted that water existed on the earth as a liquid even at the earliest stage known to geology; and the supposed original crust due to the surface cooling of a molten globe has vanished from the known geological succession.

If water existed at the earliest known times, why not also living beings? With this thought in mind the classification of the pre-Palæozoic ages into Archæozoic and Proterozoic became logical and has found wide acceptance. Probably most geologists now believe that the history of the world and of life upon the world before the Palæozoic was far longer than that of the Palæozoic, Mesozoic, and Cenozoic combined. Our familiar view, derived from text-books of geology, that most of the world's history was told in the rocks with fossils, and that the rocks below were comparatively unimportant, had to be given up, and new methods had to be adopted in order to classify series of rocks undated by fossils.

In the classification, geologists have used lithological features, or discordances, or basal conglomerates for the most part, but a very serious difficulty has presented itself in the wide separation of one sedimentary region from another, making age relationships uncertain in the absence of fossils. The vast amount of eruptives penetrating the sedimentary formations in places and the variable extent of the metamorphism they have

undergone in consequence have further complicated matters. There have been controversies too as to the relative age of the immense group of acid eruptives called the Laurentian which covers nine-tenths of the Canadian Shield. Does it penetrate only the Keewatin, Couthiching, and Grenville series, or is the Lower Huronian also involved in its mountain-building operations?

For reasons given above, the number of subdivisions of the pre-Cambrian and the mode of grouping the divisions recognized have been matters of dispute and there is still much divergence as to the proper classification.

It was hoped that the work of the International Committee for the correlation of the rocks of the Lake Superior region nine years ago would provide a standard which all could agree to,¹ but this hope has been dissipated in later years, and in the last Geological Congress no less than four new classifications were brought forward by students of the region, all differing more or less radically from the classification recommended by the Committee. Some geologists still hold to the latter, however, and it has been used in part by Dr. Adams in the two brilliant lectures on the earlier part of the pre-Cambrian of the Canadian Shield which precede the present lecture.

My own work in the Sudbury and adjoining regions, including the original Huronian and part of the original Laurentian of Logan, convinces me that the Lake Superior classification is inadequate, and therefore it will be necessary to formulate a new classification in accordance with our latest knowledge. For this purpose the Sudbury region has great advantages, not only as including well-mapped areas of the earliest defined subdivisions, but also because a wider range of formations occurs there than elsewhere. As it is central for the regions thus far studied it should furnish links to bind region to region and thus aid in correlation.

It is proposed to begin this consideration of the Proterozoic of the Canadian Shield by showing the basis of the new classi-

¹ Jour. Geology, vol. 13, 1905, pp. 89-104.

fication adopted, to pass on to the character and distribution of the formations, and to end with a discussion of the general conditions and physical features of the Canadian Shield during the latter part of the pre-Cambrian.

As the Keewatin, Couthiching, and Grenville series, and the general character and relationships of the Laurentian granites and gneisses have been fully and excellently discussed by Dr. Adams, these will not be referred to except incidentally. The two lectures on the Proterozoic will then be confined to a consideration of the formations included in the Huronian as defined in earlier years, with the addition of the Animikie and Keweenawan, which Logan did not include in the Huronian, though the former is made Upper Huronian in the International Committee's classification. The ground covered will correspond roughly to the Algonkian as defined by the American Geological Survey, which may be considered equivalent to the Proterozoic in the "zoic" classification.

Some might prefer the term Algonkian to Proterozoic; but the former word has been used in such various senses at different times and by different writers as to make it very indefinite when applied to the Canadian Shield, and it has not been generally accepted by geologists working in eastern Canada. Objection may be made to the term Proterozoic, also, on the ground that we know too little of the life which may have existed in the world during these far-off times; but probably no geologist doubts that there was a rich and varied life preceding the Cambrian, though few fossils are known to us from the pre-Cambrian rocks. That living beings were numerous, widespread, and varied in type in the time before the Cambrian must be assumed in order to account for the richness of the Lower Cambrian fauna and for the highly developed forms occurring in it. That there must have been a long line of precursors of the Cambrian animals is certain, so that the term Proterozoic seems entirely suitable. The lower boundary of the Proterozoic cannot be considered fixed, however, and it may be that a new "zoic" time should be set apart, below it and yet

later than the Archæozoic, which from its derivation should be confined to the earliest life of all.

In these lectures a distinction will be made between "early" and "late" Proterozoic.

DIVISIONS OF THE PRE-CAMBRIAN NORTH OF LAKE HURON

The mapping of the original Huronian area was the most careful work done by Logan and his assistant Murray, and the stretch of eighty miles east from Lake Superior along St. Mary's River and the north shore of Lake Huron includes not only the Huronian but also areas of Laurentian. The map distinguishes eleven subdivisions of the Huronian and shows Ordovician rocks overlying them and Laurentian beneath them. In the accompanying section the Huronian rests unconformably on the Laurentian. Thus the pre-Cambrian was broadly divided into a younger, comparatively little metamorphosed part, the Huronian, and an older, highly metamorphosed part, the Laurentian. The latter was believed to be sedimentary in origin, which was not unnatural at a time when the microscope had not yet been applied to the study of rocks.

In spite of the wild and roadless character of the region, much of the mapping was very well done and is valid now, but other parts are more doubtful and should be worked over once more under modern conditions. A thickness of 18,000 feet was assigned to the Huronian Series, and no unconformity was indicated in it, either on the map or in the report.¹

This classic region of the pre-Cambrian has naturally been visited for purposes of correlation by many geologists interested in the pre-Cambrian of other parts of America; and it was suggested by the Winchells in 1890 and 1891 that there is an important discordance in the series, and also that some older rocks, probably equivalent to the western Keewatin, were included within it.² This was confirmed by Pumpelly and

¹ *Geology of Canada*, 1863, pp. 55-59, and Atlas.

² *Am. Geol.*, vol. 6, pp. 360-370; and *Bull. Geol. Soc. America*, vol. 2, 1891, pp. 85-124.

Van Hise in 1892, the discordance being placed beneath the "Upper-slate conglomerate,"¹ and in 1902 Van Hise and Leith did field work enough to make the break quite certain.²

The members of the International Committee visited the region in 1904 and recommended that the series be divided into an upper and a lower part corresponding to the Middle and Lower Huronian of their classification. They decided, also, that the "green chlorite slate" mapped by Logan and Murray near Thessalon should be "assigned to the Keewatin division of the Basement Complex."³ These changes in the classification seem justified. The finding many years before on some islands east of Thessalon of a distinct basal conglomerate where the Huronian rests on Laurentian gneiss and is made up of fragments of this rock, had already proved conclusively that the Huronian is much younger than the Laurentian. The division of the Huronian into Upper and Lower and the separation of certain volcanic rocks as older and as belonging to the Keewatin have been the only serious changes made in Logan's classification up to the present. The break between the Upper and Lower Huronian is much less important than that between the Lower Huronian and the Laurentian and Keewatin. The recognized succession in the typical Huronian region works out, then, as follows:

The original Huronian rocks are joined toward the east by quartzites and quartz schists with other sedimentary rocks which were described by Murray in later reports as Huronian also. Canoeing along the coast and up the rivers, he crossed

¹ Am. Jour. Sci., (3), vol. 43, pp. 224-232.

² Pre-Cambrian Geology of North America: Bull. U. S. Geol. Surv., No. 360, 1909, pp. 425-426.

³ Rept. Special Com., Jour. Geology, vol. 13, 1905, pp. 89-104.

parts of the Sudbury region, where he found slate conglomerates like those of the Huronian, and he naturally extended the Huronian and Laurentian eastwards and northwards. He found some puzzling features, however, for in one case gray quartzite "abuts against one mass of gneiss and runs under another and appears to be much broken by and entangled among the intrusive rock."¹

This quartzite is really earlier than the typical Huronian and is enclosed eruptively by the Laurentian.

Following Murray's lead, the steeply tilted quartzites extending east to Wahnapiatae Lake and south to Georgian Bay have until recently been placed in the Huronian by all the geologists who have worked in the region. The present writer, in mapping the nickel district and its surroundings eight years ago, followed the usage of Murray and of Robert Bell, placing all the sedimentary rocks below the nickel eruptive in the Huronian; though it was noted that a coarse conglomerate, having the look of tillite, included boulders of quartzite, graywacke, and granite, showing that a great break occurred in the sedimentary series. It was also noted that granites and gneisses, mapped by Murray and Bell as Laurentian, upturn and penetrate the quartzites, which are therefore older than the Laurentian.² A thick group of sedimentary rocks in the interior of the nickel basin which had been classed by Bell as Upper Huronian or perhaps Lower Cambrian, has much the appearance of the western Animikie placed by the Correlation Committee as Upper Huronian. It appeared, therefore, that there were three distinct divisions of the Huronian in the Sudbury region, a lower member cut by the Laurentian, a middle one consisting of conglomerate resting unconformably on it, and an upper part equivalent to the Animikie.

The extension of the Huronian to include between its lower members the enormous break indicated by the building and the destruction of the Laurentian mountains seemed unjustifiable, and within the last five or six years opportunities have been

¹ *Geology of Canada*, 1863, p. 55.

² Bureau Mines, Ontario, vol. 14, part 3, pp. 86-93 and 127-129.

taken by the writer to follow the field relationships through to the typical Huronian region a hundred miles to the west and thus check the correlations.

It has been found that one of the basal conglomerates of the Huronian can be followed up from point to point to Sudbury, sometimes resting on the Laurentian but more often on the steeply tilted quartzites which had been called Lower Huronian. It appeared then that the quartzites, graywackes, and other sedimentary rocks of the Sudbury region are older than the typical Huronian and should be set apart as a distinct series. This result has been confirmed by the work of Collins of the Canadian Geological Survey, who has traced up the basal Cobalt conglomerate, generally considered Huronian, from Cobalt to the Ramsay Lake conglomerate of Sudbury.

It is necessary, then, to establish a new division of the sedimentary rocks, which may be called the Sudbury Series, older than the Huronian and also than the Laurentian granite and gneiss, but younger than the Keewatin or the Grenville Series. That it is younger than these oldest of known rocks of the Canadian Shield is shown at some length in a paper published in the *Compte Rendu* of the last Geological Congress, to which those interested may be referred.

A Temiscaming Series of sediments very similar to those of Sudbury has been set apart by Miller and Knight and Burrows below the Cobalt (Upper Huronian) Series eighty miles to the north; and the Pontiac Series of Quebec not far to the east, as described by Morley E. Wilson, occupies probably the same position.

Since the Sudbury rocks have been longest known, have an estimated thickness of 20,000 feet, and cover a much larger area than the Temiscaming or Pontiac Series, the term Sudbury Series or Sudburian may be expanded to cover the whole and will have equal standing with the Keewatin below or the Huronian above.

In addition to the groups of rocks just described, undoubted Keweenawan eruptives and sediments occur at Mamainse a little north of the western end of the typical Huronian, characteristic

Keewatin rocks occur at the Moose Mountain Iron Range seventeen miles north of Sudbury, and kyanite-hornblende schist and crystalline limestone, probably members of the Grenville Series, are found ten miles southeast of Sudbury. It will be seen that practically all of the recognized pre-Cambrian series of the Canadian Shield are represented in the combined Huronian-Sudbury area. It is believed that this region, extending for two hundred miles eastwards from Lake Superior along the north shore of Lake Huron to Lake Wahnapiatae east of Sudbury, gives the best possible opportunity to work out the geological succession of the pre-Cambrian. As thus worked out, the pre-Cambrian groups may be arranged as follows:

Late Proterozoic	{	Keweenawan (Mamainse and nickel eruptive)	} Typical Huronian	
		<i>Discordance</i>		
		Animikie		
		<i>Discordance</i>		
		Upper Huronian		
Early Proterozoic	{	<i>Discordance</i>		} Typical Huronian
		Lower Huronian		
		<i>Great discordance</i>		
		(Laurentian granite and gneiss)		
		<i>Eruptive contact</i>		
Archæozoic	{	Sudburian=Temiscaming, Pontiac, etc.		
		<i>Great discordance</i>		
		(Granite eruptive through lower series).		
		<i>Eruptive contact</i>		
		Keewatin and Grenville		

The lower granite and gneiss shown as eruptive through the Keewatin and Grenville doubtless occur in the region, since pebbles and boulders of these rocks are found with Keewatin pebbles in conglomerates of the Sudbury Series, but they have not yet been separated in mapping.

As the region of Lake Huron and Sudbury is central, the classification given above may be extended westwards to the Superior region, northwards to the Cobalt and Porcupine regions, and east to the Province of Quebec. It should replace the less complete classification prepared by the Lake Superior Correlation Committee, shown by Lawson to be unsuited also

to the Rainy Lake and Seine River district to the west of Lake Superior.

The classification just given corresponds in the number of its subdivisions, in the lithological character of the members distinguished, and in the relative importance of the breaks between the subdivisions, to the most recent classification of the Bureau of Mines of Ontario as given by Miller and Knight, though most of the terms employed are different, the Cobalt Series taking the place of the Huronian, the Temiscaming Series that of the Sudburian, and the lower of the two eruptions of granite and gneiss being called the Laurentian instead of the upper.¹ The classification of the pre-Cambrian adopted by Lawson for the region of western Ontario² has the same number of subdivisions, but differs in other respects more widely from the one given above than does that of Miller and Knight.

A discussion of the general question of pre-Cambrian classification in Ontario and a detailed comparison of the different modes of classification, with reasons why the one adopted should be preferred, may be found in a paper on The Sudbury Series and its Bearing on Pre-Cambrian Classification, published by the writer in the *Compte Rendu* of the Geological Congress.

EARLY PROTEROZOIC OF THE CANADIAN SHIELD

THE SUDBURY SERIES

As shown by Dr. Adams in a former lecture, the Keewatin rocks of the Canadian Shield are very largely ancient lavas, while the Grenville Series, perhaps of equivalent age, is mainly sedimentary, consisting to a large extent of limestones. The Sudbury and other series placed above these groups in the classification just given are chiefly sedimentary, but differ greatly in character from the Grenville, since they include only

¹ See legend of map of the Sudbury, Cobalt, and Porcupine Regions: Guide Book No. 7, 12th Inter. Geol. Congress, 1913.

² A Standard Scale for the pre-Cambrian Rocks of North America: 12th Inter. Geol. Congress, 1913 (Advance Copy).

insignificant amounts of limestone and are formed mainly of slate, graywacke, quartzite, and conglomerate, materials due to weathering of land surfaces and the action of rivers and of the sea, or at least of large bodies of standing water. With the sediments, though somewhat later in age, there are occasional eruptive rocks, including pillow lavas and amygdaloids as well as deep-seated rocks, such as gabbro. These eruptives occur on a very modest scale compared with the volcanics of the Keewatin. The Sudbury Series differs greatly also from Lawson's Coutchiching, which consists mainly of sedimentary mica schist and gneiss but does not include conglomerate or appreciable amounts of quartzite.

Fig. 1. Cross-bedded Sudburian Quartzite, Ramsay Lake

The Sudbury Series in the typical region is chiefly made up of quartzite though there are also considerable areas of arkose and slate and less important ones of conglomerate and limestone or dolomite. A distinct basal conglomerate has not been recognized in the Sudbury region but is prominent in the Temiscaming, Nipigon, and Doré regions, which are probably of the same age.

Where no later eruptives have penetrated them, the inner parts of large areas of Sudburian rocks are usually well preserved and comparatively little metamorphosed, so that the original bedding, cross-bedding, and even ripple marks may still be seen on weathered outcrops, though less apparent on freshly broken surfaces. As one approaches the granite or gneiss of the Laurentian at the edge of an area, metamorphism becomes well marked, except in the purer quartzite, and the rocks become schistose from the development of mica or chlorite with other secondary minerals. Where narrow strips of slate or graywacke have been caught in the Laurentian they may be highly metamorphosed into mica schist with garnets or even into well-foliated gneisses like the western Couthiching.

As the coarsest of the Sudburian rocks, the conglomerates, afford the best evidence of the conditions at the time of deposit, they may be considered first. They contain pebbles or small boulders of granites of more than one kind, vein quartz or quartzite, greenstone, and green schist, all apparently derived from the Keewatin and granites penetrating it. The pebbles are well rounded and evidently water-formed. The matrix is graywacke or quartzite. Most of the bands of conglomerate are interstratified with graywacke or quartzite and are quite narrow, but one belt that was measured near Georgian Bay has a width of a quarter of a mile. As the bedding is obscure, the thickness is uncertain, but most of the dips measured in the region are high, indicating a considerable thickness.

The graywackes often contain little pebbles as well as angular grains of quartz and feldspar in a fine ground mass charged with scales of chlorite or sericite. Weathered surfaces show a banding of finer and coarser particles, probably seasonal in origin. The bands are usually from half an inch to two or three inches thick and quite resemble modern stratified materials, with false bedding on a small scale and ripple marks, as well as other structures not easily interpreted. There is, however, very little suggestion of these structures on fresh exposures. Apparently these rocks were formed of gritty mud brought down by rivers having floods and times of slack water, and they

seem to have come from a land surface attacked in such a way that feldspar fragments were not greatly weathered.¹

The thickness of the graywacke as measured in Sudbury is 4000 or 5000 feet. It often contains staurolite crystals, sometimes five inches in length, where eruptives have caused contact metamorphism, and near granite masses it may be transformed into mica schist or fine-grained gneiss.

Fig. 2. Sudburian Graywacke, near Frood

Slaty layers are often interbanded with the graywacke and considerable areas may be formed of slate without the coarser materials. They show cleavage across the bedding, sometimes in two directions, and near eruptives they pass into phyllite and mica schist.

¹ Probably indicating a cool and moist climate, as shown by Professor Barrell's excellent analysis of the relation between climate and terrestrial deposits: *Jour. Geology*, vol. 16, 1908, pp. 159, 255, and 363, etc. The criteria developed by Professor Barrell have proved of great service in the preparation of these lectures.

The arkose of the Sudbury region is pale flesh-colored and shows little evidence of stratification, so that at one time it was taken for felsite. It has been found only near large masses of later granite and has usually undergone a good deal of recrystallization, causing the original grains of quartz and feldspar to grow outwards into an interlocking mass. The large amount of feldspar in this rock suggests either an arid or a cold climate in which silicates were little attacked, the latter supposition being the more probable.

Quartzite is much the most important rock of the Sudbury Series, covering more than 1000 square miles between Lake Wahnapiatae and Georgian Bay. Parts of it are interbedded with slate or graywacke and show excellent stratification into beds from one to four feet thick. On weathered surfaces the cross-bedding comes out distinctly and the rock might be taken for a Palæozoic sandstone, but fresh surfaces seem less granular and thin sections show the development of scales of chlorite and sericite between the somewhat recrystallized quartz grains. Examples of the slightly impure quartzite near the nickel mines, used sometimes for flux, contain 87 to 90 per cent of silica.

Farther to the southwest in the Cloche Mountains near Georgian Bay there are thick beds of almost pure quartz rock, fine-grained and quite vitreous when broken. At one place they are being quarried and shipped to the east for use as silica. As a result of its extreme hardness and resistance to weathering, this quartzite stands up as a range of high hills or mountains running for fifty miles from east to west along the north shore of Georgian Bay and Lake Huron with a height of 1000 to 1760 feet above the sea and of 400 to 1200 feet above the lake. Where the forest has been burnt the pale cliffs and summits of these mountains suggest snow and the range is very striking as seen from the deck of a steamer following the north channel.

Southwest of Sudbury the quartzites are estimated to have a thickness of 15,000 feet, unless duplicated by faults which have not been observed, and the whole mass of quartz contained in them must sum up to hundreds of cubic miles. The source of this vast accumulation of quartz is hard to imagine. Much of

it is as pure as vein quartz, and doubtless many quartz veins must have been worked up during the destruction of the Keewatin rocks previous to the formation of the Sudbury Series; but that many cubic miles of material should have accumulated in this way is incredible. The only other known source is the quartz of the granites which penetrate the Keewatin. The weathering and removal of feldspar and mica necessary to provide this immense quantity of quartz must have required a very long time, showing how great an interval separates the Sudbury Series from the Keewatin and granite below.

Fig. 3. Sudburian Quartzite, near Whitefish, Lake Huron

Carbon seems almost wanting in the Sudburian sediments, and carbonates such as limestone and dolomite are of small extent and usually impure. They are fine-grained and pale gray, unlike the crystalline limestones of the Grenville Series, and they often contain cherty ingredients which stand out on the weathered surface. Conditions were very different from those of the Grenville, which Dr. Adams proves to have included immense quantities of limestone. The Sudburian is very little

charged with iron compounds, which marks it off strongly from the Keewatin, of which the Iron Formation of banded ore and silica is a characteristic part.

SECTIONS OF THE SUDBURY SERIES

The most carefully studied section of the Sudbury sedimentary rocks extends from the nickel range southeast to the Laurentian granites and gneisses, with a breadth of eight miles where widest. They are interrupted by a narrow range of gabbro hills forming irregular laccoliths and running for seven or eight miles about parallel to the strike, which is 70° east of north. There are also some bosses of greenstone coming up through the sediments, more or less disturbing the arrangement. Near the nickel range and to a less extent near the eruptives just mentioned the attitude of the beds is sometimes doubtful, dips approaching the vertical being found; but in the least disturbed parts the dip averages 45° to the southeast. The probable arrangement begins with arkose near the nickel range, as the lowest rock of the series, followed by graywacke and ending with quartzite.

The thicknesses have been worked out as follows, reading from below upwards:

Wahnapitae quartzite .	15,000 feet
McKim graywacke .	4,000 feet
Copper Cliff arkose .	1,000 feet
	<hr/>
	20,000 feet

While this is the section at Sudbury, which may be considered typical for the series, there are considerable variations as one goes westward toward the Huronian region and southwest towards Georgian Bay. Thick beds of slate occur near Worthington; and south of Espanola there are numerous beds of conglomerate intercalated with slate and quartzite, though the latter forms the greater part of the series. Following the Algoma Eastern Railway south from Espanola to Lake Huron, almost the whole distance of thirty-two miles displays a cross-

section of these rocks with a few interruptions of greenstone, but there are probably reduplications and the whole thickness may not be greater than that near Sudbury. The southern part has been described by Robert Bell as a great syncline, the lower part of quartzite rising on each side as the Cloche Mountains, while softer rocks, such as graywacke, slate, dolomite, etc., occupy the centre. One section of quartzite near the eastern end of the syncline is six miles in width, and assuming it to be a synclinal trough, the beds are three miles or 15,840 feet in thickness.¹ The quartzite is fully equal to the Wahnapiatae quartzites in magnitude, and the rocks within the syncline, where it widens towards the west, would add thousands of feet to the section, though Bell gives no estimate of them.

Farther to the west the Sudbury Series narrows and is greatly cut up by bosses and ridges of diabase, gabbros, or greenstone. Toward the north there is generally a band of this greenstone separating it from the Laurentian. A little beyond the mouth of Spanish River the granitoid gneisses of the Laurentian come out to the shore of Lake Huron and the Sudbury Series ends.

METAMORPHISM OF THE SUDBURY SERIES

In the widest and least modified of the Sudburian areas the rocks are but little metamorphosed, considering their age, but near masses of later eruptive rock some of them show contact metamorphism, and in the vicinity of Laurentian granite and gneiss the process of recrystallization may be nearly complete. Different members of the series are, however, very differently affected, the quartzites showing the least change. In places the quartzite has been so little modified that thin sections show well-rounded grains with dusty margins; but usually some sericite or chlorite occurs between the grains. In the most highly metamorphosed examples, the granular appearance is lost, the dusty margins have vanished and the quartz areas interlock. Usually a little plagioclase or microcline and some mica occur,

¹ Geol. Surv., Canada, vol. 9, 1896, p. 15-I.

also; the whole having a clean fresh look quite different from the unmetamorphosed parts.

In the case of arkose, the least changed specimens are formed of distinct grains of quartz and feldspar, usually microcline, with dusty margins, the microcline often a good deal decomposed. In the rearranged arkose near Copper Cliff, there has been some recrystallization and at points along the Algoma Eastern Railway this has gone so far as to suggest granite. Bell and Barlow speak of such rocks as "regenerated" granites, and think they may account for much of the later granite in the region, though this seems improbable to the writer. In some cases the basic material in the arkose forms blades of green hornblende an inch or more in length.

The metamorphosed arkoses were frequently taken for syenite or felsite in the earlier work at Sudbury.

The most interesting changes are found, however, in the muddy sediments, slate and graywacke. The less changed slates have a good cleavage crossing the banding, due to sedimentation, but show little rearrangement under the microscope beyond the development of scales of sericite or chlorite and occasionally of rutile needles. In many places near eruptive masses, the slate or graywacke is filled with small paler areas like short rods, giving a variety called "rice rock" from the look of scattered rice grains. In thin sections it is found that the "rice" grains have the shapes of staurolite crystals and sometimes form St. Andrew's cross twins. They are now changed into finely granular quartz or a scaly mineral resembling sericite, and have undergone a second metamorphism so complete that unchanged staurolite has not been recognized in them. The pseudomorphs after staurolite may reach dimensions of four or five inches, and their pale forms may stand up very strikingly from the gray matrix, which is much more easily weathered.

The replacement of a mineral like staurolite, containing more than 50 per cent of Al_2O_3 and 14 per cent of iron oxides, by quartz or sericite means the removal of much alumina and iron and the introduction of a large amount of silica, or, in the latter case, of silica and potash, from the eruptives which have caused

the change. Only the granite magma seems capable of sending out solutions competent to do this work; but in many cases no granite is known in the near vicinity of the "rice rocks."

As one goes westward towards the narrower part of the area, where the band of sedimentary rock was more effectively engulfed between the slowly surging granite batholiths, the metamorphism becomes of the regional type. There is a phase which may be called phyllite, in which the minute micaceous minerals grow in amount, giving a more lustrous cleavage surface than belongs to slate. In this case there is sometimes crumpling on a tiny scale, the corrugations ranging from a tenth of an inch to half an inch in breadth. This suggests either a compressive force or a linear growth with much slack to be taken up. Some of the graywacke in this part of the region has evidence of strain in the wandering extinction of the enclosed quartz fragments. In one specimen of sericite schist or phyllite there are vague prisms of some earlier secondary mineral, perhaps andalusite.

At Webbwood, on Spanish River near its entrance into Lake Huron, these rocks show no more clastic structure and become mica schists with bright silvery lustre, or sometimes fine-grained gray gneiss like certain Coutchiching schists west of Lake Superior. The silvery scales of muscovite grow larger at Walford, eight miles farther west, and the schist is coarse-grained, with a knotty structure apparently caused by large masses of epidote. In thin sections the yellow epidote is seen to be surrounded by an obscure saussuritic border. There are also small garnets.

These shiny quartz muscovite schists are sometimes interbedded with green hornblende or diorite schist, perhaps originally basic dikes.

Still farther to the west, beyond Cutler, on the north coast of Lake Huron, the pelites seem transformed into gneiss not readily distinguished from the adjoining Laurentian. The well-bedded quartzites at Cutler are penetrated by dikes of granite and pegmatite and have been sharply folded, but are not nearly so much affected by metamorphism as the slates and graywacke.

It should be mentioned that there are intermediate rocks between slate and quartzite, such as graywacke and arkose, that present different phases of metamorphism from the extremes just described. None of the metamorphic rocks formed from the Sudburian sediments, except the gneiss west of Cutler, resemble those of the Grenville Series southeast of Sudbury, where there is crystalline limestone charged with various silicates, kyanite-biotite-garnet schist, etc., and a glassy quartzite showing no hint of stratification.

Fig. 4. Sudburian Quartzite, crumpled near Granite, Cutler

ERUPTIVES FOLLOWING THE SUDBURIAN SEDIMENTS

After the sediments which have been described had been deposited, volcanic eruptions began, basic rock of an unusual kind coming to the surface as lava streams showing pillow and amygdaloidal structures. These lavas, when fresh, are found to represent a new type of eruptive rock, consisting essentially of bytownite, hypersthene, and augite, with a considerable

amount of magnetite. They are very basic, as may be seen from the following analysis:

SiO ₂	.	.	.	.	46.69
Al ₂ O ₃	.	.	.	.	14.23
Fe ₂ O ₃	.	.	.	.	2.00
FeO	.	.	.	.	12.82
MnO	.	.	.	.	.11
MgO	.	.	.	.	8.15
CaO	.	.	.	.	13.32
Na ₂ O	.	.	.	.	.98
P ₂ O ₅	.	.	.	.	.19
TiO ₂	.	.	.	.	1.28
Moisture	.	.	.	.	.08
S	.	.	.	.	.12
					<hr/>
					99.97
Specific Gravity	.	.	.	.	3.24

More than half of the rock consists of hypersthene and augite in about equal amounts, the rest being made up of bytownite and titaniferous magnetite. In the quantitative system it belongs to the group Kedebeckase.¹

The norm works out as follows:

Bytownite	.	.	.	.	42.57
Diopside	.	.	.	.	25.73
Hypersthene	.	.	.	.	20.76
Olivine	.	.	.	.	5.34
Titaniferous magnetite	.	.	.	.	4.98
Apatite	.	.	.	.	.34
Pyrite	.	.	.	.	.27

No olivine has been found in thin sections, but otherwise the minerals found correspond well with the list just given. They are granular, with nearly equal diameters, and show no tendency to the ophitic structure. No glass has been observed in the sections studied. From the brief description just given it will be seen that this lava differs considerably from any hitherto described. It comes nearest to the more basic varieties of basalt,

¹ Bureau Mines, Ontario, vol. 14, part 3, p. 120. Analysis by J. A. Horton.

but contains no glass nor olivine and does not present the tabular forms of the feldspars usual in basalt. It is higher in lime and lower in the alkalis than the basalts, and its appearance is quite different from that of basaltic lavas.

In the mapping of the Sudbury nickel region, it was referred to as "older norite"; but it is very different from the nickel-bearing norite, which contains 52.77 per cent of silica and usually shows some quartz and a few crystals of biotite. The European nickel-bearing norites are more basic and come nearer than the Sudbury norite to the composition of the lava here described.

It has been suggested by Dr. Miller that the rock should be called sudburyite and should be defined as the effusive or volcanic phase of norite. Some of the authorities consulted would choose the shorter form, sudburite, for the name and perhaps this is preferable. Sudburite then will have the same relation to norite as basalt to gabbro.

Thin sections of sudburite are usually surprisingly fresh in appearance except for narrow bands of green hornblende along minute fissures, and four minerals in small equi-dimensional grains or crowded crystals make up almost the whole of the rock—hypersthene or enstatite, a monoclinic augite, plagioclase (bytownite), and magnetite. Usually the two pyroxenes are very much alike, with strong outlines against the feldspars, pale brownish gray in color with faint greenish and reddish change of color or none at all, and a suggestion of crystal outline. Here as so often in norites certain pleochroic crystals in general appearance exactly like the hypersthene, have a considerable angle of extinction from the cleavages or the edge of a prism, so that they are really monoclinic. It seems as if the hypersthene is merely a monoclinic pyroxene with 0° extinction angle, with transitions to an unnamed monoclinic form of the same composition, but having large extinction angles. The rhombic variety of pyroxene is generally in largest amount, and the two pyroxenes make up as a rule more than half the section. The plagioclase is in short stout crystals with few twin planes, and in many cases the crystal form is fairly perfect.

Besides the ordinary even-textured variety of sudburite, there are porphyritic ones in which a few large and generally elongated crystals of hypersthene or augite are embedded, and these may be poikilitic, including small grains of the feldspar. In other sections the porphyritic crystals are hornblende, green or brown, rough edged, and always poikilitic, sometimes thickly crowded with clear feldspars. They may represent former augites, though this seems doubtful, since both minerals some-

Fig. 5. Pillow and Amygdaloidal Structures in Sudburite, Elsie

times occur porphyritically in the same section. The magnetite is often in good crystal forms, the grains being relatively large. In most cases none of the minerals show a trace of weathering except, as mentioned before, along thin seams where hornblende develops.

A rarer variety of sudburite, which has white patches like porphyritic feldspars, shows the same composition as the others, the white areas being formed of plagioclase in the same short stout crystals as elsewhere, but without pyroxene or magnetite. There are occasionally sections wholly or almost wholly composed of the plagioclase.

The comparatively fresh sudburite as here described, with its pillow structure, and often also white amygdules crowded round the outsides of the pillows, passes into greenstones such as hornblende schist and hornblende porphyrite in many places. A band of rugged hills of these rocks, occasionally enclosing blocks or bands of graywacke, runs somewhat discontinuously for fourteen miles along the southern nickel range, often forming the footwall of the ore bodies.

Probably some of the greenstone bosses or ridges intruding into the Sudbury Series in other parts of the region were originally sudburite, but the transformation into secondary products has been too complete to allow direct proof of this. This is not the case, however, with a range of laccolithic hills three or four miles south of the band of sudburite just referred to. These hills, which run for more than seven miles and tilt up or even overturn the adjoining graywacke, are of gabbro or norite, generally much weathered, but sometimes fresh enough to determine the original composition. Labradorite makes up about half of the sections, with pale green augite and enstatite as the other important minerals. Quartz is sparingly present, and the rock is evidently more nearly related to the nickel-bearing norite of a later age than the sudburite just described.

In this greenish gray, medium-grained gabbro there are great inclusions of more siliceous material, especially along the crest of the range of hills. In the centre there is vitreous-looking quartz, sometimes in sufficient amounts to be mined as flux,

surrounded by a coarse, white, graphic intergrowth of quartz and albite, and then by albite with long prisms of dark green hornblende. Finally there are a few inches or a foot or two of similar green hornblende as a margin against the ordinary gabbro. It is probable that these curious masses are really examples of "stoping," that is, inclusions of quartzite which have sunk into the magma of the rising laccolith and have been attacked, forming a broad reaction rim about the little changed centre.

The laccolithic gabbro sometimes contains small portions of nickeliferous pyrrhotite and probably came from the original nickel-bearing magma in an early part of its history.

Later than the eruptives thus far described, bosses and dikes of granite ascended, cutting the sudburite and also the greenstones. Whether they were split off from the great Sudbury magmatic hearth or were connected with the Laurentian granites and gneisses is not certainly known. In any case they can hardly be looked on as members of the Sudbury Series.

OTHER AREAS PROBABLY OF SUDBURIAN AGE

The Sudbury Series has not yet been mapped to the northeast of Wahnapiatae River, though quartzite and arkose are known to extend in that direction. Sedimentary rocks very similar to those just described occur, however, at numerous points to the northeast and north. In the Cobalt region Miller and Knight have mapped and briefly described the Temiscaming Series extending to the lake of that name. They find the series to be composed of conglomerate, graywacke, and slate, with conglomerate in largest amount. The thickness is not known but is believed to be great, and the rocks have been steeply tilted by the rise of later granite. Overlying them unconformably is the Cobalt (Upper Huronian) conglomerate.

In the Gowganda silver region to the northwest there are similar rocks and a long band of the same kind has been mapped in the Larder Lake gold district forty or fifty miles north of Cobalt. In the Porcupine gold region farther to the northwest,

Temiscaming rocks are described by Burrows as "of great economic value since several important gold veins have been found in them. The largest area of these fragmental rocks stretches from the Dome mine in a northeast direction for about ten miles. It consists of a series of slates, quartzites, and conglomerates which have generally been greatly disturbed."¹

Fig. 6. Conglomerate, Temiscaming Series, West Dome, Porcupine

From a personal examination of these rocks, the writer has been struck with their close resemblance to the Sudbury Series in every respect except the larger amount of conglomerate. There are graywackes with slaty partings, well-bedded quartzites, etc., precisely like those of Sudbury.

When the intervening regions are studied, doubtless many other small areas of pre-Huronian and post-Keewatin sediments will be found. In connection with the Gowganda region, McMillan speaks of "isolated remnants or islands" as occurring² in various places, and there can be no doubt that these rocks were far more widely spread in northern Ontario before the

¹ Bureau Mines, Ontario, vol. 19, part 2, 1913, pp. 62-68.

² *Idem*, p. 66.

Laurentian upheaval, though the whole area may not have been covered.

The Pontiac Series just to the east in Quebec, as described by Morley Wilson, is less certainly an extension of the Sudbury Series, since quartzite appears to be absent, the sediments consisting of conglomerate and arkose, generally sheared and passing into mica schist. These rocks are shown to be older than the Cobalt Series (Huronian) and to be penetrated by

Fig. 7. Graywacke and Quartzite, Temiscaming Series, Porcupine

Laurentian granite and gneiss, so that they seem to occupy the same position as the Sudbury Series. The Matagami Series described by Bancroft farther to the north in Quebec, is probably the equivalent of the Pontiac Series and may be placed in the same position.¹ The sediments are said to have been originally conglomerate and feldspathic sandstone with shaly partings. The conglomerate contains many granite pebbles but the series has been invaded by a great batholith of later granite, and has thus been steeply tilted and rendered schistose.

¹ Dept. Mines, Quebec, 1912, pp. 157-163.

This locality on the James Bay slope in Quebec shows that rocks of the age extend for 260 miles northeast of the Sudbury region, though there is a wide gap between the areas of Larder Lake and Pontiac and this on the headwaters of Harricaw River.

Toward the northwest of Sudbury there is a long interval of Laurentian granite and gneiss before pre-Cambrian sediments are encountered, 150 miles away, at Doré River in the Michipicoten district. Here schist conglomerate with other schistose rocks and slate occurs interfolded with Keewatin green schist and iron formation. As the conglomerate includes pebbles of iron formation and green schist, there is evidently a great time interval between it and the Keewatin. On the other hand, the Doré formation has been caught in synclines by the rise of the Laurentian batholiths and is therefore older than the Laurentian. Although placed by Logan in the Huronian,¹ it is clearly older than the typical Huronian, which rests unconformably on the Laurentian, and it appears to occupy the same position as the Sudbury Series. The Doré rocks have a curving outcrop extending east along the north shore of Michipicoten Bay and then swinging inland and bending toward the west. They form long narrow synclines, more or less interrupted but with a total length on the northern arm of more than thirty miles. The greatest width recorded is 8000 feet and the thickness of the schist conglomerate in the syncline near Helen mine is estimated at 3700 feet.²

Seventy miles farther to the northwest, at Heron Bay on the north side of Lake Superior, there is an area of similar conglomerate older than the Laurentian; and on the Slate Islands south of Jackfish Bay schist conglomerate is found interfolded with a band of iron formation but containing jasper pebbles derived from it, so that it is certainly younger than the Keewatin, though it has been involved in the Laurentian uplift.³

¹ *Geology of Canada*, 1863, pp. 53-54.

² Bureau Mines, Ontario, vol. 11, 1902, pp. 162, etc.; also vol. 14, 1905, pp. 340-346 (J. M. Bell).

³ *Ibid.*, vol. 11, 1902, p. 137.

Sixty miles northwest of Jackfish, on the east side of Lake Nipigon, a band of pre-Laurentian conglomerate has been followed fifteen miles with a greatest width of one-third of a mile. Phyllite and arkose are associated with it though no quartzite has been found. As it contains pebbles of jasper and of green schist, it is older than the Keewatin. Some of the boulders enclosed in it reach diameters of two feet.¹ E. S. Moore has found similar rocks near the Onaman Iron Range farther to the north on the Hudson Bay watershed;² and it may be said in a general way that in almost all of the areas mapped as Keewatin (or Huronian) in northern Ontario such schist conglomerates younger than the Keewatin and older than the Laurentian have been found, though usually not in very large exposures.

To the west of Lake Superior, rocks probably equivalent to the Sudbury Series occur along Seine River and have been described by Lawson as the Seine River Series. They are, however, widely separated from the areas mentioned above, being nearly 200 miles southwest of Jackfish on the east side of Lake Nipigon; so that their equivalence may be considered less certain. Lawson refers to them as long synclinal bands of schist conglomerate accompanied by quartzite and slaty schist. The most interesting feature mentioned is a basal conglomerate near Mine Centre, merging downwards into granitic débris formed by weathering *in situ*, the only instance where the ancient floor has been reported beneath rocks probably of Sudburian age.³ His report on the region for the Canadian Geological Survey (Memoir 40) contains details of the Seine Series with his revised views as to its extent, origin, and classification. Besides the bands of Seine Series rocks near Atikokan and Mine Centre just referred to, there are schist conglomerates of a similar kind still farther west near Rat Root Bay, and fifty miles north near Lake Manitou.

¹ Bureau Mines, Ontario, vol. 16, 1908, pp. 142-143.

² *Idem*, pp. 183-184.

³ Summary Rept., 1911, Geol. Surv., Canada, 1912, pp. 241-242; also Guide Book No. 8, 12th Inter. Geol. Congress, 1913, part 1, p. 58.

After personal examination of the schist conglomerates and associated rocks in the Seine region and at other points mentioned above, it may be stated that in many respects these western sediments have a great resemblance to those of the Sudbury Series, and the fact that in all cases they are later than the Keewatin and earlier than the granites and gneisses generally called Laurentian puts them in line with the Sudbury Series.

Still farther to the north there is seldom evidence available to decide whether rocks of this age exist or not, though Dowling has described conglomerate with quartzite, slate, and limestone near Red Lake in Latitude 51° and Longitude 93° or 94° in a way suggesting it, since these rocks contain jasper pebbles and are penetrated by granite.¹

All of the groups thus far described have important features in common, they are later than the Keewatin and they have been upheaved and more or less metamorphosed by great outbreaks of granite having the character usually ascribed to the Laurentian. They have all been involved in important mountain-building operations and are commonly steeply tilted blocks or synclinal remnants caught between two areas of granite or between granite and Keewatin schists. Usually they have been completely lifted from their foundations, though Lawson has described the Seine Series as still in place on an ancient weathered surface. Its distance from the nearest area undoubtedly representing the Sudbury Series makes it somewhat questionable whether it should be included, however.

If the whole of the areas described is of the same age, there was at the end of Sudbury time a great belt of sedimentary rocks, conglomerates, arkoses, graywackes, slates, and sandstones, stretching, perhaps with an interval west of Lake Superior, from the Province of Quebec to Rainy Lake, a distance of 700 miles; and having a width in one place of more than 200 miles. Large areas of these rocks must have been destroyed during the slow removal of the Laurentian mountains,

¹ Geol. Surv., Canada, vol. 7, 1894, pp. 40-F, etc.

probably far more than have been preserved, so that in the beginning a very considerable part of the southern side of the Canadian Shield must have been covered with them.

It may be added that in nearly every area mapped as Keewatin, bands of a later conglomerate containing pebbles of the iron formation have been found folded in with the green schists, though often in too small amounts to be shown on maps of the usual scale. These seem to be of Sudburian age, and indicate that the series was once much more widely extended than now.

ATTITUDE OF THE SUDBURY SERIES

The sedimentary rocks of the Sudbury Series often show very distinct bedding, so that their dip and strike are easily determined, but they are sometimes disturbed by the eruptives just referred to, and over considerable areas slaty cleavage or a certain amount of metamorphism obscures the relations. It has been suggested by Barlow that the sediments between Sudbury and the nickel range have a synclinal arrangement, but other interpretations are possible. Between Sudbury and the Laurentian granites and gneisses, for a width of from four to six miles, the quartzites appear to form a continuous succession with dips averaging 45° , as though a great block had been tilted. Farther to the southwest, near the shore of Georgian Bay and Lake Huron, Bell indicates a synclinal arrangement of the quartzite and other rocks. Under these great masses of quartzite, graywacke, and slate no solid foundation can be found in the immediate Sudbury region. They are cradled in the granites and gneisses of the Laurentian as if the magma had lifted them bodily, bending them into folds or tilting great blocks to all degrees up to the vertical, penetrating every fissure in the process, and wedging sheet from sheet. Finally came the last portion of the magma to retain fluid, pushing its way into both granite and quartzite as pegmatite dikes. At the close of the Laurentian episode, the region must have been very mountainous, with batholithic domes more or less roofed with sediments.

In the other regions thought to be of the same age, the relations are usually very similar. Miller describes the rocks of the Temiscaming Series near Cobalt as "tilted up until they now rest in a vertical or almost vertical attitude," and as penetrated by dikes of lamprophyre and granite. The same series at Porcupine has been "highly tilted, dipping at angles of 70° to vertical. A secondary cleavage has frequently been developed, and the rocks have been rendered quite schistose."¹

Fig. 8. Laurentian Gneiss, near Sudburian Quartzite, north of Wanup

In the Doré region the schist conglomerate is probably bent into a closed syncline and the beds have dips of from 60° to the vertical; and the same is true of the Seine Series west of Lake Superior.

No area of rock of this age has escaped the tilting or sharp bending which resulted from the rise of the Laurentian batholiths, and in every case there has been sufficient fracturing to allow dikes of granite or porphyry to push into the sediments from the still partially molten magma of the batholiths.

¹ Burrows, Guide Book No. 7, 12th Inter. Geol. Congress, 1913, p. 123.

In the regions just mentioned, the rocks of Sudburian age have commonly been folded in with the green schists of the Keewatin, and so are sometimes not in direct contact with the gneisses which upheaved them or touch them only on one side. The presence of granite dikes proves, however, that the tilting and distortion they have suffered was connected with the Laurentian mountain-building.

The attitudes just described mark off the Sudburian and its contemporary sedimentary series in other parts of the shield very sharply from the Huronian, which usually lies nearly flat or is only gently folded.

CONDITIONS DURING SUDBURIAN TIME

Though the original surface on which the rocks of the Sudbury and other series of probably equivalent age rested has not yet been found, except perhaps at Mine Centre near the extreme western end of the known outcrops, some points in regard to it are certain. It was made up largely of green volcanic rocks of the Keewatin and of granites and gneisses which penetrated them; and in places the banded jasper and ore of the iron formation were already in existence. To a less extent the surface included sedimentary rocks of the Couthiching and Grenville series. The lands had been greatly weathered, and the surface was unequal enough to allow rain and river to assort much of the mantle of decay into finer and coarser materials, mud, sand, and pebbles; but other parts were deposited without much rearrangement as arkose and graywacke. Standing water existed in considerable volume, as shown by the finely stratified slates and graywackes, which closely resemble deposits made in some of our post-glacial lakes. Whether the water was fresh or salt cannot be decided, nor whether the work was done in lakes or in shallow margins of the sea.

The conglomerates are largely developed in most regions and range widely in size of pebbles. In many places the pebbles are large and occasionally they reach boulder size with diameters up to two feet. They are generally well rounded, though

angular and subangular ones occur also, and if due to shore action they must have required powerful waves, possible only on a comparatively large body of water.

For the conglomerate at Mine Centre, Lawson suggests "a gravel flood plain rather than the beach of a transgressing sea. If this be true, then in a general way the distribution of the conglomerate as outlined on a geological map of the region indicates the course of a river."¹ His reason for this is as follows: "The bottom portion of the conglomerate formation, while very clearly detrital, is neither waterworn nor far transported. The fragments which compose it are regular detritus of a desert alluvial slope. Where it rests upon the granite, the detritus is nearly all derived from the underlying granite, blocks of granite being enclosed in a coarse quartzite arkose matrix; and where it rests upon the nearby Keewatin, it is nearly all derived from the underlying rocks of that series, but with considerable quartz in some parts of the matrix. This facies of the accumulation is very evidently the same as that described elsewhere under the name of fanglomerate."

Relations of this sort have not been shown in the other areas and it may be doubted if the Doré conglomerate, 3700 feet thick, could be accounted for in this way.

Arkose occurs in various places, for example, just west of Sudbury, but has not been found to pass into conglomerate. The broad stretches of quartzite between Sudbury and Georgian Bay, well stratified in uniform layers, cross-bedded, and often separated by thin partings of slate, can scarcely be other than deposits, perhaps of a delta-like character, formed in standing water.

The absence of "red beds" is suggestive of a moist or cool climate rather than of a hot desert climate; but in an area 700 by 200 miles in dimensions there is room for variety of conditions. The very considerable amount of feldspar found in the arkoses and graywackes suggests a cool and perhaps moist climate.

¹ Guide Book No. 8, 12th Inter. Geol. Congress, 1913, p. 58.

It is rather surprising that no carbon-bearing rock is known of this age, since the Keewatin has graphitic slates and the Grenville Series graphitic limestones and gneisses. Direct evidence of life in Sudburian times is lacking, though the conditions do not seem to have been unfavorable to it.

THE INTERVAL BETWEEN THE SUDBURIAN AND THE HURONIAN

As already shown, the sediments of the Sudbury, Temiscaming, Doré, and Seine series were upheaved, tilted, and thrown into folds along with the older groups of rock by the floods of granitic magma making up the Laurentian. From the attitude of their present remnants it is evident that great ranges of mountains with a trend of about north 70° east resulted from this enormous welling up of molten or plastic material. From the coarseness of the grain of the granites and gneisses enclosing or adjoining the sediments, it is evident that they cooled at great depths and slowly. The upward movement of the granite magma was probably deliberate, the cooling must have required a very long time, and the destruction of the Laurentian mountains must have been an extremely slow process, since thousands of feet of granite and gneiss and greenstone and firm quartzite and schist conglomerate must have been consumed by weathering and the action of epigene forces. The Laurentian mountain region forming most of the Canadian Shield was, during this interval, carved down to a peneplain, the most tremendous and widespread example of levelling known in the history of the world. How vast a time was required for the removal of millions of cubic miles of hard rock from this great area one can scarcely guess, perhaps as long as has elapsed in all the later ages. What took place elsewhere in the world while the lofty continent of the Canadian Shield was being slowly torn to pieces, ground into dust, and pared down to the bare stumps of its mountains, has not been revealed. The materials removed would suffice to build a fresh continent from the sea bottom. They must have been deposited somewhere and perhaps some time may be found to contain a record of the long succession of

events which intervened between the end of the Sudburian and the beginning of the Huronian.

Dr. Adams has graphically described the present hummocky peneplain of the Canadian Shield, with its thousands of hollows filled with lakes by which the canoeman can make his way in any direction over the uniform expanse. The present surface is a close counterpart of that on which the Huronian was deposited and from which in places its basal conglomerate is now being stripped. In fact, it almost appears as if the present uneven plain of comparatively low relief, formed everywhere of mounds or ridges and depressions, is part of the little changed pre-Huronian continent. The work of Miller and Knight in the Cobalt silver-mining region has revealed to us in some detail a small portion of the ancient surface. If the Huronian were peeled off from it, the hills and valleys of granitoid gneiss and Keewatin greenstones and schists would fit perfectly into the surrounding landscape which is not covered by the Huronian. It looks as though far the greater part of the peneplanation was already complete in Huronian times, and as though the portions not covered by the Huronian have undergone very little further degradation in the time that has elapsed since.

It should be added, however, that much of the surface has been covered and protected by later formations, which have been removed comparatively recently, so that weathering and erosion have not everywhere gone on unbroken since Huronian times. Whether any portion of the shield has been dry land continuously since the Sudburian is uncertain; though probably one portion or another of the great area has always remained above the sea as a refuge for any land inhabitants there may have been in Canada at the time.

Though we know little of the separate events that took place during this wide gap in the record, we know, at least in a few places, the final condition in which the shield was left when the Huronian began, for the basal Huronian conglomerate has perfectly sealed up and preserved for us parts of the ancient surface. At some points the rock beneath had been weathered in place, and one can observe the fresh, unbroken material

growing fissured in the upper parts and passing into a breccia of fragments and finally into coarse sand, all now firmly cemented into rock. Good instances of this are seen on certain islands three or four miles east of Thessalon in the typical Huronian region. Irving¹ and later Van Hise² and others have observed and described this interesting locality. The granitoid gneiss of the Laurentian, including strips and masses of green schist, has its surface brecciated into angular blocks, intermixed with smaller fragments and in places forming a coarse arkose. It is evidently an old land surface weathered in place. A very similar instance along the Kerr Lake Railway south of Cobalt has been pointed out by Miller, the underlying rock in this case being Keewatin greenstone. Angular blocks can be seen loosened from the solid rock beneath, passing into finer materials above with no marked break at the base of the conglomerate. The dark color of all the materials at this point somewhat obscures the structures, but there can be no doubt of the correctness of Miller's interpretation.³

Another excellent example of an ancient surface with weathered products *in situ* has been described by Barlow and Ferrier, on the east side of Lake Temiscaming at Baie des Pères. Every transition can be seen between red unweathered granite, greenish decomposed granite with a brecciated character, and greenish arkose above,⁴ the latter evidently a regolith.

On the other hand there are a number of localities where smooth rock surfaces underlie the basal conglomerate, any weathered materials having been swept away before the conglomerate was laid down. Collins and Morley Wilson have found smoothed surfaces of granite in this position in the Gowganda and other regions, and a smoothed and rounded surface of quartzite occurs under the conglomerate about two miles east of Sudbury on the

¹ Am. Jour. Sci., (3), vol. 34, 1887, pp. 204-216, 249-263, 365-374.

² *Ibid.*, vol. 43, 1892, pp. 224-232; also Jour. Geology, vol. 13, 1905, pp. 89-104.

³ Bureau Mines, Ontario, vol. 19, part 2, 4th ed., p. 79.

⁴ Geol. Surv., Canada, vol. 10, 1897, pp. 195-199-I; also British Assoc. Adv. Sci., Toronto meeting, 1897, pp. 656-660.

Wahnapitae road; and another has been found with similar relations two or three miles south of Espanola. During the Geological Congress excursion to Cobalt, Miller pointed out a smooth granite surface beneath the conglomerate near Doherty station on the railway south of Cobalt.

The surface beneath the Huronian represents therefore a mountain region degraded by subaërial forces to a peneplain, somewhat hummocky and irregular, but in the main of low relief. In many, if not in all places, its surface was deeply mantled with the disintegration products due to this secular decay, but before the deposition of the Lower Huronian some parts had not only been swept bare of débris but had been scoured and smoothed to the solid rock.

The regolith beneath the Huronian conglomerate may be looked upon in a sense as an old soil, but whether the mineral constituents were ever mixed with decaying organic matter is uncertain. The great amount of weathering which had taken place makes it certain that water charged with carbon dioxide was at work, but the carbon dioxide might have been supplied in other ways than by the decay of plants. It is long after the pre-Cambrian before positive evidence of land plants occurs in the shape of fossils, and it would be unwise to claim their presence in pre-Huronian times merely because we have reason to believe that water containing carbon dioxide had attacked the feldspars of the granites.

Except for the absence of fossils and the usual presence of a considerable amount of metamorphic material, the rocks of the age just discussed resemble in every way later sediments. There are no special features demanding the action of causes unlike those which operated in the Palæozoic or in later times. On the contrary every type of rock has its counterpart in later ages; and where the later rocks have undergone dynamic stresses or have been penetrated by large masses of eruptives, as in various mountain regions, even the metamorphic characters are found repeated in Palæozoic schists.

The modernity of the Sudburian sedimentary rocks, when the effects due to mountain-building and the eruption of granite,

etc., are allowed for, is the most surprising impression left upon one's mind. The atmosphere must have been like that of later times in amount and composition; water did its work then as now; the extremes of heat and cold seem to have been normal; and there is little doubt that plants and animals existed, though the positive evidence for them is lacking. The world was already completely organized along the lines which have been followed ever since. There is no suggestion of primitive conditions radically unlike those which were to prevail in later times, and there is no evidence that the earth's internal heat was greater then than now.

LATE PROTEROZOIC OF THE CANADIAN SHIELD

THE HURONIAN

The name Huronian has been used for so wide a range of pre-Cambrian rocks at one time and another since it was introduced in connection with the typical region, that some further discussion of its proper limits is necessary. For a time in the earlier explorations it was made to include every pre-Cambrian rock of northern Canada, whether sedimentary or eruptive, except the granites and gneisses called Laurentian. The Keweenaw was excluded since it was thought to be Cambrian in age. Some geologists have even considered part of the granites and gneisses as of Huronian age, owing to the confusion of older rocks, like the Keewatin and Sudburian, with the Huronian. The Laurentian was thought to be the oldest series of all, and hence granite and gneiss penetrating rocks called Huronian should be classed with the Huronian or as post-Huronian.

In an earlier discussion of the classification of the pre-Cambrian, it has been shown how portion after portion has been removed from the overloaded Huronian, the last separation being that of the Sudbury Series and other groups of rocks of equivalent age.

It remains to consider what rocks should actually be included in the Huronian as defined and described by Sir William Logan and his assistant Murray, who established the series. For this purpose we may consider the account given in the *Geology of Canada*¹ as authentic, since it represents Logan's mature ideas of the series arrived at after a number of years of study in various parts of northern Ontario. His description begins with the rocks of Lake Temiscaming, which he takes up very briefly without any detailed subdivision or classification. He mentions no definite localities for the "slate conglomerate" and "sea green quartzite" described, but gives the thickness of the conglomerate as "very probably much more than 1000 feet," and of the overlying quartzite as "between 400 and 500 feet." He published no map of the region and evidently devoted little time to it. From his account, which gives the conglomerate a dip of 8° or 9°, it is probable that he did not include what has later been defined as the Temiscaming Series in his description. Both the Temiscaming and Cobalt series are exposed on the west shore of Lake Temiscaming, and according to Miller the former series is now vertical or nearly so,² while the latter has gentle dips. The Cobalt conglomerate and the overlying quartzite appear therefore to make up the Huronian of the Temiscaming region.

Farther to the southwest he refers to rocks on the Sturgeon, Wahnapiatae, and Whitefish rivers as Huronian and makes a fivefold subdivision of them. They are described as consisting of quartzite, slate conglomerate, and limestone associated with greenstone. No definite localities are named, no thickness is assigned to the five members, and no geological map of the region was published, so that the real relationships are left very vague. Much of the region mentioned consists of the steeply tilted quartzites, etc., described in the first lecture as belonging to the Sudbury Series; but there are considerable areas of conglomerate or tillite believed by the present writer to be of true Huronian age.

¹ 1863, pp. 50-66.

² Nineteenth Rept., Bureau Mines, Ontario, 1913, p. 62.

The third region placed under the Huronian is that of the Doré conglomerate on Lake Superior. This has been shown to have been caught in the Laurentian mountain-building operations, and hence should be looked on as much older than the true Huronian and equivalent in age to the Sudburian.

All three regions thus far mentioned were left unmapped and were only briefly described. After disposing of them as preliminary, Logan comes to the more important area on the north shore of Lake Huron, which has given the name Huronian and which must be considered the typical region for this division of the pre-Cambrian.

It first attracted attention because of the copper ores of Bruce Mines where Lake Huron narrows to the north channel leading toward Sault Ste. Marie and Lake Superior, and the rocks were consequently spoken of as "the Lower Copper-bearing Series." The first reference to the geology of the region was by Murray, who examined the north shore of Lake Huron from French River on the east to Bruce Mines on the west and found ancient rocks underlying the Palæozoic beds which form part or all of the islands to the south. In this report, Murray writes: "The older groups observed consist, firstly, of a metamorphic series, composed of granitic and syenitic rocks . . . ; and, secondly, of a stratified series composed of quartz rock or sandstones, conglomerates, shales and limestones, with interposed beds of greenstone." He gives a brief but good description of each of these rocks.¹ In 1857 he returns to the region to study in more detail the rocks now called Huronian and attempts to trace out the band of limestone cropping out at Echo Lake so as to give a clue to the stratigraphy.² In the following year he continues the mapping but finds serious difficulties in working out the relations. In the *Geology of Canada*, 1863, the result of the three years' work is summed up by Logan and the accompanying atlas gives a beautiful little map of the region on the scale of eight miles to an inch, and a section showing the gently folded Huronian beds resting unconformably on the

¹ Rept. Progress, Geol. Surv., Canada, 1847-1848, 1849, pp. 107-113.

² *Ibid.*, 1857-1858, pp. 21-27.

Laurentian. It may be noted that the detailed section in the letter press gives thirteen subdivisions, while the map shows only eleven. It is evident from Murray's report that the work did not wholly satisfy him, though the map gives boundaries with the appearance of precision.

The following shows in a condensed form the different subdivisions in ascending order:

1. Gray quartzite	500 feet
2. Chloritic and epidotic slates interstratified with trap-like beds	2,000
3. White quartzite sometimes passing into conglomerate	1,000
4. Slate conglomerate with interstratified greenstone	1,280
5. Limestone	300
6. Slate conglomerate like No. 4 with considerable masses of greenstone	3,000
7. Red quartzite with greenstone	2,300
8. Red jasper conglomerate with greenstone	2,150
9. White quartzite with greenstone	2,970
10. Yellowish chert with limestone and slate	400
11. White quartzite	1,500
12. Yellowish chert and impure limestone similar to No. 10	200
13. White quartzite imperfectly examined	400
	<hr/>
	18,000

The greenstone included in the section is in part at least older than the sedimentary rocks and should be omitted. The green amygdaloids at Thessalon are placed, probably correctly, with the Keewatin by the International Committee, and the total thickness of the series is reduced by Van Hise and Leith to not more than 12,000 feet.¹ The most important addition to Murray's section, as mentioned on a former page, is the finding of a basal conglomerate east of Thessalon beneath the lowest member.

After numerous visits to the typical Huronian in different years and some weeks of work in the last two, it is the opinion of the present writer that much of what is mapped as Lower Slate Conglomerate (No. 4) is really basal conglomerate; and

¹ Pre-Cambrian Geology, p. 426.

that there are patches of older sediments as well as of "traps" included in the series. Owing to the large areas covered with drift and swamp, it is by no means easy to follow the different members across country even now when there are roads running through the settlements and to the lumber camps; and one can sympathize with Murray when he says, "that until a larger number of facts is collected, it will be difficult to make the relation of those portions that have been observed perfectly understood."

The "slate" or graywacke conglomerates and the quartzites are the most evident parts of the section as seen in the field. The red jasper conglomerates are merely parts of the white quartzites in which there are streaks of pebbles of jasper, chert, and white quartz. The red quartzite would now be called arkose. It also often contains pebbles of jasper, chert, and quartz. In places the limestone band is prominent, as at Echo Lake and Garden River, but generally, as Murray complains, it is lost in low ground or in swamps or lakes and is very difficult to follow. To the student of ancient climates, the basal conglomerate is the most interesting rock, and this will be discussed at some length. No other area of Huronian contains so varied a series of rocks as the typical region, and in other areas the thickness is very much less than 12,000 feet. In many places the Huronian consists only or mainly of the basal conglomerate with a thickness of a few hundred feet, distinctly stratified materials being wanting; though in other places the quartzites and arkoses may be fairly well developed. Limestone is seldom found in the Huronian outside of the typical region.

In the following account of the Huronian, the Cobalt Series, the most carefully studied of all the Huronian areas, will receive much attention, but the general descriptions given will apply to the "slate" conglomerates of the typical region as well.

THE HURONIAN TILLITES

After the long period of weathering and destruction during which the Archæan mountains were removed, an extraordinary boulder conglomerate was spread widely over the uneven surface

of the peneplain, a conglomerate that has roused the attention of all geologists who have visited the region and that has called forth a variety of contradictory explanations. Even ordinary conglomerates have a great interest for geologists, presenting as they do samples of different kinds of rocks assembled from near and far, smoothly rounded by waves or currents and cemented to a solid rock. They furnish striking records of the construction, destruction, and reconstruction of rocks, and they are often charged with a most interesting history of past times. But the

Fig. 9. Tillite, Lower Huronian, Cobalt

Huronian boulder conglomerates far surpass the ordinary in their fascination, for they present features that cannot be accounted for by the waves of the sea or the action of river currents. The basal Huronian conglomerate often includes boulders of various kinds of rocks, weighing hundreds of pounds or even tons, miles away from any known outcrop from which they could have been quarried. Boulders of granite and greenstone with diameters up to two or three feet are common and larger ones measuring five feet through are occasionally met. The largest recorded, on a glacially smoothed surface near

Temagami, showed diameters of eight feet and five feet. These boulders may be well rounded, subangular, or angular. They may be crowded into a mass of large and small stones cemented together, or they may lie sparsely scattered in a fine-grained matrix, the red granites showing up sharply from square yards

Fig. 10. Striated Stone, Tillite, Cobalt

of dull greenish gray ground mass. Generally no marked stratification can be seen in the coarser conglomerates, though associated pebble conglomerates and slates may be well stratified. In the original Huronian region the rock was called "slate conglomerate" by Logan, but its matrix generally contains small angular particles of quartz and feldspar and also of fine-

grained rocks, so that the modern term would be graywacke conglomerate. The matrix and the boulders enclosed vary greatly from point to point, roughly corresponding to the character of the rocks beneath, and the rock strongly suggests a glacial moraine in some cases and boulder clay in others.

Fig 11. Striated Stone, Huronian Tillite, Cobalt

The evidences just given apply to the typical Huronian region and various others, but are best shown in the basal conglomerate of the Cobalt silver-mining district, where, in addition, there have been found a number of "soled boulders" with well-striated surfaces.¹ These have been submitted to many of the

¹ Jour. Geology, vol. 16, 1908, pp. 149-158; also *Compte Rendu*, 11th Inter. Geol. Congress, 1910, pp. 1069-1072.

Tillite, Cobalt

Fig. 12. Tillite, South Africa

most experienced glacial geologists of the world, and all agree that the striated stones have been formed by ice. Hand specimens of the rock, too, are found to be exactly like the Dwyka conglomerate of South Africa, undoubtedly a glacial deposit. Even in thin sections under the microscope the two are almost interchangeable.

The boulder conglomerate at the base of the Huronian may then be referred confidently to the action of glacial ice. As the floor upon which the scarcely disturbed conglomerate rests was a peneplain, the presence of glaciers cannot be accounted for by the supposition of high mountains. Since these conglomerates are found at intervals over an area of 20,000 square miles, the ice sheet which formed them must have been large, and since they occur as far south as Latitude 46° , the ice reached what would ordinarily be temperate regions. The Lower Huronian begins, therefore, not with deposits from a transgressing sea but with boulder clay, or tillite, formed by a continental ice sheet.

The whole problem of this ancient conglomerate is ably discussed by Morley Wilson, who has added to the certainty of its determination as tillite. E. M. Burwash, a member of his field party in western Quebec, succeeded in finding a characteristic striated stone sixty miles east of the original find at Cobalt.¹

The tillite just described is the most constant rock of the Lower Huronian, being found in every region, and in some cases, as near Sudbury, making up the whole outcrop. Frequently the tillite passes up into well-stratified graywacke or slate, showing that the ice sheet was succeeded by water, perhaps a glacial lake, such as those of North America in the Pleistocene. Occasionally a boulder dropped by ice indents the thinly bedded slate. Above a bed of slate and water-formed conglomerate at Cobalt there is a second tillite, proving that the stratified materials are interglacial; and similar arrangements are found in other regions.

¹ Mem. Geol. Surv., Canada, No. 17-E, 1912; and Jour. Geology, vol. 21, 1913, pp. 121, etc.

The whole thickness of glacial beds is usually not more than 500 or 600 feet, somewhat in excess of the thickness of Pleistocene glacial and interglacial beds at Toronto, which measure 400 feet, but equalled by some sections north of Toronto and also in the states to the south. The Huronian ice age was comparable in almost every respect to the Pleistocene ice age of the same region, but is far from equalling in magnitude of deposits the tremendous Permo-Carboniferous tillites of South Africa, India, and Australia. The land formation of boulder clay and lake deposits was followed in the typical Huronian region and some other localities by an invasion of the sea in which a succession of water-formed sediments was deposited.

STRATIFIED DEPOSITS OF THE HURONIAN

The basal tillite just described seems to have been overlooked by Murray in the typical region, though it has been shown by Irving, Van Hise, and others to underlie the gray quartzite put at the base of the sedimentary column by Logan. The conglomerate of granite boulders embedded in arkose resting on a weathered surface of the Laurentian is easily seen by the canoe-man on certain islands east of the gray quartzite, and it is surprising that Murray should not have observed the outcrop.

The gray quartzite above the conglomerate is well stratified and must have been formed by water, either of the sea or of a lake, and the same is true of the white quartzite (No. 3) sometimes passing into conglomerate, and of the limestone (No. 5). The true relation of the lower "slate" conglomerate (No. 4) is uncertain. In some places it appears to rest upon the Laurentian and to be the oldest of the series and it has the character of tillite as displayed on the shore of Echo Lake.

The upper conglomerate (No. 6) has been shown by Irving, the Winchells, and Van Hise and Leith to rest in some places discordantly on the limestone of which it contains fragments. It is, however, very like the lower conglomerate in general appearance and in the size of the boulders which it contains, and may also be glacial in origin. If so, there was a second

glacial period separated from the first one by a considerable interval of erosion. The evidence is, however, not clear enough to state this positively.

The arkose (red quartzite, No. 7), red jasper conglomerate (No. 8), white quartzite (No. 9), and chert with limestone and slate (No. 10), followed by white quartzite again (No. 11), form a thick series of sediments of a delta-like character formed in a large body of shallow water.

It seems as though Numbers 12 and 13 were merely a repetition of 10 and 11, since they are not shown on the map, and from the description they correspond closely to the two earlier groups of rocks.

It will be noted in the column of subdivisions of the Huronian that six of the members include greenstone, one of them, Number 2, being entirely volcanic. Some of the greenstones of Murray are probably much older rocks, such as the Thessalon amygdaloidal lavas, which have been considered by later observers as Keewatin, but others are undoubtedly later eruptives, such as the large diabase mass in which the Bruce copper mines occur. A little to the east of Bruce Harbor this diabase is found cutting red quartzite or arkose shown on the map as Number 3.¹ Hills of similar quartz diabase are found at other points in the Huronian and probably have the same relations. Dikes of more basic rocks cut the Huronian limestone of Echo Lake, having the character of weathered picrite or pyroxenite.²

Logan mentions granite also as cutting the Huronian but does not refer to any particular locality. He describes these granite dikes as younger than the Laurentian and "supposed to be of Huronian age," though the description would make them post-Huronian.³ The present writer has not found granite cutting the typical Huronian, though granite penetrates the Sudburian, which was at some places confused with the Huronian.

In reality the relations of the Huronian sediments of the typical region to one another and to the eruptives are less

¹ Bureau Mines, Ontario, vol. 8, p. 126.

² *Idem*, p. 170.

³ *Geology of Canada*, 1863, p. 58.

certain than the definiteness of Logan and Murray's map would lead one to suppose; and as shown on a former page, Murray himself felt some doubts in the matter.

Summing things up as to the conditions under which the Huronian sediments were laid down, it is probable that the thick sections of arkose and quartzite found in the upper part of the series were shallow water marine deposits, and the same may be said of the pale green quartzite and arkose of the Cobalt region,¹ probably the equivalent of the Upper Huronian. These arkoses and green quartzites suggest the cool, moist climate which might be expected to follow an ice age.

Thus far the description has been confined to the typical Huronian and the Cobalt Series, which are connected by numerous outcrops observed from point to point as far as Sudbury by the present writer and by Collins between Sudbury, Gowganda, and Cobalt itself. They may be looked upon as practically continuous.

OTHER HURONIAN AREAS

In the older reports many other Huronian areas are mentioned, but in the light of our present knowledge most of them are really Keewatin or are equivalent in age to the Sudburian, and so must be excluded from the true Huronian. There can be no doubt that the conglomerate and graywacke resting unconformably upon all the older rocks at Larder Lake are Huronian, thus extending the area fifty miles to the north; and the same is true of the Boischatel tillite with striated stones found sixty miles to the northeast of Cobalt in the Province of Quebec. In the latter case the tillite is followed by arkose, the whole having a thickness of 700 feet. Morley Wilson, who has studied the two regions, has no doubt of the relationship.²

The account given by Barlow of the Lower Huronian of the Chibougamau region 300 miles northeast of Cobalt shows that

¹ Bureau Mines, Ontario, vol. 19; Reprint, 1913, pp. 75 and 89.

² *Op. cit.*, pp. 34-46; also Summary Rept., 1911, Geol. Surv., Canada, 1912, pp. 277-278; and Jour. Geology, vol. 21, 1913, pp. 121-141.

the typical rocks are repeated there, resting with the same great discordance on the steeply tilted Keewatin and Laurentian. "At the base of the series is usually a conglomerate made up of comparatively large angular, subangular and rounded fragments, derived from the degradation of the underlying granites, anorthosite, greenstones and schists. . . . These are embedded in a dark greenish matrix, made up chiefly of very small pieces of feldspar and quartz, with a much larger proportion of chlorite and sericite." Of the upper part he says: "The Lower Huronian presents a transition upward from a basal conglomerate, usually into arkose or arkose-quartzite, this in turn to a comparatively dark grey or greenish grey feldspathic sandstone, and this again upward into slates. . . . Sometimes there is an alternation of coarser and finer grained sediments, so that at the tops of some of the hills, as on Wako Mountain, we find in the upper beds a comparatively coarse conglomerate, while further down the hill were noticed strata of sandstone and slate."¹

Barlow's account of the basal conglomerate would serve for that of the tillites of the Cobalt region, though he does not suggest that they were formed by ice action. Earlier students of Chibougamau, Low for instance, lay stress on the great size of some of the boulders in the conglomerate which may reach many tons in weight.² The upper stratified beds sometimes show well-formed ripple marks, like those found on quartzite near Cobalt Lake, and Barlow concludes that "there is undoubtedly evidence of the presence of a great ocean, with abundant land surfaces in the form of islands and points upon which the littoral deposits were laid down, which were afterwards consolidated into thick and massive beds of conglomerate and arkose. Then followed the sandstones, indicative of shallow water conditions, with very beautiful ripple marks."

The greatest thickness mentioned by Barlow is 625 feet and

¹ *Geology and Mineral Resources of the Chibougamau Region, Quebec*: Quebec, Dept. Colonization, etc., Mines Branch, 1911, pp. 121-122 and 134-138.

² *Geol. Surv., Canada*, vol. 1, 1885, p. 30-D; and vol. 8, 1895, p. 259-L.

he makes the area twenty-two square miles. Beyond the statement that "the Lower Huronian is, in large part, a true epiclasic formation," he gives no suggestion as to its origin.

Huronian rocks have been described also in the great island of Newfoundland, which may be looked on as marginal to the Canadian Shield. Murray himself first suggested the age, but the somewhat vague descriptions of the rocks of the Avalon Series and its great distance from the nearest known Huronian region, that of Chibougamau, 900 miles to the west, make it too doubtful to require much consideration. It has some interest on account of the finding of annelid tracks by Walcott. He places the Random terrane in which they occur in the upper Algonkian, which probably corresponds to the Animikie rather than the Huronian as here defined.¹

Northward and westward of the typical region many areas of Huronian are shown on the maps, but there is doubt as to whether any of them are later than the Sudburian; and only one of them will be mentioned, that of Steeprock Lake, near Atikokan, 100 miles west of Lake Superior. It begins in the orthodox way with a conglomerate followed by quartzite and limestone, the latter bluish gray, not much metamorphosed, and very like some of the typical Huronian limestones. It is of special interest because fossils were found in the limestone by Lawson and his assistants two years ago. Walcott distinguishes two species of *Atikokania*, as the genus is called, *A. lawsoni* and *A. irregularis*, and considers them related to the sponges or possibly to both the sponges and Archæocyathinæ. He says further that "the genus *Atikokania* has more of a Cambrian aspect than we should expect to find in a very ancient pre-Cambrian fauna. The Archæocyathinæ are of late Lower Cambrian age, and if the stratigraphic position were not well determined, I should be inclined to consider *Atikokania* as a Lower Cambrian genus."²

Within the past year, Lawson has published accounts of the Steeprock Series, making it older than the Seine Series, which

¹ Bull. Geol. Soc. America, vol. 11, 1900, pp. 3-5.

² Mem. Geol. Surv., Canada, No. 28, 1912, pp. 16-20.

is probably of the same age as the Sudbury Series, and hence no less than two stages beneath the Lower Huronian as defined here, and separated from it by an enormous length of time.

After visiting the Steeprock Series during the past summer with Lawson himself, thus reviving memories of two former visits, it seems to me not improbable that the rocks are younger than he has estimated, though one hesitates to question the opinion of so able a geologist who has spent considerable time in the study of the region. If it were not for his conclusion in the matter, the fresh appearance of the limestone, the fact that fossils occur in it, and the fact that the Steeprock Series has not been found in immediate contact with the Seine Series would incline one to doubt its extreme age and to make it no older than the limestone of the typical Huronian. It may be added that the Seine Series not far from Steeprock is far more metamorphosed than the rocks of Steeprock Lake and is decidedly older in appearance.

ATTITUDE OF THE HURONIAN

It has already been mentioned that the Huronian rests with a profound discordance upon an ancient peneplain. In most parts of the original Huronian region as described by Logan, the series has not undergone much deformation by folding, though he and Murray indicate some important faults. Logan says of the Huronian that "on the line of section the dips of the strata approach the horizontal, the slope seldom being over six degrees and often not over two." He speaks of the beds as forming a main trough "divided into three subordinate and nearly parallel troughs by two anticlinal forms."¹ The folding is described as gentle, and in general the beds approach horizontality. There are, however, parts of the region mapped in which steeper dips occur, as near Garden River. Most of the steeply dipping or vertical beds sometimes included in the original Huronian are really older and belong to the Sudbury Series. This is true probably of the highly inclined quartz-

¹ *Geology of Canada*, 1863, pp. 61-62.

ites at Blind River and in the Cloche Mountains. The comparatively undisturbed attitude of the typical Huronian is continued eastwards at various points, as at Espanola and Sudbury, and northwards to Cobalt. Everywhere the dips are comparatively slight, and the old surface, as found by myself and as described by Collins and Miller, has been little deformed, though there are often faults of some magnitude, and dikes or sills of eruptive rock penetrate the Huronian in most of the localities. What has been said of the great region just referred to applies also to its eastward extension in Quebec, as shown by Barlow for the district of Chibougamau.¹

Over this wide area the old surface appears not to have been greatly deformed nor involved in mountain-building changes since the Huronian. This part of the Canadian Shield has doubtless been several times elevated and depressed, but apparently in a comparatively gentle way and as a whole rather than as separate blocks. There is clear evidence of gentle warping of the surface in connection with differential changes of level in Pleistocene lake basins in geologically recent times; and it may be that equilibrium has scarcely been attained even yet. We must think of the shield as having been only relatively stable since Huronian times, rising and sinking, perhaps in an undulatory way, for hundreds or possibly a thousand feet, but generally without important dislocations, and always without mountain-building foldings.

It is probable that the original Huronian region, where small parts of the sediments of the series are quite steeply tilted, is at the margin of the relatively undeformed shield; for the area of Lower Huronian to the southwest of Lake Superior, as described by American geologists, has often undergone great folding. The descriptions of the Lower Huronian of the Marquette, Menominee, and Mesabi regions of the states south and west of Lake Superior show these beds to have been involved in very important orogenic operations, which the Huronian of Canada to the northeast escaped. Unless the rocks classed as Lower Huronian in Michigan, Wisconsin, and Minnesota are

¹ *Op. cit.*, pp. 134-138.

really equivalent in age to the Sudbury and Temiscaming series of Ontario, we must conclude that the margin of the relatively undisturbed Huronian, resting on an ancient peneplain still comparatively level, ends with the basin of Lake Superior. The question has been excellently discussed by Morley Wilson.¹

CLIMATE AND PHYSICAL CONDITIONS OF THE HURONIAN

The Huronian was a time of cool and moist climate so far as the Canadian Shield is concerned, beginning with an ice age probably divided into two parts by an interglacial period, and continuing under somewhat milder conditions in which weathering caused the decay of granites and gneisses often without much kaolinization of the feldspars, as shown by the large amount of arkose. The only red rocks occurring receive their color from the red feldspar which they contain; more commonly the rocks are of a greenish tone. Carbon suggesting plant life is seldom found in the Huronian as defined in this paper, though carbonaceous slate occurs in thin beds at Cobalt and some other points. As carbon is found in considerable amounts in the Keewatin and in large amounts in the Grenville, we may assume that marine plants existed, though they have left little evidence of their presence in the Sudbury Series or the Huronian.

The limestone occurring in various Huronian areas suggests animal life, though no fossils have yet been found in the typical region, where the rock looks so modern that one might naturally expect them. If the Steeprock Series is Huronian, the two or three species of *Atikokania* give some idea of the animal life of the age.

There is no certain evidence of volcanic eruptions in the Huronian, since it has been shown that the amygdaloidal lavas of the original Huronian region are really much older, unless the Steeprock Series be included, where volcanic ash has been described.² There are many dikes cutting the Huronian, but these are, of course, later in age.

¹ Jour. Geology, vol. 21, 1913, pp. 385-398.

² Mem. Geol. Surv., Canada, No. 28, 1912, p. 13.

The glacial beds at the base of the Huronian were undoubtedly continental deposits, showing that a large part, if not the whole, of the shield was then above the sea; but the later well-stratified members of the series were formed under water, either in great lakes or a shallow sea. Their great thickness in the typical region at the margin of the shield and their wide distribution toward the northeast suggest something more than lakes; and it is probable that the sea transgressed from the southwest, finally reaching Chibougamau, which is 500 miles from the southwestern end of the Huronian and more than 200 miles north of the southern boundary of the shield. Careful exploration of the regions beyond will probably disclose patches of the Huronian in the future and so extend the known area of transgression.

None of the interior Huronian areas show very thick water-formed rocks and the encroaching sea was probably shallow; but at the southwestern border the thousands of feet of coarse Huronian sediments imply a continued sinking of the sea bottom to a corresponding depth. This seems to have been the case also in the Huronian regions of the states southwest of Lake Superior, as shown by the survey reports.

THE TYPICAL ANIMIKIE

The Animikie, included by some American geologists in the Huronian as its upper member, is generally placed by Canadian geologists in a separate position above the Huronian. It does not occur in the original Huronian region, so that its relative position cannot be positively settled. Its general character is so different from the Huronian of Lake Huron, however, that it seems wiser to give it a separate position in the classification so far as the Canadian Shield is concerned. The Animikie rests with a great unconformity upon the truncated edges of the Keewatin and Laurentian on the shores of Thunder Bay, where the series was first described by Logan. The flat or gently tilted beds of unmetamorphosed and modern-looking Animikie rocks make so strong a contrast with the contorted and highly

crystalline schistose rocks beneath that one is strongly impressed with the greatness of the discordance. The vast gap between them is named by Lawson the Eparchæan Interval.

The surface beneath the Animikie is a peneplain of the same character as that beneath the Lower Huronian. In fact, it appears to be the same peneplain little modified during the time since the beginning of the Huronian, as has been suggested by Wilson.¹ That Huronian sediments once covered far more of the surface than at present is certain, but whether Huronian tillite extended over the whole region where patches of Huronian still remain is not known. If it ever existed where the Animikie is now found it seems to have been removed before the later sediments were laid down.

The Animikie on Thunder Bay begins with a thin conglomerate containing pebbles of the Keewatin schist and of the Laurentian gneiss beneath. This passes up into chert, often well banded with lighter and darker gray and sometimes showing a very distinct oölitic structure. In places the chert includes jaspery varieties showing the same oölitic character, and in other places there are beds of impure limestone or dolomite with intermixed chert. The oölitic forms show no suggestion of organic material in thin sections under the microscope, but are small scale concretions of chalcedonic silica.

Higher up in the formation black slate or argillite is found, thinly laminated but without slaty cleavage. It splits readily parallel to the lamination and is crossed in various directions by joints giving small polygonal blocks. There are large concretions, apparently of marcasite, enclosed in the slate, and when the latter weathers they accumulate. The black color of the argillite and also of the chert is due to carbon, and occasionally little veinlets or masses of nearly pure carbon or anthraxolite occur in these rocks.

The most striking feature of the Animikie near Port Arthur is due to the sills of diabase which lie at various levels between the strata of argillite. These may be of all dimensions from a fraction of an inch to 200 feet or more in thickness, and

¹ Jour. Geology, vol. 21, 1913, p. 392.

occasionally a dike may be seen to join a sill or a sill may be observed to pass diagonally up or down from one level to another. The slate both above and below the sill is somewhat baked. Evidently the sheets of diabase are later in age than the Animikie, but the two are so mingled that they cannot be separated. The diabase sheets were thought by Logan to represent lava flows, the uppermost being called "the crowning overflow."

Since the argillite is much more easily attacked by the weather than is the diabase, all the hilltops are formed of a sheet of this eruptive, giving the flat-topped or mesa appearance so characteristic of the Thunder Bay region. As the sills have a rude columnar structure, all the cliffs are of columns and nearly vertical, and often there are two sills with two sets of cliffs, as in the splendid promontory of Thunder Cape.

The Thunder Bay region, though first described, does not show a great thickness of the series, only 1500 to 2000 feet as estimated by Logan, including the sills of diabase; and presents only an incomplete set of the rocks known to belong to the Animikie. Farther to the southwest along the shore of Lake Superior there are sandstones or quartzites of the same age and near Port Arthur one finds impure siderite, while near Loon Lake, twenty miles toward the east, the siderites grow more important and give rise to iron ores on a small scale.

The Animikie passes southwest into Minnesota, becomes much thickened, especially in the iron-bearing member, and supplies the immense iron deposits of the Mesabi.

The Animikie of Thunder Bay shows no folding but has been faulted into blocks which have a slight tilt, usually not more than 5° or 10° . The sediments of this series in Ontario are less deformed than the Huronian and are scarcely at all metamorphosed, while the Huronian generally shows considerable metamorphism.

THE ANIMIKIE OF THE NICKEL BASIN

The thickest set of rocks described as Animikie on the southern part of the Canadian Shield is found near Sudbury overlying

the great sheet of eruptive rock which carries the nickel ores. This basin-shaped area, having a length of 35 miles and a breadth of 10 miles, is 385 miles southeast of the nearest part of the original Animikie region, so that there may be some doubt as to the correlation; but the lithologic character of the Sudbury rocks and the absence of metamorphism, except where in contact with the nickel eruptive, correspond much better with the Animikie than with any other pre-Cambrian series, so that they will be taken up here as probably of that age. Collins, who has done some work in the region, prefers to give the rocks of the nickel basin a local name, the Whitewater Series, from Whitewater Lake at its margin.

From its proximity to the great nickel mines this series has been worked out in greater detail than any other part of the Animikie in Canada. It has been subdivided as follows:

Chelmsford sandstone	.	.	.	1500 feet
Onwatin slate	.	.	.	3700
Onaping tuff	.	.	.	3800
Trout Lake conglomerate	.	.	.	450
				<hr/>
				9450

The basal conglomerate rests at present on the surface of the sheet of eruptive rock carrying the nickel ores, but before the latter reached its position the conglomerate seems to have lain upon the upturned edges of the Laurentian gneiss and of rocks of the Sudbury Series. In most places the Trout Lake conglomerate has been so greatly metamorphosed by the eruptive beneath that not much can be determined of its original character; but at the southwest end of the basin the sheet of nickel-bearing rock thins greatly and the conglomerate above it is comparatively unchanged. At this point it is a boulder conglomerate suggesting tillite, consisting of a dark gray matrix enclosing pebbles and boulders of granite and other rocks often two or three feet in thickness. The largest observed boulder measured five by three and a half feet in dimensions.

The basal conglomerate, usually so transformed as to pass gradually into the micropegmatite below, merges upwards into

cherty material or quartzite and then into a fine-grained breccia of volcanic glass (vitrophyre tuff) which is unique in the region. The tiny glass splinters are now changed to chaledony and serpentine. Along with the volcanic materials there are rounded fragments of quartzite and of granite, suggesting a water-formed deposit, the volcanic ash having rained down into the sea or a lake. No volcanic vent has been found from which the tuff could have come, and the neighboring eruptive rocks, except the nickel eruptive itself, are either more basic or more acid than the glass. The nickel eruptive is much later than the tuff, and cannot be directly connected with its formation.

The top of the thick sheet of tuff becomes slaty and black, passing upward into the next formation, which is a characteristic carbonaceous slate. It has well-marked stratification, the laminae being distinct, but it splits in accordance with a pronounced slaty cleavage caused by the settling of the once flat sheet of sediments into a synclinal form. This caused compressive strains in the upper members of the series.

The most interesting feature of the slate is the large quantity of carbon which it contains, specimens analyzed showing from 6.8 to 10 per cent.¹ Evidently the slate was once a bituminous shale or something like boghead coal. At various places in the slate there are irregular veins of anthraxolite, once bitumen. When the thick sheet of nickel-bearing magma made its way beneath the Whitewater Series, the volatile hydrocarbons were driven off and the bitumen was changed to nearly pure carbon, anthraxolite with 94.92 per cent of carbon and 1.52 per cent of ash, the other 4 per cent consisting of oxygen, hydrogen, nitrogen, and sulphur. This material has been taken for anthracite and has roused vain hopes of coal mines. If the whole of the carbon in the 3700 feet of Onwatin slate were assembled in one sheet, there would be from 250 to 300 feet of anthracite; and the original bitumen must have formed a far larger portion of the rock.

One must conceive of the Onwatin slate as originally a mud highly charged with organic matter, later changed to bitumi-

¹ Bureau Mines, Ontario, vol. 14, part 3, pp. 95-96.

nous shale and finally to anthracitic slate. The sea must have been swarming with algæ and perhaps other forms of life.

The uppermost member of the series is a gray sandstone or graywacke, well stratified and containing many oval concretions of impure limestone.

From the description just given, it will be seen that the Whitewater Series is like the typical Animikie of Thunder Bay in having a basal conglomerate followed by chert and later by black slate containing carbon of an anthracitic kind. The sandstone, too, is not unlike some phases of the Animikie. On the other hand, the basal conglomerate is much coarser and thicker than that of Thunder Bay, and the vitrophyre tuff has no analogue. However, eruptive material, such as volcanic ash, must be looked on as an accidental member of any sedimentary series, and should not be taken as an argument against the equivalence of the Whitewater Series with the Animikie.

It has been suggested that the Whitewater Series may really be Huronian, but it has no analogy with the typical Huronian, only eighty miles to the west, except in its thick basal conglomerate resembling tillite. There is scarcely any quartzite and no jasper conglomerate, arkose, or limestone included in it. If the Whitewater Series was formed at the same time as the typical Huronian, it must have been in an entirely separate basin with totally different conditions; for the Huronian contains no volcanic ash and no carbonaceous slate, rocks which form more than three-fourths of the Whitewater Series.

If this series is not the equivalent of the Animikie, it must have a position entirely to itself, since it is different from the Huronian and also from the Keweenawan, the only other post-Laurentian series of the Canadian Shield.

The Whitewater Series is unique in its structural relations. Once a flat series of sediments, it has been cradled in a flood of molten rock averaging more than a mile in thickness, and has been hollowed into a boat-shaped basin with sides dipping inwards at an angle of 30° . In the process the sandstone forming the top of the series has been compressed into narrow anticlinal domes running parallel to the axis of the basin. The

basin shape is due probably to the collapse of the foundations when the nickel eruptive rose from its hearth and spread out as a sill between the steeply tilted schists beneath and the horizontal sediments above.

Fig. 13. Ruins of Antieline, Chelmsford Sandstone, Larchwood

The original basin still preserves in a striking way the basin-like appearance. In the interior, old lake deposits lie almost as flat as a prairie except where broken by the ruined anticlines of the Chelmsford sandstone. All round can be seen the rugged hills of the "acid edge" of the nickel eruptive, along with the greatly metamorphosed and hardened Trout Lake conglomerate. In the Pleistocene the basin formed an almost completely enclosed bay of Lake Algonquin.¹

OTHER ANIMIKIE REGIONS

The two best-known areas of the Animikie have been described at some length and it will not be necessary to go into detail in

¹ The Nickel Industry: Geol. Surv., Canada, Mines Branch, 1913, pp. 3 and 9.

regard to the other areas. These are often large and are widely and somewhat uniformly scattered over the shield. Most of the areas have been little studied and the Animikie sediments are often mixed up with eruptives belonging to the next formation, the Keweenawan, so that the two have not been separated in the mapping.

Fig. 14. Animikie and Keweenawan Areas on the Canadian Shield

For a long distance along the east shore of Hudson Bay, there is a band of these rocks, and the Nastapoka Islands running parallel to the shore are of the same kind, as described by Bell and Low.¹ The latter geologist notes that "the unaltered sedimentary rocks with their associated sheets of trap or diabase bear not only a remarkably close resemblance to the so-called Cambrian rocks of other parts of the Labrador peninsula, but

¹ Geol. Surv., Canada, vol. 13, 1900, pp. 45-47-D.

also to the iron-bearing rocks of the southern shores of Lake Superior and the Animikie and Nipigon rocks to the north of Lake Superior." His description includes sandstones, arkoses, argillites, carbonaceous shales, cherty carbonates, and iron ores, the whole sometimes making up several thousand feet.

In the interior of Labrador the same observer has mapped a broad band of similar rocks running for more than 300 miles at the headwaters of the Koksoak and Hamilton rivers, with a thickness estimated at 2518 feet at one place near the former river.¹ He finds areas also along the south side of Hudson Strait and near the shore of Ungava Bay, where there are beds of bituminous shale, ferruginous chert, dolomite, and magnetite with sills of gabbro.² He believes also that the cherty limestone of Mistassini is of the same age. Its black chert and anthraxolite suggest a relationship, but there is little else to connect this area with the Animikie.³ Barlow considers these limestones Palæozoic,⁴ but no determinable fossils have been found in them.

On the west side of Hudson Bay, where it widens westward from James Bay, there is a small area of Animikie rising through Palæozoic sediments at Sutton Mill Lake and on Winisk River, showing iron ore with oölitic jasper and slate.⁵ The largest area of all is perhaps at the far northwest of the shield near Great Bear Lake, where more than a thousand feet of sediments are described by Robert Bell as including limestone or dolomite, shale, sandstone, and conglomerate with "overflows of greenstone."⁶ The lowest beds are ferruginous, but in the upper parts, towards Coppermine River, there are amygdaloids with some native copper, evidently belonging to the Keweenawan.

¹ Geol. Surv., Canada, vol. 8, 1895, pp. 261-266-L.

² *Ibid.*, vol. 11, 1898, p. 32-L.

³ *Ibid.*, vol. 8, 1895, pp. 266-268-L.

⁴ *Op. cit.*, p. 131.

⁵ Summary Rept., 1901, Geol. Surv., Canada, 1905, pp. 115-116-A; and 1902-1903, 1906, pp. 100-108-AA.

⁶ Geol. Surv., Canada, vol. 12, 1899, pp. 106-107-A; also p. 26-C (J. M. Bell); also vol. 13, 1900, 101-A.

CONDITIONS DURING THE ANIMIKIE

From the outline just given, it will be seen how widely rocks having the character of the Animikie extend over the Canadian Shield. That they once extended far more widely is certain, since there has been great erosion in later times and the comparatively unconsolidated rocks of the Animikie would be more easily attacked than the older and more crystalline rocks. While we now find the Animikie largely in basins in the older rocks, this is probably because it was thicker at such points and also better protected from later destruction. Whether the Animikie sediments ever covered the whole shield cannot be determined, but that they covered a very large part of it is evident. It was a period of great extension of the sea when the surface of the pre-Cambrian continent of North America was widely submerged. The parts rising above the Animikie sea must have been low and comparatively small.

The widespread shallow seas of the Animikie had one feature scarcely repeated on the same scale in later times, the deposition of iron compounds with associated silica. In nearly all of the Animikie areas there is an "iron formation" with cherty ferruginous carbonate or oölitic greenalite or jasper, "taconite," as it is sometimes called, as the initial stage, from which are formed by secondary causes small or large bodies of ore, culminating in the immense and rich deposits of the Mesabi to the southwest of the shield in Minnesota. What caused the solution of so much iron and silica in the waters of the time? It has been suggested that basic volcanic eruptions or perhaps magmatic waters have been the source of the iron and silica and that the original deposits were largely of a chemical nature,¹ but it will be noted that the Animikie is singularly free from contemporaneous volcanic materials. The only important instance of such materials forming a regular part of the series is the thick deposit of tuff in the Sudbury nickel basin; and this is almost the only Animikie region in which the iron-bearing member is absent.

¹ Monograph U. S. Geol. Surv., vol. 52, 1911, pp. 500, etc.

It is true that dikes and sheets of diabase are frequent among the sediments and were once described as lava flows intercalated between the slates; but where closely examined, as the Logan sills were by Lawson at Thunder Bay, it is found that they are all later injections, and so cannot have provided the raw materials for the iron-bearing beds.

The suggestion of Wolff and Spurr that the oölitic iron-bearing rock resembled the glauconite of later foraminiferal deposits found in deep seas,¹ and hence might be in a sense of organic origin, does not agree with the results of later investigators, which show that the oölitic material differs in important ways from glauconite, containing little or none of the necessary potash.² The name greenalite has been given to this mineral so important in the iron-bearing portion of the Animikie.

In a very interesting discussion of the probable mode of production of the various pre-Cambrian "iron formations," Van Hise and Leith, after referring to several theories which have been suggested, state their preference for that of iron- and silica-bearing magmatic fluids poured out during basic volcanic eruptions beneath the sea. This seems much more applicable to the earliest, the Keewatin, iron formation, than to the latest one, that of the Animikie, since the greater part of the contemporary rocks of the Keewatin are basic eruptives, while most of the Animikie iron formations have no such relationships. On their own showing the Mesabi range, the most important of all, is not accompanied by basic eruptives. Nevertheless, they consider its iron and silica to be mainly derived from basic lavas at a distance.³

It seems more reasonable to assume that surface weathering of basic rocks was the source of the Animikie iron deposits, since they are not associated with volcanic rocks but with characteristic sediments such as quartzite, chert, dolomite or limestone, and carbonaceous slate. Whether the original iron-

¹ Bull. Geol. and Nat. Hist. Surv., Minnesota, No. 10, 1894, pp. 232, etc.

² Monograph U. S. Geol. Surv., vol. 52, 1911, pp. 521, etc.

³ *Idem*, pp. 500-516.

bearing rocks were formed as terrestrial deposits, for example, in peat bogs or lagoons, is not easy to settle. Van Hise and Leith admit that a part of the Animikie iron formation has originated in that way, but they believe that the greater part was submarine and from the basic magmatic waters mentioned above.

The vast amount of carbon found in the Animikie slate in many places was probably of organic origin, due to marine plants, and while the supposed fucoids were thriving on the muddy sea bottom, there could have been no important influx of hot solutions of iron and silica.

The laterite theory, which would make the iron-bearing rock a land deposit in a hot climate, finds little support in the associated rocks, the quartzites and slates, which suggest rather delta deposits in shallow water.

Except for the immense amount of iron which they contain, the rocks of the Animikie resemble Palæozoic sediments and were long held to be Cambrian. They are usually very little metamorphosed, except where penetrated by later eruptives, and they have not been greatly tilted or folded at any point on the Canadian Shield, though they are faulted into blocks and gently tipped in the Thunder Bay region. In the cherty limestones and carbonaceous slates or shales which make up so much of the Animikie, one naturally expects to find fossils, but none have yet rewarded those who have sought them. In the Canadian region these rocks are known to underlie the Ordovician near Hudson Bay, but they have not been found associated with rocks bearing Cambrian fossils, so that their position cannot be finally determined. That they underlie the Keweenawan in many places is sure, and if the Keweenawan is pre-Cambrian the Animikie is undoubtedly so. For the present, until fossils are found, the Animikie must be looked upon as older than the Palæozoic, though in places where Palæozoic rocks have been caught in mountain-building folds or have been penetrated by granite they are often far more metamorphosed than the usual flat-lying Animikie sediments just described.

THE KEWEENAWAN

In the earlier Canadian reports on this group of rocks, the name Nipigon was used, but there is now no doubt that the Nipigon is equivalent to the Keweenawan of Keweenaw Point, so that the latter name is accepted by Canadian geologists. On the Canadian Shield the Keweenawan is often closely associated with the Animikie and, except in the better-known regions near Lake Superior, they have not been separated on the survey maps. There is, however, a distinct break in time between the two series, the later one generally beginning with a basal conglomerate which contains pebbles or boulders of the Animikie when it overlies rocks of that age. The Keweenawan sometimes covers Animikie beds and also the adjoining older rocks in ways suggesting a considerable erosive interval before the basal conglomerate was laid down; but usually the angular discordance is slight.

There are a number of localities where the Keweenawan rests directly on the ancient peneplain of the Laurentian and Keewatin. Low reports an area of Keweenawan in the deep valley of Hamilton Inlet on the Labrador coast, and suggests that the original peneplain had been elevated and long and deep valleys carved by rivers before the Keweenawan was deposited.¹ If this took place after the transgression of the Animikie sea, the time interval must have been great.

The best-known Canadian areas of the Keweenawan lie on or near the north and east shores of Lake Superior, from Thunder Bay to Nipigon Bay and northwards to Lake Nipigon, on Michipicoten Island, and at Mamainse. The rocks of this region may be divided into a lower sedimentary series and an upper series chiefly volcanic but containing some sheets of conglomerate and sandstone. The uppermost division recognized south of Lake Superior appears to be wanting on the Canadian Shield.

In the region extending from Thunder Bay eastward, there are conglomerates, white and red sandstones, limestones of various colors, and shaly rocks sometimes called marls; the whole

¹ Geol. Surv., Canada, vol. 8, 1895, p. 263-L.

having a thickness of 1300 or 1400 feet. They include no surface volcanics but are penetrated by dikes and sills of diabase like the Logan sills of the Animikie to the west on Thunder Bay. The volcanic eruptions so characteristic of the later Keweenawan had not yet begun.

Fig. 15. Diabase Sill in Keweenawan, Nipigon

The sediments are usually coarse but fairly well stratified, the sandstones often alternating with beds of conglomerate. There are frequently ripple marks indicating shallow water. The materials are largely derived from the granites and gneisses of the Laurentian, but red jasper pebbles occur also. The sandstones are often feldspathic, so that they might be called arkose, and evidently weathering had not gone to an extreme. Facts like these and the presence of mud cracks in some of the shales suggest a continental origin for the series. Apparently after the erosion following the Animikie, there was no transgression of the sea.

The basal conglomerate toward the east end of Lake Superior is thicker and more bouldery than on Thunder Bay, and

Robert Bell reports an outcrop containing stones reaching three feet eight inches in diameter at Pointe aux Mines. Some of them have grooves like glacial striæ. The matrix of the conglomerate is sandy.¹ If this is really tillite, the climate must have been cold, at least at the beginning of the Keweenaw, and the frequently undecomposed feldspar in the sandstones might point in the same direction. However, many of the rocks of the Keweenaw, shales and conglomerates as well as sandstones, are red; in fact, this is the characteristic color of the sediments of the series, suggesting desert conditions. The points in favor of a terrestrial origin of these rocks are well summed up by Van Hise and Leith, who call attention to the thickness and repetition of coarse sediments including conglomerates, their feldspathic, poorly assorted, and completely oxidized character, etc., concluding that they "were neither exclusively terrestrial nor exclusively subaqueous, though too little is known to warrant definite statements concerning their origin."² They add that "the question still remains open as to whether the water-deposited parts of the Keweenaw were submarine or continental, for deposits laid down in great lakes are usually classed as continental."

In a general way it may be said that these sedimentary rocks differ greatly from any observed in earlier series in the predominance of the red coloring. The absence of carbonaceous beds makes a striking difference from the Animikie and is perhaps a proof of terrestrial rather than marine conditions.

KEEWEENAWAN VOLCANICS

While the lower part of the Keweenaw is exclusively sedimentary, the upper part, as found north and east of Lake Superior, is essentially volcanic, though a few beds of sandstone and conglomerate are intercalated between the lavas. Most of the formation consists of basic lava flows, variously called trap or diabase or melaphyre, some being really basalts, but there

¹ Rept. Progress, Geol. Surv., Canada, 1876-1877, 1878, p. 214.

² *Op. cit.*, p. 417.

are also more acid flows referred to as porphyries and felsites, really rhyolites. In subordinate amounts ash rocks and lapilli are found between the lava sheets, and the conglomerates and sandstones are made of almost contemporary material, especially of fragments of the rhyolites and porphyries.

Many of the lava streams are amygdaloidal and the surface of a stream is often rough and slaggy. Pillow structure has not been observed in these lavas, so that they appear to have been poured out upon dry land, a point of difference from the ancient lavas of the Sudbury Series and the Keewatin, which often display the pillow structure. In addition to surface flows there are also dikes and intruded sheets of the same lava but without amygdaloids or slaggy surfaces.

One of the thickest series of lavas known on the Canadian side of Lake Superior occurs on Michipicoten Island, which has been carefully studied by E. M. Burwash. Of the measured thickness of 11,230 feet, only a small part consists of sediments and these are in short lenses which do not run the whole length of the island.¹

Though no basal conglomerate occurs on Michipicoten Island, it may be found in patches at many points on the mainland to the north and east, especially filling ravines of the ancient land surface. These boulder conglomerates begin as a breccia and are made up almost entirely of the subjacent Laurentian gneiss and Keewatin green schist. As the cement is calcareous and easily attacked, the pebbles and boulders of the ancient shore are being set free once more to be rolled on the beach of Lake Superior, a sort of second avatar. In the examples studied by myself, there is evidence of an old weathered surface passing up into water-rounded materials, and no proof of ice action like that suggested by Bell was seen.

On Point Mamainse conditions are similar to those on Michipicoten Island. The basal conglomerate seems to be absent, as described by Macfarlane, and only the upper part of the Keweenawan is exposed, consisting of 16,208 feet of beds,

¹ Geology of Michipicoten Island: University of Toronto Studies, No. 3.

mainly lava sheets, but including in the higher portions conglomerates and sandstones, the thickest bed reaching 852 feet.

The Keweenawan rocks east of Thunder Bay extend north to Lake Nipigon, with a lower sedimentary part consisting of conglomerate, sandstone or quartzite, shale, and limestone, and an upper eruptive part consisting of diabase showing no evidence of volcanic origin such as slaggy surfaces or amygdaloids. It may have been injected as sills into the sedimentary part of the Keweenawan, the overlying materials having been more easily attacked and removed, leaving the resistant diabase to form the present surface.

No definite volcanic vents have been found to account for the great thickness of lava exposed in the regions just described and the same is true of the still more extensive volcanic rocks on Keweenaw Point to the south of the lake; and it is probably true, as suggested by Van Hise and Leith, that the eruptives came from fissures and not from volcanic cones with craters. In this case the numerous dikes of diabase cutting the lower rocks may have been the channels of ascent for the lava. Much of the molten material spread out as sills in the Animikie and Keweenawan sediments and never reached the surface.

The outline just given sufficiently explains the nature of the Keweenawan rocks on and near Lake Superior, and so far as descriptions are available, the areas scattered over the Canadian Shield to the north and east are similar. Red conglomerates and sandstones associated with amygdaloidal lavas are characteristic everywhere, though in several places, as on the Nastapoka and Manitounuck islands on the east side of Hudson Bay, they have not been separated from the underlying Animikie sediments containing iron-bearing rocks. Sills of diabase have the same relation to the sediments as those near Lake Superior or Lake Nipigon and give rise to similar flat-topped hills, often with a gentle tilt seaward.¹ Low reports sills of gabbro in the sections at the head of Koksoak and Hamilton rivers in central Labrador, and also on the south side of Hudson Strait; but

¹ Rept. Progress, Geol. Surv., Canada, 1877-1878, 1879, pp. 11-19-C (Bell).

amygdaloids are not mentioned, so that the presence of Keweenawan rocks is not certain.

J. B. Tyrrell names three great stretches of reddish conglomerates and sandstones penetrated by quartz porphyries near Lake Athabasca, Great Slave Lake, and Doobaunt Lake, the "Athabasca sandstones," and describes them as presenting "a remarkable resemblance to the red sandstones and Cambrian quartz porphyries of the Keweenawan rocks of Lake Superior. This resemblance is so strongly marked that small specimens of rocks from the shore of Doobaunt Lake are usually indistinguishable from specimens from Lake Superior. The two terranes are regarded as holding similar positions in the geological time scale."¹

Another great area of Keweenawan, larger than the whole Lake Superior region, occurs east of Great Bear Lake and north along Coppermine River to the Arctic coast. The western part as described seems to belong to the Animikie, but nearer Coppermine River there are quartz conglomerates, reddish and green shales, and pinkish sandstones along with intrusive sheets of greenstones and amygdaloids, the latter carrying native copper.² Specimens collected west of Coppermine River by the Douglasses, by Stefánsson from the mainland of the Arctic shore and from little-known islands to the north, and by Hanbury from east of Coppermine River show a set of basic eruptives in most respects closely like those of Lake Superior, and the presence of native copper has been proved at numerous points.³ A. Sandberg, who accompanied the Douglasses as geologist, maps considerable areas of limestone, red shale, red sandstone, and gray slate as occurring interbedded with the sheets of basalt.⁴

CONDITIONS DURING KEWEENAWAN TIME

While it is possible that the sea encroached on all sides of the shield, and also from the central depression now occupied

¹ Geol. Surv., Canada, vol. 9, 1896, pp. 171-174-F.

² *Ibid.*, vol. 13, 1900, pp. 101-102-A.

³ Gratton, in Trans. Can. Mining Institute, 1913, pp. 102-114.

⁴ *Idem*, p. 88.

by Hudson Bay, during the deposition of the red conglomerates and sandstones of the early Keweenawan, the evidence points rather to continental deposits at that time. The amygdaloidal lavas that came later appear to have flowed out upon a land surface, since they are devoid of the pillow structure found in lavas entering the sea. It seems most probable that the shield as a whole was dry land with more or less desert conditions at this time, the well-stratified sediments found in places having been formed in either permanent lakes or temporary bodies of water, such as are sometimes left by cloudbursts in desert regions.

It is of interest to note that there is no proof of life in the Keweenawan sediments unless the thin sheets of impure limestone in the lower part be looked on as evidence. One nowhere finds the black carbonaceous shales so widespread in the Animikie and even in the Keewatin. It may be that the earth in pre-Cambrian times was not yet clothed with land plants and that life existed only in the water. If so, continental deposits should be free from organic materials. Even the lakes would probably be barren of life. The tremendous volcanic activity of the later Keweenawan would for the time be hostile to life, though the carbon dioxide usually given off from volcanoes might be of benefit to plant life in later times. The customary red color of the sedimentary rocks suggests that the climate was warm.

SOURCE OF THE LAVAS

The Keweenawan was one of the two great periods of volcanic activity within the area of the Canadian Shield, the other being the Keewatin. Which was the more important of the two is hard to decide. The Keewatin lavas are more evenly distributed and perhaps once covered more of the surface, before the rise of the Laurentian batholiths squeezed them into synclines and the pre-Huronian peneplanation removed large parts of them. At present the Lake Superior or the Coppermine River area of Keweenawan lavas far surpasses in extent any

existing Keewatin area. In both the Keewatin and Keweenawan eruptive periods much more basic lava than acid lava came to the surface, though both include subordinate rhyolitic eruptions as well as those of the basaltic type. So far as the existing evidence goes, far more of the Keweenawan magma halted as sills beneath the surface than was the case in Keewatin times. Individual sills often cover many square miles, with thicknesses of 200 or 500 feet. It is highly probable that in some regions no eruptions took place at the surface, all of the magma congealing beneath overlying beds of rock. If any vents reached the surface above the sills of the Thunder Bay Animikie, no evidence remains to prove the fact. It is possible, of course, that lava flows once covered the region but have been completely removed.

A large amount of the more basic magma was retained also in the dikes, which not only penetrate all the rocks of the Keweenawan regions, but occur far and wide in parts of the shield where no Keweenawan sediments or lavas have been found. Moderately fresh olivine diabase dikes, probably dating from the Keweenawan, are known from every carefully mapped portion of the Canadian Shield, some of them 100 yards or more in thickness and traceable for miles. If the unmapped regions are as thickly gridironed with diabase dikes, the amount of magma which cooled in this way before reaching the surface may surpass all the many cubic miles which were piled up as lavas around Lake Superior and in the other Keweenawan regions.

Where were these vast floods of molten rock generated, or were they pre-existing, stored away somewhere until the opportune moment? Why should they all have welled up from the depths in the later Keweenawan time and not before nor after? Did volcanic activity reign at that time in other parts of North America, now covered with later rocks, or was it confined to the higher parts, the continental area of those times?

The questions just suggested are not easy to answer in full, though partial answers are possible. In a few cases there is evidence that the molten rock came from immediately beneath

the area where it poured out on the surface. The depression of Lake Nipigon is an example of this. The great sheets of diabase now cut up into islands in the lake and hills upon its shores would just about fill the former cavity, and this seems to have been formed by collapse as the diabase rose from beneath. A similar explanation may be given for the Sudbury nickel basin, formed probably in Keweenawan time, where the huge laccolithic sheet of the nickel eruptive rose from directly under the present basin. Erosion has removed enough of the superstructure to bring to light the collapsed and down-faulted crystalline rocks beneath.

It is highly probable that the basin of Lake Superior was mainly hollowed by the removal, from beneath, of the immense amount of lava now piled up about its shores. The suggestion of Irving, supported by Van Hise and Leith, that the basin of Lake Superior is an ordinary syncline due to thrust from the south against the horst of the Canadian Shield seems to be inadequate. The synclinal arrangement of the basin may be accounted for by lack of support beneath, permitting a progressive collapse of the foundations. Otherwise there is no special reason for its existence at that particular place. There are no counterbalancing anticlines on either side and no continuations of the syncline toward east and west. The quantity of lava proved to exist amounts to hundreds of cubic miles and doubtless the amount removed since Keweenawan times must be greater than what remains. Where did this vast quantity of lava come from if not from beneath the present hollow of the lake? There must have been great subsidence over the area from which it ascended.

Just why molten lava should accumulate beneath the present basin of Lake Superior is not easy to explain. Possibly some thick blanket of sediments where the lake now is may have depressed earlier basic rocks, lavas of the Keewatin for instance, to a depth where the isogeotherms would cause fusion. A thrust from the south, against the Laurentian block of the Canadian Shield, as assumed by some geologists, might lift the load a little on each side and allow the white-hot rock, hitherto

kept solid by pressure, to expand, become liquid, and make its way upwards by virtue of its expansion until volcanic vents became active all round the shallow basin. This would naturally grow deeper as its support was removed from beneath.

But why should the whole southern side of the Canadian Shield have been so shattered that diabase dikes and sheets could arise for 600 miles, from Minnesota to Cobalt on the eastern side of Ontario? and from what source came the supplies of molten diabase which filled the many fissures opened up along the southern edge of the shield? After the low stage of the Animikie, when the sea encroached widely on the shield, as shown by the marine sediments, there must have been a considerable uplift of the whole shield to allow the formation of the continental deposits of the Keweenawan. This uplift, if confined to the shield, must have implied strains round the edges where the neighboring rocks did not join in the movement. Relief from these strains would come by the shifting of blocks, and the shattering of too solid connections between the rising and the unmoved parts of the earth's crust. Then would come the partial relief from pressure of potential lavas which would become liquid and fill all the fissures as they were opened.

Just why the shield should lift itself in the middle of the Keweenawan age and start all the terrifying machinery into operation, with earthquakes and volcanic floods over so vast an area from Lake Superior to Lake Temiscaming, along all the eastern margin of Hudson Bay, over tens of thousands of square miles of the region between Mackenzie River and Coppermine River along the Arctic Ocean, who can say? That such changes of level have taken place and have had effects like those described is certain, but the final causes of these epeirogenic uplifts are mysterious.

KEWEEAWAN METALLIFEROUS DEPOSITS

From the human and economic point of view, the advent of the Keweenawan lavas is the most important event in the pre-Cambrian history of the Canadian Shield, since most of the

valuable ore deposits of the region, so far as known, are connected with eruptions of this age. At Thunder Bay the silver ores of Silver Islet and other mines were supplied by the Keweenaw diabase dikes and sills. The unrivalled mines of native copper in Michigan belong to the amygdaloids and conglomerates of Keweenaw Point, and similar ores of native copper, perhaps on a larger scale, exist in the extensive area of amygdaloids east of Great Bear Lake and near Coppermine River. The Sudbury deposits of nickel and copper, including much the largest mines of nickel in the world, are connected with a sheet of norite-micropegmatite probably of Keweenaw age; and Miller has concluded that the singularly rich silver veins of Cobalt have derived their ore from a great diabase sill which ascended into the Cobalt conglomerate at this time.

The Keweenaw eruptives seem to have brought with them copper and nickel and silver in large amounts, cobalt, gold, platinum, and palladium in much smaller amounts; and if the iron mines are left out of account, almost all the metalliferous deposits of the southern margin of the Canadian Shield have resulted from the coming of its dikes or sheets or lava streams.

Since the close of the Keweenaw no ore deposits of importance are known to have been formed within or near the Canadian Shield. Its floods of molten magma seem to have exhausted the treasure-house.

SUCCESSION OF EVENTS IN THE HISTORY OF THE CANADIAN SHIELD

[The table is presented in the inverted order for easier reading.]

Archæozoic	{	Coutechieing—marine deposits (materials derived from a land area)
		Keewatin—volcanic eruptions, often submarine, and some marine sediments
		Grenville—marine sediments (a land area near by)
		First mountain-building period
		Destruction of mountains by epigene forces—continental conditions

Early Proterozoic	{	Sudburian—at first probably continental conditions—later marine invasion Second mountain-building period=Laurentian Destruction of mountains and formation of a peneplain—continental conditions
Late Proterozoic	{	Huronian—tillite formed by continental ice sheet followed by fresh water or marine deposits—cool climate Animikie—marine deposits—most or all of shield submerged Keweenawan—great volcanic activity on land and continental deposits—desert conditions
Palæozoic	{	Cambrian—(Lake Superior sandstones)—southern part of shield submerged

The outline of the events in the pre-Cambrian history of the Canadian Shield given above must be looked upon as tentative, though the table represents the conclusions drawn from more than twenty years of field work, covering several of the more important parts of the great area concerned. It is probable that the gaps in the record indicated by the first and second times of building and destroying mountains were far longer than the constructive periods described in these lectures. Possibly some other pre-Cambrian shield may in time fill out the record, providing evidence of what took place in the lost intervals.

APPENDIX TO LECTURES ON THE PROTEROZOIC OF THE CANADIAN SHIELD

A. P. COLEMAN

Though a number of advances have been made in our knowledge of the region described in the lectures on the Proterozoic of the Canadian Shield since the first edition of *Problems of American Geology* was issued, the main results have not been disturbed and it does not seem necessary to re-write the account as there given. It is proposed instead to supplement the previous account by references to the new information available and also to mention the most recent attempts to classify the pre-Cambrian rocks of the region.

The most important advance in our knowledge is due to W. H. Collins, who has studied carefully certain selected parts of the pre-Cambrian north of Lake Huron. His results are given briefly in two *Museum Bulletins* of the Canadian Geological Survey,¹ and his final detailed report is to appear before long as a *Memoir*.² A portion of the area has already been described by one of his field assistants, T. T. Quirke, in *Memoir 102* on the Espanola District. The field work carried out between the Sudbury area and the Original Huronian gives a much better idea of the relations of the formations than the brief account contained in the lectures on the Proterozoic, since the latter was based upon only a few days' reconnaissance along the Sault Ste. Marie railway.

To give the results of this work in detail would demand more space than is available; but it may be stated that Collins's work shows the break between the Upper Huronian (Cobalt Series) and the Lower Huronian (Bruce Series) to be greater than had previously been supposed; and his work with that of Quirke

¹ *Bulls.* 8 and 22.

² See *Sum. Rep.*, G. S. C., 1916, pp. 183-185.

seems to place the quartzite of the Cloche Mountains in the Lower Huronian or Bruce series instead of the Sudbury series as supposed by the present writer.

The classification of the rocks of the Temiscaming region adopted by Collins corresponds fairly closely with the one used in the lectures, though several of the names employed are different. In the following table the classification used by the writer is given in column I, that of Collins for the Temiscaming region in II, and that adopted by Miller and Knight for the Bureau of Mines of Ontario in III;

*Mus. Bull. No. 8 (Infolded at the end).
†Bur. Mines, Ont., 1914, Vol. XXIII, p. 203.

It will be observed that the three classifications agree as to the broad features, though differing in nomenclature; so that it is probable that a solid foundation has been reached in the study of these ancient and difficult formations. The classification used by Miller and Knight is revolutionary in abolishing the historic name Huronian, which is replaced by Animikean. The reason assigned for the change is the great variety of meanings assigned to the Huronian by different geologists, causing confusion as to the scope covered by the term. It seems to the writer, however, that the proper method would be to return to the usage of Logan and to restrict the name to formations equivalent to those found and mapped on the north shore of Lake Huron, rather than to drop the name altogether. That a name has been abused by some writers is surely a reason for correction of the abuse and not for casting aside the name completely.

It will be noticed that in using the name Animikean to cover the original Huronian as well as the Animikie the writers are committing the very fault they object to in the inordinate extension of the term Huronian. The Animikie has never before been used as extending below the base of the formation as shown in the Lake Superior region, and it does not occur at all in the typical Huronian region. The new use of the term seems quite unjustifiable.

CHAPTER IV

THE CAMBRIAN AND ITS PROBLEMS IN THE CORDILLERAN REGION

CHARLES D. WALCOTT

INTRODUCTION

James D. Dana was exceptional as a man, as an investigator of Nature from both the zoölogic and geologic sides, and he was also a wise teacher of geologists the world over. It is a privilege and an honor to assist in paying tribute to one whom I learned to appreciate when a young man, who inspired students of geology with such high ideals through the influence of the spoken and the written word.

The subject assigned to me on this occasion, "The Cambrian and its Problems in the Cordilleran region of Western America," is one in which I have been long interested, and Nature has been most generous in revealing to me many of her records of Cambrian time. During the past four or five years, while making researches in the Canadian Rockies, it has been my good fortune to discover highly organized marine fossils deep in the Middle Cambrian formation. The minutest details of the internal structure of some of these invertebrate fossils are wonderfully preserved and reveal a great deal not before known of the life history of that period. In the course of my studies, particularly in recent years, data have also come to light which help us more definitely to outline the boundaries of the three great marine incursions of Cambrian time. There are also presented to us new conceptions of geological conditions in Cambrian time and

more accurate information indicating the probable sources of the Cambrian fauna of the Cordilleran area. As a trustee for the moment of these records I am glad to place conclusions drawn from them and from the observations of other geologists where they may be available to student and layman, and also to indicate some of the still unsolved problems of the Cambrian. We must recognize, however, that the data gathered over the greater part of the Cordilleran area have been only of a reconnaissance nature, and that areal geologic mapping and detailed stratigraphic studies have been confined to a few relatively small and isolated localities.

When we closed the field season of 1913 in British Columbia, after several years' research in that region, I realized that I was ready to go back to Nevada and take up the study of some of the problems of the southern Cordilleran Cambrian from the twentieth century point of view. This I hope soon to do myself in a limited way and will leave to others the task of pressing the work forward in the future.

NOMENCLATURE

Algonkian. In referring to the pre-Cambrian series of formations I am using in this paper "Algonkian" or "Proterozoic" to designate the sedimentary rocks and included eruptives down to the base of the Huronian, and for the pre-Algonkian the term "Archæozoic."

Ozarkian. For the post-Cambrian system of formations immediately above the Upper Cambrian in the Mississippian area, I think Ulrich's term "Ozarkian" is eminently suitable, as it includes a great thickness of sedimentary rocks characterized by a distinctive invertebrate marine fauna. This Ozarkian system or era has been more or less confounded in its lower portion with the upper part of the Cambrian, but we are now able to draw the line between the two systems on both stratigraphic and faunal evidence in the northern Mississippian area.

The Jordan sandstone terminates the Cambrian above and the Madison sandstone and Mendota limestone mark the base of the Ozarkian.¹

Upper Cambrian or Croixian. "St. Croixan" was proposed by Ulrich, as the Saratogan of Walcott had been previously used as a geologic formation name² in quite a different sense.

Lists of fossils occurring in the Upper Cambrian formations of the Cordilleran and Mississippian areas are given on pp. 221-227.

Middle Cambrian or Acadian. "Acadian" was proposed by Sir J. W. Dawson in 1867 and has been used by authors as synonymous for "Middle Cambrian" in the Atlantic realm.

For lists of Middle Cambrian fossils of the Cordilleran area, see pp. 210, 211, and 227.

Lower Cambrian or Waucobian. "Waucoban" is a recent term proposed to replace "Georgian."³ The terms Upper, Middle, and Lower Cambrian are of world-wide application and come to have a very definite meaning, and I now anticipate that "Croixian," "Acadian," and "Waucobian" may come into general use, more particularly in America.

For lists of Lower Cambrian fossils of the Cordilleran area, see pp. 205-208, and 227.

PRE-CAMBRIAN CONTINENTAL CONDITIONS

To more clearly understand the history of the western North American continental area during Cambrian time, it is desirable to outline the probable geologic conditions during the great eras preceding the transgressions of the Cambrian sea.

The character and structure of the pre-Cambrian sedimentary

¹ See Ulrich, Bull. Geol. Soc. America, vol. 22, 1909, pp. 627-647. The author (Ulrich) did not have a very clear idea of the boundary between the Cambrian and Ozarkian in 1909, but during the field season of 1913 he secured evidence in Wisconsin and Minnesota that convinced him of the stratigraphic break at the summit of the Jordan sandstone.

² See Smithsonian Misc. Coll., vol. 57, 1912, pp. 306, 307.

³ *Idem*, pp. 305-306, also vol. 53, 1908, p. 169.

formations¹ indicate that toward the close of the Archæozoic era a period of world-wide diastrophism ensued, a revolution, as Dana would term it, resulting in the receding of ocean waters or in the uplift of the American and other continental masses in relation to the oceans. This great change (Laurentic revolution) was accompanied or followed by local disturbances which produced profound folding and the metamorphism of the pre-Proterozoic complex, with the formation of mountain ranges, uplands, valleys, and lowlands.

Two broad continental geosynclines subparallel to the western and eastern coast lines of the continent began to form early in Algonkian (Proterozoic) time. When cut off from the outer oceans or while the surface of these great areas was above the level of marine waters, they received terrigenous Algonkian sediments which began to accumulate on river flood plains and other favorable areas, or were deposited in the epicontinental fresh and brackish water seas or lakes that filled the shallow depressions within the area of the geosynclines. The western or Cordilleran geosyncline extended from the vicinity of the head of the Gulf of California northward nearly to the Arctic Ocean, although considerable portions of its eastern section in the Montana-Canadian area were not inundated by the Cambrian sea until late Middle Cambrian time and some areas were not submerged until Carboniferous (Mississippian) time.

In Arizona the Algonkian period of sedimentation is represented by nearly 12,000 feet (3658 m.) in thickness of sandstones, shales, and limestones of the Grand Canyon group. In Utah and Nevada sediments forming only sandstone and siliceous shale appear to have gathered, while in Montana there is a development of limestone 4800 feet (1463 m.) in thickness in addition to nearly 20,000 feet (6093 m.) of siliceous and

¹ Van Hise and Leith, Monograph U. S. Geol. Surv., vol. 52, 1911, table facing p. 598. Also see map 1, accompanying Bull. U. S. Geol. Surv., No. 360, 1909.

arenaceous beds.¹ To the north, the Siyeh limestone has a thickness of 4000 feet (1220 m.).²

In western Alberta and eastern British Columbia to about 54° North Latitude the Algonkian sediments are much like those of Montana. In the Montana region of greatest accumulation of Algonkian sediments the Cordilleran trough appears to have been filled to such an extent before Cambrian time, possibly by a river delta, that the Cordilleran Cambrian sea advancing to deposit its sediments encountered a central barrier³ extending out from the eastern side of the trough. This barrier continued through the greater part of Cambrian time. The evidence of the faunas in the Cambrian beds of British Columbia on the north, and in Idaho and Utah to the south, proves that the seas in which they lived were connected around the barrier, but how or where we do not know.

Briefly summarized, the Algonkian era in North America with its great epicontinental formations was a time of continental elevation and largely terrigenous sedimentation in non-marine bodies of water, and of deposition by aerial and stream processes in favorable areas. Marine sediments accumulated in the waters along the outer ocean shores of the continent and great quantities of eruptive matter were extruded into the central Lake Superior region (Keweenaw). The agencies of diastrophism continued to exert their influence for a long period, though with decreasing energy, until they became practically quiescent during the latter part of Algonkian time.

The North American continent was larger at the beginning of known Cambrian time than at any subsequent period other

¹ Bull. Geol. Soc. America, vol. 17, 1906, p. 7.

² Bull. Geol. Soc. America, vol. 17, 1906, p. 19. Daly has placed the Siyeh limestone of the Algonkian in the Cambrian, but in the absence of direct areal stratigraphic relations and all fossils in the Siyeh limestone I do not see my way clear to accept his conclusions based on lithologic similarity of the Siyeh and the Middle Cambrian limestones of the Bow Valley and Kicking Horse Canyon. (Report Chief Astronomer for year 1910, Ottawa, 1913; *Geology of North American Cordillera*, part 1, R. A. Daly, pp. 174-178 and accompanying table.)

³ Smithsonian Misc. Coll., vol. 53, No. 5, 1908, p. 169.

than possibly at the end of the Palæozoic and the end of the Cretaceous, when the land was equally extensive. Indeed, it is highly probable that its area was greater then than even now, for no marine deposits containing pre-Cambrian life, as they were laid down in Lipalian¹ time immediately preceding the Cambrian period, have been discovered on the North American continent or elsewhere so far as known.²

It was upon this great continent that the Cambrian sea began to encroach in early Lower Cambrian time, first filling in the western and eastern geosynclinal depressions, and later spreading over the more depressed areas of the interior.

Pre-Cambrian Surface. From the evidence afforded by the stratified rocks and their contained fossils, the first known sediments were deposited in a shallow marine basin that occupied an area now included in southwestern California and adjacent portions of Nevada. The incoming Cambrian sea encountered a land surface deeply disintegrated and more or less eroded nearly to base-level. Compared with the earlier epochs of Algonkian time it was a featureless surface, the elevations caused by folding and uplift in the geosynclines and the adjoining geanticlines of the Cordilleran, Lake Superior, and Appalachian areas of Algonkian time having been largely degraded. The rising waters met with only slight elevations in the Cordilleran trough, as evidenced by the almost entire absence of coarse conglomerates and the presence, above the coarse basal sandstones and fine conglomerates, of deposits of very fine-grained sandstones and mud rocks.³

¹ Smithsonian Misc. Coll., vol. 57, 1910, p. 14 (footnote).

Lipalian (λεϊπα + αλς) is proposed for the era of unknown marine sedimentation between the adjustment of pelagic life to littoral conditions and the appearance of the Lower Cambrian fauna. It represents the period between the formation of the Algonkian continents and the earliest encroachment of the Lower Cambrian sea.

² See p. 230 for quotation.

³ Darton has described coarse conglomerates at the base of the Cambrian of the Black Hills, South Dakota, but this is in an early Upper Cambrian formation and far east from the Cordilleran region. It seems to be a local deposit. (Prof. Paper, U. S. Geol. Surv., No. 65, 1909, pp. 12, 13.)

LIMITS OF THE CORDILLERAN SEA

The advance of the marine waters in the Cordilleran geosyncline began early in the Cambrian, and later the extension across the basins of the interior continental area was as irresistible as was the advance of the continental glacier from the north in the Pleistocene glacial period. This great continental sea crept in over the land, time after time, overcoming in the Cambrian era all obstacles that lay in its path, until at its maximum height it spread its waters from side to side of the vast interior of the continent as far north as the 45th parallel, with a broad sea on the western side extending to the Arctic Ocean. On the east, Appalachia barred the inland seas from the Atlantic, and on the west the coast ranges of Ensenada, Cascadia, and Yukonia¹ held back the Pacific. At the period of greatest inundation in early Upper Cambrian time, Schuchert estimates that the continental sea covered 2,587,000 square miles or 31.6 per cent of the present land area of North America.²

The southern Cordilleran sea in early Cambrian time appears to have been restricted to the west of the 111th and east of the 118th meridians. The extent of the passage connecting with the Pacific is unknown, but it was probably an unobstructed wide channel affording free ingress for the ocean waters and faunas. The broadest known portion of the sea was across western Utah and Nevada into California, where the Lower Cambrian beds have been found in localities 300 to 350 miles (480 to 560 km.) apart. The sea may have extended farther westward in northern Nevada and on the north into eastern Oregon and Washington, but of this we have no evidence because of the masking of all the older formations by eruptive and Quaternary deposits.

In early Middle Cambrian time the sea widened somewhat and in the Upper Cambrian it spread to the eastward into the Colorado region, also across Wyoming to connect with the

¹ Schuchert, Bull. Geol. Soc. America, vol. 20, 1910, pl. 49, opposite p. 464.

² *Idem*, p. 601.

Mississippian sea on the north and across Arizona and Texas to join it on the south.

There is also a strong presumption that the Cordilleran sea was directly connected in Lower and Middle Cambrian time with the Appalachian sea either by a wide open sea somewhere across Central America or more doubtfully by an east and west epicontinental connection existing across the southern states. Such a connection is called for by the presence of almost identical species of *Olenellus* from Labrador on the Strait of Belle Isle, Vermont, central Pennsylvania, Virginia, and Alabama on the east, and on the west from Nevada, California, and British Columbia.

To the north, in western Alberta and eastern British Columbia, the evidence of the presence of the sea is confined to a belt 150 to 200 miles (240 to 320 km.) wide, bounded on the east by overthrust faults which have often pushed the Cambrian over on to the Cretaceous and Carboniferous formations.

Pre-Cambrian and supposed metamorphic Palæozoic rocks bound the Cambrian formations on the west, a condition that leaves the question of the western boundary of the Cordilleran sea very uncertain.

To the far north in the Yukon and Mackenzie province there is a great widening of the later Palæozoic seas and it is quite probable that the Cambrian Cordilleran sea here covered a larger and broader area than to the south.

Cordilleran Streams of Cambrian Time. The outline of the land area and of the Cordilleran sea of Lower Cambrian time¹ indicates that there probably could have been no long and broad rivers entering from the west. The land bordering the sea on the west must, however, have been high, as appears by the vast quantities of Lower and Middle Cambrian mud deposits with some limestone extending from Nevada to central eastern British Columbia, their thickness usually measuring between 8000 and 10,000 feet (2440 m. to 3050 m.). Toward the east the vast Canadian Shield extended across the continent as a

¹ Schuchert, *Op. cit.*, pl. 51.

low peneplained land to the Appalachian trough, for here again the sediments indicate rivers with a gradient only sufficient to enable them to carry mud and sand to their outlets. This is evidence that if great rivers existed on the Canadian Shield, they flowed over low lands bordering these inland seas. A large amount of fine sand was carried into the early Cambrian sea of the Cordilleran region, but this might readily have come from a district 200 miles (320 km.) or less in width. The arenaceous Algonkian formations afforded an unfailing supply of sand and mud with which even a relatively small river could have built up a delta either above or below the water-level of the Cambrian sea.

The absence of great amounts of coarse material in nearly all exposures of the basal Cambrian sandstones proves that the gradient of the rivers was too low to enable them to transport large masses of rock or any considerable quantity of moderately coarse gravel. In general some sand and mud were laid down at first, and then followed the limestone seas of the Middle Cambrian but more especially of Upper Cambrian time. The great central area of the continent was probably drained in Cambrian time as at present by river systems flowing north and south.

CAMBRIAN BASAL UNCONFORMITY

From the Robson Peak region of British Columbia and Alberta to Arizona and southern California, a distance of over 1000 miles (1600 km.), clear evidence of a transgressing Cambrian sea has been found in many localities, proving conclusively that a general unconformity occurs here between the Cambrian and pre-Cambrian. This marked unconformity is the record of the advancing, overlapping Lower Cambrian sea of southwestern Nevada, the Middle Cambrian sea of Utah and Idaho, and finally the Upper Cambrian sea of Colorado and the interior continental area.

The Cambrian rocks may be abruptly conformable upon the

Algonkian or Archæan,¹ or apparently conformable, as in areas where there has been very little disturbance of the subjacent Algonkian beds.² Over the interior of the continent the Upper Cambrian strata unconformably overlap the Algonkian and Archæan,³ and there is here no record of any part of the Lower Cambrian period. I do not know of a case of proven conformity with transition deposition between Cambrian and pre-Cambrian Algonkian rocks on the North American continent. In all localities where the contact is sufficiently extensive, or where fossils have been found in the basal Cambrian beds or above the basal conglomerate and coarser sandstone, an unmistakable hiatus has been found to exist. Stated in another way, the pre-Cambrian land surface was formed of sedimentary, eruptive, and crystalline rocks, the deposition of which did not in any known instance immediately precede the Cambrian sediments. Everywhere there is a marked stratigraphic and time break between the known pre-Cambrian rocks and the Cambrian strata of the North American continent.⁴

The Lower Cambrian is characterized by the presence of the Lower Cambrian⁵ (Waucobian)⁶ fauna. In southwestern Nevada this fauna ranges through some 4000 feet (1220 m.) of strata that have no known line of demarcation at the base to separate the Cambrian from some pre-Cambrian Palæozoic formation. This leads to the hope that still older beds and faunas will be discovered in this region which will establish a base to the Cambrian not entirely founded on unconformable superposition of the Cambrian on pre-Cambrian formations.

Figures 1, 2, and 3 illustrate the unconformity between the Cambrian and pre-Cambrian and give some conception of the extent and profound character of the Algonkian revolution.

¹ Tenth Ann. Rept. U. S. Geol. Surv., 1891, p. 551, fig. 48.

² Bull. Geol. Soc. America, vol. 10, 1899, pp. 210-213.

³ Tenth Ann. Rept. U. S. Geol. Surv., 1891, pl. 44, pp. 561-562.

⁴ Twelfth. Ann. Rept. U. S. Geol. Surv., 1892, pp. 546-557.

⁵ Tenth Ann. Rept. U. S. Geol. Surv., 1891, pp. 515, 549.

⁶ Smithsonian Misc. Coll., vol. 57, 1912, p. 305.

Fig. 1. Grand Canyon section. This section crosses the Algonkian and pre-Algonkian strata nearly at right angles to their strike and illustrates the unconformity between the Cambrian and pre-Cambrian rocks. The Cambrian (Tonto) formation has been removed by erosion on the direct line of the section, but it is shown on the sides of the canyon as indicated by the dotted line. The letters G C, and C' equal the Grand Canyon and Chuar formations, or strata referred to the Algonkian. T=Tonto formation of the Cambrian. W=Aubrey sandstone of the Carboniferous. A=Aubrey sandstone of the Carboniferous. The plane of the pre-Cambrian surface is shown by the lower dotted lines when the Tonto sandstone is absent.

Fig. 2. Panoramic view from the south slope of Fort Mountain looking to the southeast and south from a point 4 miles (6.4 km.) northeast of Laggan, Alberta, Canada.

The lower dark cliff in the mountain is formed by the basal conglomerate of the Cambrian. Below, the slope is formed of the arenaceous shales of the Algonkian Hector formation. The rounded hills in the foreground are formed of the sandstones of the Corral Creek formation overlain by the shales of the Hector formation. In the distance on the right are the high peaks of Cambrian rocks of the Bow Range on the southwest side of the Bow Valley. (Photograph by C. D. Walcott, 1909.)

Fig. 3. Northwest end of Scapegoat Mountain on the Continental Divide north-northwest of Helena, Montana, and north-northeast of north fork of Blackfoot River.

The unconformity between the Cambrian and Algonkian occurs about the centre of the view where the basal Cambrian beds are turned up from beneath Scapegoat Mountain. (Photograph by C. D. Walcott, 1905.)

ORIGIN OF SEDIMENTS

Following the deposits of late Algonkian time in the Cordilleran trough the first Cambrian sediments were oftentimes the Algonkian sediments worked over by the advancing Cambrian sea and deposited almost conformably on the underlying and undisturbed Algonkian beds. In such instances where the waves and current action were weak the passage between the strata of widely differing age is almost imperceptible and often could not readily be distinguished if it were not for the abundant remains of animal life in and on the Cambrian layers of sandstone and shale. The pre-Cambrian beds, like those of the Cambrian, have many mechanical markings, such as ripple marks and mud cracks, but in no instances have traces of life been found in beds near the contact with the Cambrian.¹ Usually the sands of the Cambrian have been so washed and cleaned by the shore waves that the sandstones formed of them are readily recognized and separated from the normally dirty sandstones of the Algonkian.

Another characteristic of the Cambrian sandstones is the absence of fragments of feldspar so abundant in many of the Algonkian sandstones. Often this is the first indication in a broken and partially covered section that the line between the Algonkian and Cambrian has been crossed. The grains of quartzite in the pre-Cambrian beds also have a dull, lustreless aspect rarely seen in the Cambrian sandstones. This occurs most strikingly at Gordon Mountain, north of Ovando, Montana, and in the Bow River Valley, Alberta, Canada.²

The muds and silts that often accumulated during Cambrian time were derived from the deeply disintegrated pre-Cambrian rocks. Apparently the supply was very great and every river flood brought much material, while the advance of the Cambrian

¹ The fossils now known from the pre-Cambrian of Montana and Arizona occur at an horizon several thousand feet beneath the later Algonkian strata that came in contact with the basal Cambrian. (Bull. Geol. Soc. America, vol. 10, 1899, p. 235.)

² Smithsonian Misc. Coll., vol. 53, 1910, p. 427.

sea over the land worked this regolith together and eroded the high points into the deposits of the sea. That quantities of calcareous matter were also being carried into the sea in solution throughout Cambrian time is evidenced by the presence of limestones and calcareous sandstones and shales in the Lower Cambrian, and by calcareous rocks largely predominating in the Middle and Upper Cambrian. The source of this calcareous material was in the limestones and calcareous shales of the Algonkian and the crystalline Archæozoic rocks.

CHARACTER OF SEDIMENTS

The sorting action of the transgressing Cambrian sea gathered the sands and small pebbles into beaches that nearly everywhere formed along its advancing strand-line. Sometimes the sand was mixed with fine silt and in places the transgressing silt settled directly on the pre-Cambrian surface, but this was exceptional. Where streams brought in sand and pebbles, the lateral play of the waves and currents spread them over the bottom of the shallow sea and in the intervals between the times of such deposits calcareous, siliceous, and argillaceous muds were often deposited. Occasionally, limited areas of the bottom were exposed between tides and a record made of gentle wavelets, sun-cracked muds, and trails of annelids and crustaceans on both mud and sand.

The character and depth of the various deposits are outlined in a broad way in the following generalized typical sections:

SUMMARY, HOUSE RANGE SECTION,¹ WESTERN UTAH

STRATIGRAPHIC SECTION

	Formations	Character	Feet	Feet
Upper Cambrian	Notch Peak .	Gray arenaceous limestones.....	640	
		Gray siliceous limestones.....	850	
	Orr	Bluish-gray compact limestones with bands of shale.....	1490	
		Gray arenaceous limestones.....	335	3315
Middle Cambrian	Weeks.....	Thin-bedded and shaly bluish and gray limestones	1390	
	Marjum	Thin-bedded gray limestone.....	305	
		Massive-bedded blue-gray thin-bedded and shaly limestones with thick beds below.	797	
	Wheeler	Shaly limestone and calcareous shale	570	
	Swasey	Oölitic, arenaceous and shaly limestone...	340	
	Dome	Massive-bedded, cliff-forming limestone...	355	
	Howell	Bluish-black limestone and siliceous lime- stone.....	435	
		Spence shale	20	
Lower Cambrian	Langston ?	Arenaceous limestone.....	205	4417
	Pioche.....	Arenaceous and siliceous shale.....	125	
	Prospect Mountain ...	Gray and brownish quartzitic sandstone ..	1375+	1500+
	Total thickness House Range section.....			9232+

¹ Smithsonian Misc. Coll., vol. 53, No. 5, 1908, p. 173.

Below the horizon of the Pioche shale formation there is a great thickness of alternating sandstones, shales, and limestones of Lower Cambrian age that are best known in the vicinity of the Silver Peak Range, Nevada,¹ and Saline Valley, California.² Both sections have several zones in their 5500 feet (1676 m.) of strata where fossils occur.

SUMMARY, EUREKA DISTRICT SECTION,³ NEVADA

STRATIGRAPHIC SECTION

Formations		Character	Feet	Feet
Upper Cambrian	Dunderberg ..	{ Yellow argillaceous shale with layers of cherty nodules.....	350	
	Hamburg		1200	
	Seeret Canyon shale	{ Thin-bedded limestones near summit with argillaceous shales below	1600	3150
Middle Cambrian	{ Eldorado { Gray compact, usually thick-bedded limestone		3050	
				3050
Lower Cambrian	{ Prospect Mountain { Shaly sandstone at summit and massive-bedded brown quartzitic sandstone below		1500	1500
Total thickness, Eureka District Section.....				7700

¹ Smithsonian Misc. Coll., vol. 53, 1908, pp. 188, 189.

² *Idem*, pp. 185-188.

³ Monograph U. S. Geol. Surv., vol. 8, 1884, p. 284.

SUMMARY, BLACKSMITH FORK SECTION,¹ NORTHERN UTAH
STRATIGRAPHIC SECTION

	Formations	Character	Feet	Feet
Upper Cambrian ²	St. Charles..	1. Fossiliferous limestone.....	190	1227
		2. Arenaceous limestone.....	777	
		3. Fossiliferous limestone.....	94	
		4. Shaly and thin-bedded sandstones.....	166	
Middle Cambrian	Nounan	1. Arenaceous limestone.....	1041	
	Bloomington	1. Limestone and shales	220	
		2. Thin-bedded limestone	1100	
	Blacksmith .	1. Arenaceous limestone.....	570	
	Ute	1. Thin-bedded limestone	483	
		2. Limestone and shales	246	
		<i>Spence shale</i>	30	
	Langston ...	1. Massive limestone	108	
		2. Arenaceous limestone.....	390	
	Brigham....	1. Quartzitic sandstones (estimated)	1232+	5420+ ³
	Total thickness, Blacksmith Fork Section.....			6647+

¹ Smithsonian Misc. Coll., vol. 53, 1908, pp. 199-200.

² An unconformity exists between the St. Charles and the superjacent Ordovician Garden City limestone, according to Richardson. (Amer. Jour. Sci., (4), vol. 36, 1913, p. 408.)

³ The line of separation between the Middle and Lower Cambrian occurs somewhere in the Brigham formation, and this thickness (5420 feet) likely includes several hundred feet of Lower Cambrian beds.

SUMMARY OF MOUNT BOSWORTH SECTION,¹ BRITISH COLUMBIA,
CANADA

STRATIGRAPHIC SECTION

Formations		Character	Feet	Feet
Upper Cambrian	Sherbrooke ...	Gray, partly cherty limestones	175	1375
		Oölitic limestones and shaly band	590	
		Arenaceous dolomitic limestone	610	
	Paget	Massive-bedded bluish-gray limestone	60	360+
		Oölitic limestone with bands of shale	300+	
	Bosworth	Gray, arenaceous, dolomitic limestone	600+	1855+
Shaly and thin-bedded dolomitic lime- stone with two bands of shale		987		
Shales		268		
Middle Cambrian	Eldon	Siliceous and arenaceous limestone . .	788	2728
		Bluish-gray limestone	95	
		Arenaceous limestone	1845	
	Stephen	Thin-bedded, dark and bluish-gray limestone	315	640
		Alternating limestones and shale . . .	325	
	Cathedral	Arenaceous dolomitic limestone	1595	1595
Lower Cambrian	Mount Whyte.	Thin-bedded limestones	224	390
		Sandstone	31	
		Siliceous shale	115	
		Gray limestone	20	
	St. Piran	Sandy shales and quartzitic sandstones as exposed at Lake Agnes		2705
	Lake Louise . .	Compact siliceous shale as exposed at Lake Louise		105
	Fairview	Quartzitic sandstones as exposed at Lake Louise		600+
	Total thickness of sections examined			

¹ Smithsonian Misc. Coll., vol. 57, No. 12, 1913, p. 342.

SUMMARY OF ROBSON DISTRICT SECTION,¹ ALBERTA, CANADA
STRATIGRAPHIC SECTION

Formations			Character	Feet	Feet			
Cambrian	Ordovician	{	Robson	{	Massive and thin-bedded lime- stones partly siliceous, arena- ceous and dolomitic	3000	3000	
			Lynx	{	Thin-bedded gray and bluish-gray limestone with bands of shale	2100		
	Upper	{	Titkana	{	Massive beds of thin layers of bluish-gray limestone interbed- ded with bands of dolomitic limestone	2200		
			Mumm	{	Massive-bedded gray arenaceous limestones	600		
			Hitka	{	Alternating bands of thin layers of arenaceous limestones and shales	1700		
			Tatay	{	Massive-bedded gray arenaceous limestone	800		
			Chetang	{	Bluish-gray thin-bedded lime- stones	900	8300	
			Middle	{	Hota	{	Gray arenaceous limestone, alter- nating with massive quartzitic sandstone	800
	Mahito	{			Massive-bedded quartzitic sand- stone with bands of siliceous shale	1800		
	Tah	{			Siliceous shale and interbedded siliceous limestones	800		
	McNaughton	{			Quartzitic sandstones	500	3900	
	Total thickness, Cambrian sediments						12200	
	Unconformity							
	Algonkian	Belt	{	Miette	{	Massive gray sandstones with interbedded siliceous shales... Base concealed	2000+	

Arenaceous and Calcareous Sediments. The proportion of arenaceous and calcareous strata in these typical Cambrian sections is briefly stated as follows:

¹ Smithsonian Misc. Coll., vol. 57, 1913, pp. 336, 339.

Stratigraphic sections	Arenaceous deposits	Calcareous deposits		
		Upper Cambrian	Middle Cambrian	Total
House Range, Utah.....	1500 feet	3315 feet	4417 feet	7732 feet
Eureka District, Nevada.....	1500 "	3150 "	3050 "	6200 "
Blacksmith Fork, Utah.....	1400 "	1061 "	4158 "	5219 "
Mt. Bosworth, B. C., and Alberta	3842 "	3322 "	4963 "	8285 "
Robson District, B. C., and Alberta	3900 "	2100 "	6200 "	8300 "

The presence of from 5000 to 8000 feet (1520 to 2440 m.) of limestone of Middle and Upper Cambrian age over nearly all of the Cordilleran area where Middle and Upper Cambrian formations occur is the record of the change that followed the Lower Cambrian period. The regolith awaiting the advance of the Lower Cambrian sea had been worked over and deposited and the streams had cut their valleys nearly to base-level. With the deepening of the geosyncline, as the Middle Cambrian fauna was quietly distributed throughout the Cordilleran sea, the streams brought in almost no mechanical sediment; the drainage was from lands being reduced by solution and not by corrosion. This points to low topographic relief in western America and little diastrophic movement during Middle and Upper Cambrian time.

Illustrations of Robson District Section. In order to illustrate the remarkable character of the sections in the Rocky Mountains, there are here included several views taken in the Robson District section. Figure 4 includes about 2000 feet¹ (600 m.) of the Lower Cambrian quartzitic sandstones. The summit of these sandstones is shown on the left side of Figure 7 at **Ma**. Beyond the stream at **C.B.** (Fig. 7) the various limestone formations rise, cliff on cliff, to the summit of the Middle Cambrian at **T**. In Figure 6 the western slope of this Peak, **T**, is shown on the left, and in Phillips Peak, Iyatunga, and Mount Robson the strata are exposed that carry this section up and into the Robson formation, which is of post-Cambrian age.

¹ Includes 244 feet of limestone.

Fig. 4. Near view of Tah Peak, rising above Moose Pass, Jasper Park, Alberta, Canada. On the left, Tokana Mountain rises just west of the fault that has thrust the lower Cambrian of Tah Peak over on the Upper Cambrian to the left of the pass. (Photograph by R. C. W. Lett, Grand Trunk Pacific Railway, 1912.)

Fig. 1. a. Tidal Power Model; b. Power Plant to which tidal power was fed; c. The Tokamak Monopolar generator; d. The first test of the generator; e. The first test of the plant; f. The first test of the power.

Fig. 4. West view of the Tarp Peak over the top of Tokara Mountain.

Courtesy of The Smithsonian Institution

Горы Ледяе Реймъ, 1915.)

In the distance on the right Little Clinging Peak. (Photograph by R. C. H. Galt, standing the foot of Hinga Glacier at its base, and beyond a portion of Blue Glacier above Berg Lake.

Canada. In the foreground Clinging Cliff; in the center Laramie (black rock) Mountain with Fig. 9. Horns Peak from north-west slope of Little Mountain. Horns Peak, British Columbia.

Fig. 5. Robson Peak from northwest slope of Mahto Mountain, Robson Park, British Columbia, Canada. In the foreground Chetang Cliff; in the centre Iyatunga (black rock) Mountain with the foot of Hunga Glacier at its base, and beyond a portion of Blue Glacier above Berg Lake. In the distance on the right Little Grizzly Peak. (Photograph by R. C. W. Lett, Grand Trunk Pacific Railway, 1912.)

Fig. 6. Panoramic view of the Robson massif from a point on the ridge south of Mumm Peak, and 1800 feet (546 m.) above Berg Lake. The Continental Divide passes over the rock knoll on left side of Hunga Glacier, water on the right flowing to the Pacific, on left to the Arctic Ocean. The mountains on the left of the Glacier are in Jasper Park, Alberta, and those on the right are in Robson Park, British Columbia, Canada. (Photograph by C. D. Walcott, 1912.)

Titkana
Peak

Phillips Mt.
=P.
Hunga
Glacier
=H. G.

Iyatunga Mt.
(9,000 ft.)

Blue Glacier
=B.
Robson Peak
(13,068 ft.)

Chupo Glacier
=C.

Little
Grizzly Peak
=L. G.

Berg Lake

Miniohan Mountains
Courtesy of The Smithsonian Institution

Fig. 7. Looking southwest from south slope of Mahto Mountain, Jasper Park, Alberta, Canada. On the left, Coleman Glacier and Creek, and rising above the creek Chetang Cliffs, Tatay Cliff, and Titkana Mountain, with Robson Peak in the distance. (Photograph by C. D. Walcott, 1912.)

Mt. Mahto = Ma.

Mahpiya Snow Field = Mp.
Coleman Glacier = C.

Titkana Peak = T.

Iyatunga Mt. = I.
Robson Peak = R.

Miniohan Range = Mi.

Coleman Brook = C. B.

Courtesy of The Smithsonian Institution

Berg Lake

River Delta Deposits. The evidence for the presence of deltas in the Cambrian is not as decisive as could be desired, but with a vast amount of disintegrated surface material unprotected by vegetation and ready for transportation into the forming and rising Cordilleran sea it would be quite natural, in fact almost inevitable, that deltas should be made at the mouth of streams and rivers entering the sea. Much of the sediment was worked over by the rising waters and thus the deposits by river and sea became interleaved along their adjoining margins in a most complicated manner.

The great non-fossiliferous sandstone beds of the early Lower Cambrian in central Nevada and Utah suggest river deposition and the interbedded layers carrying marine fossils prove the presence of marine waters. In the House Range section of Utah there is a barren sandstone base 1375 feet (431 m.) thick, and above it, at Pioche, Nevada, are highly fossiliferous shaly arenaceous beds.¹ In the Waucoba Springs section² the same type of barren sandstone is interbedded with fossiliferous shales and limestone. The material forming the sandstones appears not to have been subjected to any considerable wave or prolonged current action. The view is suggested that these southwestern deposits were partly delta and partly marine. A series of relatively small rivers entering the sea on the west and east could readily have brought the sands and silts to form confluent deltas.

Barrell has called attention to the great sandstone series of the Lower Cambrian and suggested that possibly the earlier sandstones were accumulated on the land by river aggradation or, as portions of a great river delta, were pushed out into a shallow sea,³ and that these sands later were modified by the marine transgression and deposited as the *Olenellus* quartzite. This may possibly have been true in a limited area of the Appalachian trough, but in the great Cordilleran area the

¹ Smithsonian Misc. Coll., vol. 53, 1908, p. 184.

² *Idem*, pp. 186-188.

³ Jour. Geology, vol. 14, 1906, pp. 451-452.

presence of marine fossils deep down in the section¹ suggests that the previously existing sands were brought into the shallow Cambrian sea by river drainage and usually distributed by its currents far and wide and often interbedded with marine calcareous deposits. If not distributed by the currents, the sands and silts would soon form a delta and gradually fill up that section of the sea to its surface.

An example of supposed delta sands may be found in the great series of sandstones beneath the upper *Olenellus* zone on the western slope of the Wahsatch Mountains near Big Cottonwood Canyon, Utah. These sandstones, whether they be considered of Cambrian or pre-Cambrian age, strongly suggest that they originated as river sands which were deposited as a delta formation.²

Glacial Deposits. As yet no beds of glacial origin have been recorded from the Cambrian of North America. Willis reported evidence of glaciation in the Cambrian of Eastern China³ in the presence of tillite and scratched boulders toward the summit of the Lower Cambrian at the base of the Man-t'o formation, but these deposits may as well have been of late Algonkian age. It is probable that a cold period may have existed over the Cordilleran region at about the close of the Lower Cambrian epoch. This is indicated by the scarcity of fossils in the arenaceous limestone and the frequent presence of siliceous shales at the upper horizon of the Lower Cambrian in all known sections from southern Nevada to the Robson District⁴ of Alberta, Canada. One of the problems to be seriously investigated is the probable existence of a cold period at the close of Lower Cambrian time.

Land Deposits. The presence of non-marine or continental deposits within the Cambrian sections of the Cordilleran area

¹ See Cambrian Cordilleran sections. Smithsonian Misc. Coll., vol. 53, 1908, pp. 185-189. Also *idem*, 1910, p. 301. Locality of *Wanneria gracilis*.

² For further notes on deltas see p. 183.

³ Research in China, Carnegie Inst. of Washington, Pub. No. 54, vol. 2, 1907, p. 39.

⁴ Smithsonian Misc. Coll., vol. 57, 1913, p. 338.

has not heretofore been asserted except indirectly by the comparison of certain Upper Cambrian rocks of the Bosworth section¹ of British Columbia with rocks corresponding in character in the Algonkian Belt terrane of Montana. Previously Barrell had considered many of the Algonkian Belt rocks to be of epicontinental non-marine origin.²

Those of the Upper Cambrian strata of the Bosworth section³ of British Columbia that may be of non-marine origin are Numbers 1, 2*a*, *b*, *c*, and 3 of the Bosworth formation. They include:

1. 2*a-c*. Dolomitic,⁴ arenaceous limestone, 1587 feet.

3. Greenish, deep red, buff, yellow-colored arenaceous and argillaceous shales, 268 feet.

Ripple marks and mud cracks are abundant. There are no traces of life in 1 and 2 of the Mount Bosworth section, but in the Mount Stephen section, 20 miles (32 km.) to the southeast, fragments of small trilobites were found at about the same horizon as 2*b*.

It is difficult to resist the conclusion that the 268 feet of shales of Number 3 of the Bosworth Upper Cambrian section were deposited in fresh or brackish water or on a river flood plain or delta such as Barrell describes so graphically in his studies of the Geological Importance of Sedimentation.⁵

The presence of marine fossils in the limestone beneath the shales of Number 3 indicates either that the sea bed had about filled up or else that a river was forming a delta so rapidly that the marine sediments and life could not gain a foothold in the immediate Mount Bosworth area during the deposition of Number 3 and probably 2 and 1. The reddish shales of Number 3

¹ Smithsonian Misc. Coll., vol. 53, 1908, p. 208. Note.

² Jour. Geology, vol. 14, 1906, pp. 553-560.

³ Smithsonian Misc. Coll., vol. 53, 1908, p. 208. Note.

⁴ Dolomitic limestones are usually considered to be of strictly marine origin, but I think we now have to consider whether some at least have not been deposited in continental seas which were not connected at the time with the ocean.

⁵ Jour. Geology, vol. 14, 1906, pp. 336-354.

also appear west of Mount Stephen in the northwest ridge of Mount Dennis and it is quite probable that the drab-colored and reddish shales of the Chancellor formation of Allan,¹ west of Mount Dennis, belong to the deeper water delta deposits of a Cambrian river. The fine sediments of the shales and dolomitic limestones indicate that the river was transporting material from a region of low topographic relief.

It should be noted in this connection that there is a thin series of reddish and variegated shales at the base of the Upper Cambrian in the Robson Peak district, 200 miles (320 km.) north-northwest of Mount Bosworth,² which in a minor degree suggest land deposits similar to those of Mount Bosworth. These shales are so strikingly unlike the marine limestones beneath and above them, and also so unlike the shales far below, that they challenge attention and study.

It should be borne in mind in this connection that all through Cambrian time land deposits of greater or less extent were being laid down on certain favorable areas of the land surface not covered by the Cambrian sea. Traces of such deposits may possibly be found where they have been preserved beneath the transgressing Cambrian or Ordovician rocks, but otherwise they would have been removed by erosion in the Middle Palæozoic time. There is also the difficulty of distinguishing between the later deposits of Algonkian time and the land deposits of early Cambrian time, and as there was no opportunity for any remains of the Cambrian faunas to be embedded, such rock remnants as may have survived have heretofore not positively been recognized and separated from the Algonkian, although they may have been deposited in Cambrian time.

It has been suggested that the Keweenawan formation of Lake Superior is of Cambrian age³ and that the Upper Keweenawan and Lake Superior sandstone should be correlated⁴ with each other. If the sandstones containing the fossils

¹ Summary Rept. Geol. Surv., Canada, for 1911, pp. 178, 179, 1912.

² Smithsonian Misc. Coll., vol. 57, 1913, p. 337.

³ Lane, Jour. Geology, vol. 15, 1907, pp. 681, 687.

⁴ See Van Hise and Leith on Lake Superior sandstone: Monograph U. S.

listed by Lane¹ belong to the Lake Superior sandstone formation, the latter is certainly of Upper Cambrian age, but with our present information it is doubtful if the sandstone containing the fossils and the Lake Superior sandstone are to be correlated, unless we consider the fossiliferous beds of marine origin and the Lake Superior sandstone as a river or delta deposit. That the Upper Keweenawan graduates up into the basal beds of the Lake Superior sandstone appears to be capable of demonstration,² but that the latter sandstone is of Cambrian age is not proven. I think, however, in view of all the evidence, we are justified in considering the Upper Keweenawan and Lake Superior sandstone as possible examples of terrestrial deposits laid down in Cambrian time.

The Lake Superior sandstone strongly suggests land deposition, both by its physical characters and by the absence of traces of life. Close search should be made along the Cambrian shore lines in the Cordilleran Cambrian area for a similar formation that may have been interleaved with the marine Cambrian by the shifting of the strand-line from time to time.

Marine Coastal Deposits. While Cambrian sediments to a thickness of many thousands of feet were accumulating in the great Cordilleran basin, there must have been considerable thicknesses accumulating on the Pacific, Atlantic, and Gulf slopes of the continent. Of these, however, there is no known record in the Cordilleran region. On the Atlantic side there are fragments of the Cambrian section in eastern Massachusetts, New Brunswick, Nova Scotia, and Newfoundland, but there is a strong probability that even these marginal occurrences were deposited in basins protected by land barriers from the outer ocean.³ Of the deposits laid down beneath the great

Geol. Surv., vol. 52, 1911, pp. 415-416, 615-616. These authors discuss the possible pre-Cambrian age of the sandstone; also the possibility of the Keweenawan sandstone representing the Lower and Middle Cambrian rocks of other areas in North America.

¹ Jour. Geology, vol. 15, 1907, p. 692.

² Monograph U. S. Geol. Surv., vol. 52, 1911, pp. 415-416, 616.

³ Bull. U. S. Geol. Surv., No. 81, 1891, pp. 367, 368.

oceans and the permanent breeding grounds of the faunas of early Cambrian and late pre-Cambrian time, we have yet not the slightest definite evidence.¹ This subject is further considered under Coastal Deposits (p. 230) as one of the unsolved problems of the Cordilleran Cambrian.

DIASTROPHISM

The most important diastrophic movement within the Cordilleran area in Proterozoic and Cambrian time was the formation and gradual deepening of the great geosyncline extending from the Gulf of California north to the Arctic Ocean. This geosyncline was broader when the Algonkian sediments of the Grand Canyon, Llano, Needle Mountain, Uinta, and Black Hills² series were being deposited than at the beginning of Cambrian time. Indeed, it is highly probable that it extended eastward to central Texas, Colorado, and South Dakota, where a depression connected it across the upper Mississippian region with the Lake Superior depression.

Narrowing of the Cordilleran Sea. Before the Lower Cambrian transgression into the Cordilleran area a diastrophic movement³ began, which resulted in a broad geanticline which raised the areas of the Grand Canyon in Arizona, Needle Mountain in Colorado, Uinta in Utah, the Black Hills of South Dakota, and the present site of the Rocky Mountains, above the horizon of wide sedimentary deposition, and subjected the region affected by the uplift to erosion during Lower and Middle Cambrian time. This uplift narrowed the Cordilleran sea on its eastern side and kept it out of the area captured until the

¹ See pp. 167, 187, and 230, referring to Chamberlin and Salisbury, *Geology*, vol. 3, 1906, p. 529.

² Bull. U. S. Geol. Surv., No. 360, 1909, pp. 45, 46.

³ This movement began some time before the Lower Cambrian transgression, but how long we have no means of determining, as it is not until the beginning of the Upper Cambrian that we find transgressing Cambrian deposits. It also undoubtedly raised the Sierran geanticline west of the Cordilleran area and kept this barrier intact throughout Cambrian time.

Upper Cambrian transgression came. From the distribution of the Algonkian formations enumerated above, there must have been a revival of the broad geanticline of early Proterozoic or late Archæozoic time that initiated the Rocky Mountain line of uplift. The pre-Proterozoic geanticline was largely reduced to base-level before the first Cambrian transgression, and the late Proterozoic uplift resulted in relatively minor stratigraphic disturbance. This is shown by the broad, comparatively low undulations of the Algonkian formations subjected to erosion in Lower and Middle Cambrian time. This late Proterozoic movement on the eastern side of the Cordilleran geosyncline was not as great in the Rocky Mountain area of Canada. This is proven by the Lower Cambrian sea having deposited its sediments over the slightly disturbed Algonkian Bow River Series of Alberta.

Pre-Middle Cambrian Movement. After the narrowing of the Cordilleran geosyncline prior to the Cambrian transgression, the deposition of sediments went on with little if any interruption until toward the close of the Lower Cambrian period, when changes occur in the sedimentation and succession of the faunas which serve to draw a boundary line between the Lower and Middle Cambrian series. These changes are described in notes on the Faunal Record (pp. 202-204). They do not appear to have been the result of any considerable disturbance within the Cordilleran area, but rather the result of a grading up, as it were, of the shallow Cordilleran sea by deposition of sediments and the consequent cutting off of free access from the Pacific both of marine life and waters. The length of this period of interruption must have been considerable, or else the Cordilleran sea fauna persisted until it was killed out, and when connection with the Pacific was resumed a new fauna that had been developing in the Pacific was then introduced into the Cordilleran sea and constituted the Middle Cambrian fauna. The change in the species from the Lower to the Middle Cambrian fauna is very great. Of seventy-seven species of brachiopods in the Lower Cambrian, six are found in the Middle Cambrian. Among the trilobites the disappearance of the Mesonacidæ is

the most marked change. Some of the species of the Conocephalidæ may have continued on into the Middle Cambrian, but the study of this and other crustaceans of the Cambrian time has not yet advanced so that any reliable data are available.

Most of the genera of the Lower Cambrian pass up into the Middle Cambrian, and this leads to the thought that the interruption, though important and of considerable duration, was not of a degree comparable with the unconformity immediately preceding the pre-Cambrian revolution, nor like the great faunal change that came at the close of Cambrian time, although the later diastrophic movement appears to have been relatively insignificant on the western side of the continent.

In the Appalachian geosyncline east of the Adirondack land, a barrier was formed at the close of Lower Cambrian time, either by the grading up of the shallow sea with sediments or by a local upwarping of the sea bed. This barrier, the Green Mountain barrier of Ulrich and Schuchert,¹ continued on through Middle Cambrian time and shut out the Middle Cambrian *Paradoxides* fauna of the Atlantic realm from the Appalachian trough south and east of the Adirondack area, but it may not have fully prevented portions of the Middle Cambrian fauna of the Pacific realm from passing into the Atlantic area. This is shown by the association of the *Dorypyge* and *Paradoxides* faunas at Borgholm, Denmark.² Possibly the *Dorypyge* phase of the fauna was carried from Manchuria along the shore lines of Siberia and Russia into Europe and thus introduced into the western European waters; if that be so, the Green Mountain barrier of Middle Cambrian time was then unbroken and extended far to the south, uniting with Appalachia, which extended across the Atlantic continental shelf. This was probably the case, for the *Olenoides* Middle Cambrian fauna is not known in New England or the Canadian Provinces.

Pre-Upper Cambrian Movement. After the close of Middle Cambrian time, the waters of the Pacific, the Gulf of Mexico,

¹ Bull. N. Y. State Mus., No. 52, 1902, p. 638.

² See Grönwall, Dänmarks Geologiska Undersøgelse, Række 2, No. 13, 1902, pl. 3.

and the Atlantic began to rise and to flood lands that had not known the presence of marine waters since far back in the Proterozoic and may be since Archæozoic time. The Cordilleran geosynclines had been gradually deepening during the Middle Cambrian era, but near its close shallow seas with barriers formed by sediment or local warpings of the surface had cut off free circulation with the Pacific, and the Middle Cambrian fauna, like the Lower Cambrian fauna that preceded it, was gradually killed out. Then came the great invasion and transgression of early Upper Cambrian time, which indicates a greater diastrophic movement affecting both North and South America. The Cordilleran and Appalachian geosynclines were gradually deepened all through Upper Cambrian time. That the first rising of the marine waters was relatively rapid is shown by the presence of a similar grouping and succession of Upper Cambrian subfaunas from central Texas to Wisconsin, a distance of 950 miles (1520 km.). How much, if any, local diastrophic movement took place in the Cordilleran era is unknown, other than that caused by the deepening of the great geosynclines.

Post-Cambrian Movement. The diastrophic movement at the close of the Upper Cambrian appears to have caused very little disturbance in the Cordilleran area, but in the upper Mississippian area the unconformity between the Upper Cambrian Jordan sandstone and the superjacent Mendota limestone and Madison sandstone of the Ozark Series is very marked. The break in the faunal succession between the fauna of the pre-Jordan St. Lawrence formation and the Ozarkian Eminence formation of the post-Cambrian is distinguished by the advent in the Eminence fauna of cephalopods and a great development of gastropods and trilobites of a post-Cambrian type.¹

Résumé. A diastrophic movement of late Proterozoic time narrowed the Cordilleran geosyncline and increased the Rocky Mountain geanticline and probably also the Sierran geanticline.

The dominant diastrophic movement within the Cordilleran area was the gradual deepening of the geosyncline with tem-

¹ See p. 232.

porary cessations of the process between the Lower Cambrian and Middle Cambrian periods and between the Middle Cambrian and Upper Cambrian periods.

At the close of the Lower Cambrian a local diastrophic movement in southwestern Nevada prevented the deposition of sediment during the Middle Cambrian period, and another local movement east of the Adirondack land raised the Green Mountain barrier across the Appalachian geosyncline throughout the Middle Cambrian period.

Near the close of Upper Cambrian time a broadspread movement resulted in the temporary withdrawal of the Cambrian sea from the upper Mississippian area and probably produced the conditions that caused a great change in the character of the faunas, not only in the Cordilleran area, but over the North and South American continents wherever the Upper Cambrian faunas occur.

The Great Invasion of Marine Waters. The physical record of two great invasions of marine waters in Cambrian time is well known. The first invasion began early in Lower Cambrian time and the second when the early Upper Cambrian sea pushed its strand-line from the Pacific far into the interior and distributed the Upper Cambrian fauna from Texas to Wisconsin. In the Cordilleran geosyncline the Lower Cambrian fauna was spread from Nevada a thousand miles (1600 km.) to the north and probably reached the Arctic Ocean, if not already introduced there from the Pacific realm, and in the Appalachian geosyncline that fauna has been found from Alabama to the Gulf of St. Lawrence.

The physical and faunal changes at the close of Lower Cambrian time in the Cordilleran area may have been greatly influenced by the filling up, in part at least, of the basins in the geosyncline by deposits that reached the surface of the sea, or the marine waters may have been gradually withdrawn. This would interrupt the connection with the outer ocean and give the conditions necessary for limited interior basins in which the barren beds of late Lower Cambrian time were deposited.

With the renewed rising of the ocean waters or the deepening

of the Cordilleran geosyncline at the opening of Middle Cambrian time, the various basins were again connected, and with the free circulation of ocean water there was introduced a modified and vigorous fauna which flourished until a repetition of the filling up and stagnating conditions again gradually restricted the fauna at the close of Middle Cambrian time. Those waters, however, at no time spread east of the Cordilleran geosyncline.

When the great continental influx of marine water and life came with the beginning of Upper Cambrian time, the record of Upper Cambrian sedimentation and life was made, not only in the two great geosynclines but over the Mississippian interior. The invasion also left its record in eastern Asia, which leads to the conclusion that it was a movement of the ocean level rather than a movement of the continents or the warping of sections of their surface.¹

The early Cambrian transgression was not a uniform movement of rising waters over all continents, but it was a localized phenomenon which did not involve any considerable upward movement of oceanic waters. The Cordilleran geosyncline deepened and let in the early Lower Cambrian sea before it entered the Appalachian geosyncline. The Cordilleran and Appalachian geosynclines were deepened toward late Lower Cambrian time and this continued throughout Middle Cambrian time.

Local down-warplings depressed the New England and eastern Canadian areas during late Lower Cambrian and Middle Cambrian time, and the same thing occurred *locally* in western and northwestern Europe, Siberia, eastern Asia from Manchuria to Indo-China, southern Asia (southern India), Australia, and the Antarctic continent. With the transgression of the Upper Cambrian waters a world-wide movement of the ocean waters was inaugurated which caused them to overlap, not only the depressed continental areas of Lower and Middle

¹ It is also interesting in this connection to note that this is the period of first known invasion of the South American continent by the Cambrian sea.

Cambrian time, but to enter upon the great central areas of North and South America and probably areas on other continents now imperfectly known, or concealed by later deposits.

If the above view is correct, the cause of the invasion of marine waters in Lower and Middle Cambrian time was the formation of depressed areas by diastrophic movement of limited portions of the continents receiving Cambrian deposits, and it was not until after the close of Middle Cambrian time that a general elevation of oceanic waters submerged large areas on the American continents and continued deposition over the previously submerged areas of Middle Cambrian time on the other continents exclusive of Africa.

Distribution of the Seas near the Close of Upper Cambrian Time. The accompanying map was prepared by Prof. Charles Schuchert for his *Paleogeography of North America*.¹ There has not been any decided addition to our knowledge of the distribution of the late Cambrian seas since the publication of Mr. Schuchert's memoir. I think that in all probability the outlines of nearly all of the seas should be extended, but as long as the outlines are so largely concealed beneath post-Cambrian formations, there would be little gained by indicating them.

In the accompanying theoretic section (Fig. 8) east and west across the North American continent at the close of Cambrian time, the seas are given a more extended distribution than on the map (Plate I, p. 195). This section limits the Cordilleran and Appalachian troughs during Lower and Middle Cambrian time, and gives the Upper Cambrian the wide distribution mentioned in the accompanying text (Fig. 8, p. 196). The theoretic section at the close of Cambrian time crosses the North American continent through California, Nevada, and Utah to the Rocky Mountains, and then eastward across Wyoming, so as to cut through the Black Hills and, near Wisconsin, the uplifts of pre-Cambrian rocks in the northern portion of that state. Continuing eastward it cuts the Adirondack Mountains in New York and the Green Mountains of Vermont.

¹ Bull. Geol. Soc. America, vol. 20, 1910, pl. 52.

Fig. 8. Theoretic section at close of Cambrian time.

UNCONFORMITIES WITHIN THE CAMBRIAN

The unconformities within the Cordilleran Cambrian series of formations have not yet been so traced by areal mapping as to indicate the extent of the area involved by them. We find in the Silver Peak region of western Nevada¹ that the Lower Cambrian Silver Peak group has a great development; the Middle Cambrian is practically absent; and the Upper Cambrian Emigrant formation is comparatively insignificant in its development. There is here full evidence of a great unconformity by erosion of the Lower Cambrian formation and non-deposition of Middle Cambrian sediments, for the missing strata have a thickness of over 5500 feet (1770 m.) in the Eureka district section² 142 miles (227 km.) to the northeast. There is no evidence of unconformity in the position of the strata of the Cambrian of the Big Cottonwood Canyon, Wahsatch Mountains section of Utah. Here about 250 feet³ (76 m.) in thickness of shale represents the 6200 feet (1900 m.) of limestone and shale of the Eureka district Middle and Upper Cambrian section.

Other unconformities by non-deposition of sediments undoubtedly occur, but at present the data are not sufficient to describe them.

BARRIERS

The great land barrier of the Cordilleran area in Cambrian time was the Montana Island now included in the Lewis and Clark ranges of the Rocky Mountains in northern central Montana. As this area is approached from the south the Cambrian strata rise in the slope of the synclinal folds until the basal Flathead sandstones cap the north and south ridges as narrow synclines in which long strips of light gray Middle Cambrian limestones appear like streaks of foam on the crest

¹ Bull. Geol. Soc. America, vol. 20, 1909, pp. 239-243.

² Monograph U. S. Geol. Surv., vol. 8, 1884, p. 284.

³ Bull. U. S. Geol. Surv., No. 81, 1891, pp. 319, 320.

of ocean waves. All Cambrian beds so far as known disappear before reaching Marias Pass, over which the Great Northern Railway crosses the Continental Divide. From Marias Pass to Crownest Pass, Canada, I was unable to discover a trace of any fossiliferous Cambrian formation and, so far as could be determined, the entire mass of strata between the great eastward overthrust fault of the Rockies and the valley of the north fork of the Flathead River is formed of pre-Cambrian Algonkian strata. Far to the north, the Lower Cambrian formations again appear south of the line of Kicking Horse Pass through which the Canadian Pacific Railway crosses the Continental Divide.

This great Montana Island barrier may not have fully closed the passage between the Cordilleran seas north and south of it, for the Lower Cambrian fauna of Nevada is represented by forms that appear to be identical with those from Vermilion Pass west of Banff, Alberta, Canada.¹

The continental land barrier on the west of the Cordilleran trough, between it and the Pacific (Cascadia and Yukonia), appears to have been several hundred miles in width north of Nevada and to have extended north to the Arctic Ocean. To the east of the Cordilleran sea, the great Canadian Shield separated the Cordilleran and Appalachian troughs until well toward the close of Middle Cambrian time, when the southern seas invaded the broad interior and served to distribute the Upper Cambrian subfaunas both in the western and eastern geosynclinal troughs and also widely over the interior as far north as Wisconsin and Minnesota.

Of the presence of faunal barriers resulting from cold and warm currents, or from shallow and deep seas, we have little evidence, because of the limited data available for determining the detailed geographic distribution of the faunas. We might suppose that the Arctic waters would have different faunas due to their high latitudes, but as yet there is little evidence for drawing conclusions along these lines.

¹ *Wanneria ? gracilis*, Smithsonian Misc. Coll., vol. 53, 1910, p. 298.

CLIMATE

In the absence of all traces of land plants and terrestrial animal life in Cambrian rocks the criteria for the determination of climatic conditions are limited to the terrigenous sediments and the character of the marine life. In the subjacent Algonkian rocks of the Grand Canyon and Belt series the presence of great thicknesses of red sandstones and shales suggests an arid and possibly a cold climate. Opposed to this are the great limestone beds which indicate a fair supply of water to form inland seas whose temperature was sufficiently high to permit of an abundant growth of algæ of a simple type that served as the agency for the precipitation of vast quantities of calcareous matter. The only characterizing, possibly marine, fossil of this period was a crustacean, *Beltina danai*,¹ which, like the Atlantic coast lobster (*Homarus americanus*), might have lived in quite cold water, or adapted itself to warmer, impure water.

With the incursion of the marine Lower Cambrian sea, warm conditions are indicated by the presence of calcareous beds containing brachiopods and trilobites associated with the coral-like Archæocyathinæ of world-wide distribution, a type which like modern corals probably requires a temperature above 68°.² There is also an almost total absence of red sandstones and shales throughout the Cambrian series of strata.

In China a cold period near the base of the Cambrian section is suggested by the presence of glacial deposits at or below the base of the Man-t'o formation.³ In the Cordilleran region a cold period appears to be indicated by the barren arenaceous limestones between the highly fossiliferous upper *Olenellus* beds of the Lower Cambrian and the fossiliferous limestones near the base of the Middle Cambrian. The great change of the faunas at this horizon is very marked, not only in the Cordilleran area but also in the Appalachian and St. Lawrence province.

¹ Bull. Geol. Soc. America, vol. 10, 1899, p. 239, pls. 25, 26, 27.

² Dana, *Manual of Geology*, 4th ed., 1895, pp. 46-47.

³ Willis, *Research in China*, vol. 2, 1907, p. 39.

The presence of reefs of the Archæocyathinæ in the Lower Cambrian strata of the southern Cordilleran region indicates tropical temperature for the sea in that area. To the north, in the Rocky Mountains of British Columbia and Alberta, strata of the same general stratigraphic position have yielded *Olenellus* but as yet no traces of the Archæocyathinæ. This may mean that the warm climate did not extend so far north in the Cordilleran region. In Asia the Archæocyathinæ occur in Siberia; they occur also to the south in Australia and on the Antarctic continent;¹ and appear in the form of extensive reefs in the Lower Cambrian of Labrador. Archæocyathinæ of Middle Cambrian age appear on the island of Sardinia, and in China they are found low in the Middle Cambrian.² The abundant and varied marine faunas during Middle Cambrian time point to temperate waters and climate throughout the Cordilleran province from Nevada to the Arctic Ocean and the same is true of the late Upper Cambrian, although the latter epoch was one of shifting strand-lines and changing conditions of sedimentation.

Résumé. In Lower Cambrian time the climate was warm in the Cordilleran area, changing toward the close of that epoch to a cold climate which resulted in the deposition of barren arenaceous rocks in the Cordilleran trough.

In Middle Cambrian time, the climate was temperate and equable from the Gulf of Mexico to the Arctic Ocean. The marine waters were favorable to a large and varied marine life accustomed to a temperature that was nearly uniform, with a free circulation of waters well supplied with calcareous matter in solution. Toward the close of this period there may have been climatic changes restricting and altering the development of the fauna, but the evidence for or against such changes is too indefinite to warrant any conclusion of value.

In Upper Cambrian time a more varied climate may have prevailed. Perhaps also there was irregular restriction of the Cordilleran sea, bringing about more varied and limited

¹ Griffith Taylor. Mt. Darwin, 86° south.

² Research in China, vol. 3, 1913, p. 47.

sedimentation, while the marine life was confined mainly to localities more favorable to the presence and growth of a limited fauna.

CLOSE OF CAMBRIAN

The Upper Cambrian formations are usually fossiliferous limestones or calcareous shales passing without apparent stratigraphic break or marked unconformity into the superjacent lower Ozarkian formations. To the south, in Nevada¹ and Utah,² the upper beds of the Cambrian are mainly thick-bedded, siliceous, and coarse limestones with few fossils. In Idaho,³ however, a limestone with siliceous nodules contains a varied fauna, although in the section along the Canadian Pacific Railway at Kicking Horse Pass⁴ and again north of Yellowhead Pass, the beds carry very few fossils except in the conformably superjacent layers of the Ordovician⁵ limestone.

The study of existing data shows, however, that the extent of the changes of the strand-line and the resultant character of the sedimentation have not been worked out for the closing epochs of Cambrian time in the Cordilleran area. Schuchert states that a pronounced withdrawal of the interior Mississippian sea occurred in late Cambrian time and was followed by the Ozarkian transgression.⁶ While as yet we have no faunal or physical data by which to correlate the geologic history of the Cordilleran and Mississippian areas toward the close of the Cambrian, there is evidence of changing conditions of the sea and in sedimentation and also in the faunas which present unsolved problems of the Cambrian in the Cordilleran Province. One of these problems will be to determine the unconformities

¹ Highland Range: Bull. U. S. Geol. Surv., No. 81, 1891, p. 318.

² Eureka District: Monograph U. S. Geol. Surv., vol. 8, 1884, p. 284; Smithsonian Misc. Coll., vol. 53, 1908, p. 173.

³ *Idem*, p. 191.

⁴ Summary Rept. Geol. Surv., Canada, for 1910, 1911, p. 137; Smithsonian Misc. Coll., vol. 57, 1913, pp. 229-231.

⁵ *Idem*, p. 337.

⁶ Bull. Geol. Soc. America, vol. 20, 1910, p. 484.

by non-deposition¹ of formations strongly developed elsewhere on the continent.

Faunal Changes. The only large portion of the Cambrian fauna thoroughly studied is the Brachiopoda. This research shows that nearly all of the Cambrian species had disappeared with the close of Cambrian time and that but eleven of the forty-four genera in the Cambrian pass into the lower Ordovician, while of these eleven genera only two extend very far above the Cambrian.² Among the trilobites a few genera pass from the Cambrian into the Ordovician, but I do not anticipate from my studies in hand that there will be found a very much larger percentage than among the brachiopods.

THE FAUNAL RECORD

Pre-Cambrian Fauna. The faunal record and character of the Algonkian rocks included in the Grand Canyon, Llano, and Belt series of the Cordilleran region, and in formations correlated with them,³ prove that the marine waters of the extra-continental seas very rarely had access to the epicontinental seas and lakes in Algonkian time. Such connection appears to have been established in mid-Beltian time when at least a hydroid, a crustacean, and a few annelids penetrated into and became adapted to the conditions of the Montana-Alberta sea, and more or less similar forms to the Arizona sea.⁴ Other and different forms may have lived in these and other interior bodies of water, but as yet we have no knowledge of them. The fauna of the Lower Huronian of Steeprock Lake, western

¹ The importance of this type of unconformity in otherwise conformable successions of formations is such that intensive studies of the succession of faunas must be made over wide areas before the palæogeographer and stratigraphic geologist can feel at all assured that he has the correct history of any given epoch or period of geologic time. In a great area such as the Cambrian Cordilleran geosyncline, years of effort by many field investigators will be required to collect the necessary data.

² Monograph U. S. Geol. Surv., vol. 51, 1912, pp. 315, 316.

³ Bull. U. S. Geol. Surv., No. 360, 1909, pp. 42-46.

⁴ Bull. Geol. Soc. America, vol. 10, 1899, pp. 199-244.

Ontario, was presumably derived from a marine fauna and possibly lived under brackish-water conditions. The principal species of the Steeprock Lake pre-Cambrian fauna, *Atikokania lawsoni*, is probably a spongoid of a rather advanced stage of development, although it suggests the Archæocyathinæ. We are here given a glimpse of a fauna that existed near the base of the (Algonkian) Proterozoic and which must have had its beginnings in Archæozoic time. It further indicates the presence of a sufficient supply of calcareous matter in this inland water to form its skeleton and also a massive limestone deposit in which its remains now occur. This also implies calcareous beds in the great Lipalian deposits of the marine waters on the borders of the continents.

The vertical range of the small Beltian (Algonkian) fauna is limited to a few hundred feet of strata in the Cordilleran area, a fact which tends to demonstrate that the environment was not favorable to its development and survival for any considerable period.

The most satisfactory explanation of the absence of a characteristic marine life in Algonkian deposits is the probability that all the known rocks of Algonkian time are of non-marine origin¹ and hence could not have embedded a marine fauna.

¹ The presence of dolomitic limestones of great extent and thickness in the Belt series has been regarded as positive proof of the marine origin of the dolomitic beds. As the thought that the entire Algonkian series of western America were of epicontinental origin came to me, I began to doubt the marine origin of the dolomites. Fifteen years ago when studying a series of specimens of the algoid-like fossil *Cryptozoon** as it occurs in both the Grand Canyon and Belt series of formations the question arose as to its position in systematic classification. *Cryptozoon* had been referred to the Hydrozoa on account of its resemblance to some forms of *Stromatopora*; to the Spongïæ as a possible calcareous sponge, and I compared it with specimens of calcareous algæ. The subject was laid aside until the problem of the origin of the pre-Cambrian dolomitic limestones recently came up for consideration. It then occurred to me to seek further information from the geologists who have been studying the origin of fresh-water calcareous deposits and the palæobotanists acquainted with the calcareous

* Bull. Geol. Soc. America, vol. 10, 1899, p. 233, pl. 23.

The existence of a large and varied marine life (Lipalian) in the extra-continental pre-Cambrian seas is inferred from the presence of a highly organized and varied fauna in Lower Cambrian time, in both the Cordilleran and Appalachian geosynclines. The world-wide distribution of the Lower Cambrian fauna also indicates the great antiquity of the fauna from which it was derived.

THE COMING OF THE CAMBRIAN FAUNA

Just when the Cambrian fauna was differentiated from some preëxisting biota of marine organisms we do not know, nor do we know very much except inferentially of the extent of the fauna that accompanied the first incursion of the marine waters of the Pacific Ocean into the Cordilleran area in early Cambrian time. At the best it would have been only a small portion of the entire Pacific realm, and the California assemblage probably also represented but a small part of the fauna that existed along the shore lines of the continents and in the non-continental seas of Algonkian time. The extent of the fauna will not be known until fossiliferous marine deposits of Lipalian time are discovered.

The presence of a much larger fauna in the early Cordilleran Cambrian sea than has been found so far in the oldest fossil-bearing Cambrian beds is rendered highly probable by the occurrence of large and varied faunas in Middle Cambrian time¹ of such a character that similar faunas could not presumably have left evidence of their existence in or on the known sedi-

algæ as active agents in secreting and depositing the calcium carbonate. The result of these inquiries has led me to prepare an article on the subject which has been published under the title of *Pre-Cambrian Algonkian algal flora* (Smithsonian Misc. Coll., vol. 64, No. 2, 1914). The conclusion is that the origin of the limestones is largely owing to the action of lime-secreting algæ and that precipitation of calcium carbonate from a saturated solution is of very rare occurrence and not an important agent of deposition in geologic time.

¹ See pp. 210-213, 227.

ments of Lower Cambrian time. The discovery of a bed of fine, unaltered, siliceous, fossiliferous, dark or black shale might at once change the whole aspect of the earliest known Cambrian fauna and give some conception of its richness in annelids, delicate crustaceans, and other animals with very thin external coverings. Such biotas undoubtedly lived all through Cambrian time.

Lower Cambrian or Waucobian Fauna. This fauna in Nevada ranges through more than 5000 feet (1524 m.) of sandstone, shales, and limestones. Its earliest faunule at Barrel Spring, Nevada,¹ has but two trilobites, *Nevadia weeksi* and *Holmia rowei*. At an horizon about 4000 feet (1220 m.) higher (No. 3 of this section), the following larger and much more varied fauna occurs² in a green calcareous shale (arenaceous at top, 390 feet thick) :

Archæocyathus ?

Kutorgina cingulata (Billings)

Kutorgina perugata Walcott

Siphonotreta ? *dubia* Walcott

Acrotreta claytoni Walcott

Acrothele spurri Walcott ?

Swantonina weeksi Walcott

Swantonina ? sp.

Helcionella cf. *elongata* (Walcott)

Helcionella cf. *rugosa* (Hall)

Salterella

Ptychoparia sp.

Wanneria ? *gracilis* Walcott

Olenellus ? *argenteus* Walcott

Olenellus gilberti Meek

East of Waucoba Springs, California, the fauna in Number 3d

¹ Smithsonian Misc. Coll., vol. 53, 1908, p. 189.

² *Idem.* The changes in identifications and names of the trilobites are explained in the paper on *Olenellus and other genera of the Mesonacidae*: Smithsonian Misc. Coll., vol. 53, 1910, pp. 351-371.

of the section,¹ which occurs at about the same horizon as the above fauna, includes the following:

Archæocyathus

Ethmophyllum gracile Meek

Mickwitzia occidens Walcott

Obolella vermilionensis Walcott

Wanneria ? *gracilis* Walcott

The two species, *Obolella vermilionensis* Walcott and *Wanneria* ? *gracilis* Walcott, also occur together at Vermilion Pass, Alberta, Canada, where they are about 2000 feet (610 m.) below the summit of the Lower Cambrian. In Nevada these species are nearly 4000 feet (1220 m.) above the zone of *Nevadia weeksi* if the sections as published are correct.² There still remains above the zone of *Wanneria gracilis* in Nevada a thickness of 2000 feet (610 m.) or more of strata which are referred to the Lower Cambrian. Toward the summit of this upper series of beds the *Olenellus thompsoni* type of the Mesonacidæ³ appears along with the genera *Wanneria* and *Callavia*.

Of the genera of the Mesonacidæ mentioned above, *Nevadia* is the most primitive form and it is associated with *Holmia rowei*, a more advanced type which also occurs higher in the section. The faunal zones of the Lower Cambrian which may be arbitrarily drawn on the basis of the Mesonacidæ are:⁴

D = *Olenellus*, or upper zone.

C = *Callavia* zone.

B = *Elliptocephala* zone.

A = *Nevadia*, or lower zone.

In the *Nevadia* zone (A) we find the genus *Nevadia* (Pl. 1) with one species, also a species that is referred to *Holmia*, *H. rowei* (Pl. 1).

¹ Smithsonian Misc. Coll., vol. 53, 1908, p. 187.

² *Idem*, pp. 185-189.

³ *Idem*, vol. 57, 1913, p. 229.

⁴ *Idem*, vol. 53, 1910, p. 250.

Plate 2. Lower Cambrian Trilobites

In zone "B," which is above zone "A," *Elliptocephala* occurs, also doubtfully *Wanneria* and *Olenellus*.

In zone "C," which is high up in the Lower Cambrian but not the uppermost zone, *Callavia* is represented by five species, *Mesonacis* by two, *Holmia* by two, *Olenellus* by one, and two are doubtfully referred to this horizon.

In zone "D," *Olenellus* is represented by twelve species, *Pædeumias* by one, *Wanneria* by three, *Callavia* by three, *Mesonacis* by one, and one *Holmia* may occur here.

The characters of the Mesonacidae referred to are shown by Figure 1.

DESCRIPTION OF PLATE 2

- Fig. 1. *Nevadia weeksi* (Walcott)
2. *Mesonacis vermontana* (Hall)
3. *Elliptocephala asaphoides* Emmons
4. *Callavia bröggeri* (Walcott)
5. *Holmia kjerulfi* (Linnarsson)
6. *Wanneria walcottanus* (Wanner)
7. *Pædeumias transitans* Walcott
8. *Pædeumias transitans* Walcott

Enlargement of the posterior portion of fig. 7 showing the rudimentary segments and pygidium beneath the telson-like segment.

9. *Olenellus thompsoni* Hall

The above series of figures is reproduced in order to illustrate the variation in the principal genera of the Mesonacidae, also in order that the student may at a glance note the changes from the most primitive form *Nevadia* (Fig. 1) through one line of descent, as represented by Figures 2, 3, and 7, to *Olenellus* (Fig. 9).

On another line of descent the figures serve to illustrate through Figures 1, 3, 4, 5, and 6 the probable line of descent from *Nevadia* (Fig. 1) to *Holmia* (Fig. 5) and on to *Paradoxides*.

The uppermost Lower Cambrian or *Olenellus* fauna of zone D has a variety of genera and species which are distributed in

nearly all parts of the Cordilleran area where beds of this epoch occur. The fauna at Pioche in eastern Nevada includes:¹

Eocystites ? ?

Obolus (*Westonia*) *ella* (Hall and Whitfield)

Micromitra (*Iphidella*) *pannula* (White)

Acrothele subsidua White

Acrotreta primæva Walcott

Billingsella highlandensis Walcott

Olenellus gilberti Meek

Zacanthoides levis Walcott

Crepicephalus augusta Walcott

Crepicephalus liliana Walcott

Oryctocephalus primus Walcott

At a locality below Mumm Peak, Alberta, Canada, the fauna from the siliceous shale is unusually fine and includes in a subfauna about the same horizon:²

Mickwitzia muralensis Walcott

Lingulella chapa Walcott

Lingulella hitka Walcott

Obolella nuda Walcott

Obolella cf. *chromatica* Billings

Wanneria occidentis Walcott

Callavia eucharis Walcott

Callavia perfecta Walcott

Olenellus truemani Walcott

These lists of species from widely separated localities, but not synchronous except in a general way, serve to outline the character of the subfaunas which are more fully described and illustrated in the Tenth Annual Report of the United States Geological Survey.³

¹ Tenth Ann. Rept. U. S. Geol. Surv., 1891, p. 571. Generic names of brachiopods revised.

² Smithsonian Misc. Coll., vol. 57, 1913, pp. 309-326.

³ At this time (1891) 59 genera, 141 species, and 11 varieties of fossils were recorded. To these a number of genera and species have since been added.

If we compare the fauna of the Lower Cambrian *Olenellus* zone with that of the lower Ozarkian group, the superiority of the latter in number of species, genera, and families is at once apparent. If the comparison be restricted to class characters, the disparity between the two is very much reduced and it is made evident, with one or two exceptions—the most notable of which are the corals, lamellibranchs, and cephalopods—that the evolution of life between the epoch of the *Olenellus* fauna and the epoch of the lower Ozarkian fauna has been in the direction of differentiating the class types that existed in the earlier fauna. The classes represented by non-testaceous species may or may not have existed.

The *Olenellus* fauna adds a little more to our knowledge of the rate of convergence backward in geologic time of the lines representing the evolution of invertebrate animal life, and at the same time proves that an immense time interval elapsed between the beginnings of life and the epoch represented by the *Olenellus* fauna.

Boundary between the Lower and Middle Cambrian. With the disappearance of the genus *Olenellus* in the stratified rocks there is often a change in their character. Massive-bedded arenaceous and magnesian limestones in which there are few traces of life usually appear in the sections of the Cordilleran area, and there are indications of a possible lowering of temperature. (See Climate, p. 199.)

In southwestern Nevada a great unconformity is shown by the absence of Middle Cambrian formations, and in the Wahsatch Mountains section of Utah, which was deposited near the eastern border of the Cordilleran sea, there are only a few beds of the *Olenellus* zone¹ and one thin belt of basal Middle Cambrian, the remaining Middle and the Upper Cambrian formations and faunas being absent. In central Nevada 3000 feet (815 m.) of the Eldorado limestone of the Eureka District² represents the Middle Cambrian, but there is no known transition from the

¹ Bull. U. S. Geol. Surv., No. 81, 1891, p. 319.

² Monograph U. S. Geol. Surv., vol. 8, 1884, p. 284; Smithsonian Misc. Coll., vol. 53, 1908, p. 184.

Olenellus to the Middle Cambrian fauna although this is one of the localities where the lithologic differences between the Lower and Middle Cambrian are less marked than elsewhere.

The *Olenellus* zone in British Columbia and Alberta is succeeded by massive, coarse limestones in which no traces of fossils have been found for a long distance upward to the base of the formations referred to the Middle Cambrian fauna.¹

Middle Cambrian Fauna. After the passing of the Lower Cambrian *Olenellus* fauna and the interval following, which is represented by barren arenaceous and calcareous strata, the Middle Cambrian fauna appears in great variety and abundance. There is every evidence that a decided change had taken place and the relatively sparse fauna of late *Olenellus* time had been replaced by a strong and vigorous stock from some source outside of the Cordilleran area. Both the rocks and the faunas point to clearer, warmer, and more quiet seas with the influx of a group of genera and species which evidently were developed in some more favorable area existing within the Cordilleran sea.

The Blacksmith Fork section of northern Utah and southern Idaho in stratum 1b of the Langston formation contains the following Middle Cambrian fauna near Malade, Idaho, in a bluish-gray limestone:²

Micromitra haydeni Walcott

Micromitra (Iphidella) pannula (White)

Micromitra (Iphidella) pannula ophirensis Walcott

Lingulella desiderata (Walcott)

Lingulella helena (Walcott)

Lingulella isse (Walcott)

Acrotreta idahoensis sulcata Walcott

Acrotreta pyxidicula White

Acrotreta ?

Acrothele artemis Walcott

Acrothele subsidua (White)

¹ Smithsonian Misc. Coll., vol. 53, 1908, p. 212; also *idem*, vol. 57, 1913, p. 338.

² *Idem*, vol. 53, 1908, pp. 198, 199.

Acrothele subsidua var.
Acrothyra minor Walcott
Billingsella coloradoensis (Shumard)
Hyolithes
Orthotheca
Helcionella
Platyceras
Agnostus
Eodiscus
Solenopleura
Ptychoparia (two species)
Oryctocephalus
Dorypyge (two species)
Neolenus (two species)
Asaphiscus
Ogygopsis ?

This fauna is separated from the Lower Cambrian sandstone by several hundred feet of dark arenaceous limestone, passing below into calcareous sandstone.

At Kicking Horse Pass in the Canadian Rockies, 400 miles (640 km.) north of the Idaho locality, there are nearly 1600 feet (484 m.) of arenaceous limestone between the *Olenellus* zone and the first Middle Cambrian fauna which includes Number 2*d* of the Stephen formation:¹

Cruziana
Micromitra (*Iphidella*) *pannula* (White)
Obolus (*Westonia*) *ella* (Hall and Whitfield)
Hyolithes
Leperditia
Ptychoparia
Bathyriscus

At an horizon from 200 to 300 feet (60 to 90 m.) above 2*d*, from 3.5 feet (1 m.) of shale in a thick bed of siliceous shale I have taken over ninety genera of invertebrate fossils. This is

¹ Smithsonian Misc. Coll., vol. 53, 1908, p. 211.

the most wonderful Cambrian fauna known and it is called the Burgess shale assemblage. It includes sponges, annelids, medusæ, holothurians, cystids, brachiopods, pteropods, and a large variety of crustaceans,¹ which proves that the marine waters swarmed with a highly developed animal life. A large fauna also occurs at this horizon in the Spence shale of southern Idaho.²

The Stephen formation fauna as represented in the *Ogygopsis* shale³ includes the following species:

- Hyolithellus annulatus* (Matthew)
- Hyolithellus flagellum* (Matthew)
- Orthotheca corrugata* Matthew
- Orthotheca major* Walcott
- Hyolithes carinatus* Matthew
- Hyolithes* sp.
- Helcionella wheeleri* (Walcott)
- Platyceras bellianus* Walcott
- Platyceras romingeri* Walcott
- Acrotreta depressa* (Walcott)
- Micromitra* (*Iphidella*) *pannula* (White)
- Obolus mcconnelli* (Walcott)
- Nisusia alberta* Walcott
- Philhedra columbiana* (Walcott)
- Scenella varians* Walcott
- Anomalocaris* ?? *acutangula* Walcott
- Anomalocaris canadensis* Whiteaves
- Anomalocaris* ? *whiteavesi* Walcott
- Agnostus montis* Matthew
- Dorypyge* (*Kootenia*) *dawsoni* (Walcott)
- Bathyriscus ornatus* Walcott
- Bathyriscus pupa* Matthew
- Bathyriscus rotundatus* (Rominger)

¹ For partial account of this fauna see Smithsonian Misc. Coll., vol. 57, 1911, 1912.

² Smithsonian Misc. Coll., vol. 53, 1908, pp. 197-198.

³ *Idem*, pp. 210, 211.

Karlia stephenensis Walcott
Neolenus serratus (Rominger)
Ogygopsis klotzi (Rominger)
Oryctocephalus reynoldsi Reed
Burlingia hectori Walcott
Ptychoparia cordilleræ (Rominger)
Ptychoparia palliseri Walcott
Zacanthoides spinosus (Walcott)

The Middle Cambrian fauna gradually diminishes in variety and abundance above the horizon of the Spence and Stephen formations, and each succeeding series of beds contains fewer species until finally all of the typical Middle Cambrian forms have disappeared.

Boundary between Middle and Upper Cambrian. The Middle Cambrian is absent in the most southwesterly outcrop of Cambrian strata in Nevada,¹ where in the Silver Peak Mountains the Upper Cambrian shaly beds lie unconformably on the Lower Cambrian. In the House Range section of western Utah there are 335 feet (102 m.) of arenaceous and cherty limestones at the base of the Orr formation of the Upper Cambrian;² and in the Eureka District section of Nevada³ the lower Secret Canyon argillaceous barren shales appear from the faunas below and above them to be in a corresponding horizon.⁴ To the north, in northern Utah, the arenaceous limestones of the Nounan formation at the summit of the Middle Cambrian are over 1000 feet (304 m.) in thickness and show only a few traces of annelid borings and fossils in the lower portion.⁵ Still farther north, on the Continental Divide at Kicking Horse Pass, Canada, the siliceous and arenaceous limestones, nearly 900 feet (274 m.)

¹ Bull. Geol. Soc. America, vol. 20, 1909, p. 242.

² Smithsonian Misc. Coll., vol. 53, 1908, p. 177.

³ Monograph U. S. Geol. Surv., vol. 20, 1892, p. 44.

⁴ *Idem*, vol. 8, 1884, p. 284. There is confusion in the lists of species from this section that will have to be revised before a clear understanding of the succession in the fauna of the central portion of the Cambrian is determined.

⁵ Smithsonian Misc. Coll., vol. 53, 1908, p. 193.

thick, of the Middle Cambrian Eldon formation, have afforded only a few traces of fossils and it is highly probable that much of the overlying Bosworth formation is a fresh-water deposit.¹ The Robson Peak District section, 200 miles (322 km.) north of the Kicking Horse Pass, also presents similar conditions at the close of the Middle and beginning of the Upper Cambrian.²

The few examples here given serve to demonstrate that there were extensive emerging agencies at work toward the close of Middle Cambrian time which influenced the character of the sediments and also the marine life. Apparently they were of the same general character as those which brought about the depositions of the barren beds of late Lower Cambrian time.³

Upper Cambrian Fauna. In the opening epoch of the Upper Cambrian there was an increase in the variety and abundance of marine invertebrates due to more favorable conditions of environment and sedimentation, and probably prior to the influx of a fresh and vigorous fauna from the Pacific Ocean.

Eastern Nevada. In the Highland Range of eastern Nevada,⁴ the fauna in the upper bluish-black limestone (23 of section) includes:

Owenella antiquata (Whitfield)

Pleurotomaria 3 undt. spp.

Hyolithes attenuatus Walcott

Hyolithes curvatus Walcott

Hyolithes ? corrugatus Walcott

Saukia pepinensis (Owen)

Dikelocephalus cf. *minnesotensis* Owen

Ptychoparia (*Euloma*?) *dissimilis* Walcott

Arctusina ?? *americana* Walcott

Illænurus sp.

Central Nevada. The Eureka District, Nevada, Dunderberg⁵ shale of the Upper Cambrian afforded a relatively large fauna

¹ Smithsonian Misc. Coll., vol. 53, 1908, p. 208.

² *Idem*, vol. 57, 1913, p. 337.

³ See pp. 199, 200 and 210 for further remarks on this subject.

⁴ Bull. U. S. Geol. Surv., No. 81, 1891, p. 318.

⁵ Smithsonian Misc. Coll., vol. 53, 1908, p. 184.

marked by the presence of species of trilobites not found lower in the Cambrian. This fauna includes :

- Micromitra sculptilis* (Meek)
- Obolus anceps* Walcott
- Obolus discoideus* (Hall and Whitfield)
- Obolus mæra* (Hall and Whitfield)
- Obolus nundina* Walcott
- Obolus* (*Westonia*) *iphis* Walcott
- Lingulella desiderata* (Walcott)
- Lingulella manticula* (White)
- Lingulella punctata* (Walcott)
- Linnarssonella minuta* (Hall and Whitfield)
- Acrotreta attenuata* Meek
- Acrotreta idahoensis* Walcott
- Acrotreta idahoensis alta* Walcott
- Acrotreta spinosa* Walcott
- Acrotreta* sp.
- Hyalithes primordialis* Hall?
- Agnostus communis* Hall and Whitfield
- Agnostus bidens* Meek
- Agnostus neon* Hall and Whitfield
- Agnostus prolongus* Hall and Whitfield
- Agnostus tumidosus* Hall and Whitfield
- Proampyx nasutus* Walcott
- Lisania angustifrons* Walcott
- Osceolia osceola* (Hall)
- Euloma affinis* Walcott
- Euloma similis* Walcott
- Anomocarella oweni* (Meek and Hayden)
- Ptychoparia haguei* (Hall and Whitfield)
- Ptychoparia granulosa* (Hall and Whitfield)
- Ptychoparia unisulcata* Hall and Whitfield
- Pagodia breviceps* Walcott
- Arethusina* ?? *americana* Walcott
- Ptychaspis minuta* Walcott

At the base of the Hamburg limestone, 1200 to 1500 feet

(365 to 457 m.) below the Dunderberg shale, a fauna occurs which is essentially Upper Cambrian in its aspect. It includes among others the following genera and species:

- Micromitra sculptilis* (Meek)
- Micromitra (Paterina) crenistria* Walcott
- Obolus discoideus* Hall and Whitfield
- Obolus mæra* Hall and Whitfield
- Obolus mcconnelli* Walcott
- Obolus nundina* Walcott
- Obolus (Acritis) rugatus* Walcott
- Lingulella clarkei* Walcott
- Lingulella desiderata* Walcott
- Lingulella punctata* Walcott
- Acrothele dichotoma* Walcott
- Acrotreta idahoensis alta* Walcott
- Acrotreta microscopica* (Shumard)
- Protospongia fenestrata* Salter
- Hyolithes primordialis* Hall
- Agnostus bidens* Meek
- Agnostus communis* Hall and Whitfield
- Agnostus neon* Hall and Whitfield
- Agnostus seclusus* Walcott
- Agnostus tumidosus* Hall and Whitfield
- Ptychoparia anytus* (Hall and Whitfield)
- Ptychoparia haguei* (Hall and Whitfield)
- Ptychoparia laviceps* Walcott
- Ptychoparia ? linnarssoni* Walcott
- Ptychoparia richmondensis* Walcott
- Ptychoparia unisulcata* (Hall and Whitfield)
- Proampyx pernasutus* Walcott
- Chariocephalus tumifrons* Hall and Whitfield
- Ogygia ? problematica* Walcott

The next fauna above that of the Dunderberg shale is in the base of the Pogonip limestone and is similar to that of the shale. It includes:

Obolus mæra Hall and Whitfield
Obolus (*Westonia*) sp. undt.
Lingulella manticula (White)
Lingulella pogonipensis Walcott
Acrotreta ?? *cancellata* Walcott
Acrotreta curvata Walcott
Acrotreta idahoensis alta Walcott
Eoorthis hamburgensis Walcott
Agnostus communis Hall and Whitfield
Agnostus bidens Meek
Agnostus neon Hall and Whitfield
Euloma affinis Walcott
Ptychoparia oweni Walcott
Ptychoparia ? *granulosa* (Hall and Whitfield)
Ptychoparia haguei (Hall and Whitfield)
Ptychoparia unisulcata (Hall and Whitfield)
Arethusina ?? *americana* Walcott

Northern Utah and Southern Idaho. The fauna of the Upper Cambrian St. Charles formation of northern Utah¹ is not unlike that of Nevada. It includes from near the summit of the formation :

Fauna (25 feet below the top) :

Lingulella manticula (White)
Eoorthis coloradoensis (Meek)
Syntrophia nundina Walcott
Dikelocephalus

Fauna (105 to 125 feet below the top) :

Schizambon typicalis Walcott
Eoorthis coloradoensis (Meek)
Eoorthis newberryi Walcott
Syntrophia nundina Walcott
Solenopleura
Menocephalus
Illænurus

¹ Smithsonian Misc. Coll., vol. 53, 1908, pp. 191, 192.

Fauna (20 to 30 feet above base) :

Lingulella (*Lingulepis*) *acuminata* (Conrad)

Eoorthis coloradoensis (Meek)

Eoorthis newberryi Walcott

Agnostus

Solenopleura

Menocephalus

Asaphus ?

A considerable fauna also occurs deeper down in the St. Charles formation, which has a total thickness of 1227 feet (375 m.).

Western Canada. The Upper Cambrian fauna of the Kicking Horse Pass section of Canada¹ is limited to a few species, and in the Robson Peak section I found only fragments of small trilobites, while in the passage beds just above in the Upper Cambrian Lynx formation the remains of a considerable fauna occur.²

Comparison with Upper Cambrian of Interior or Mississippian Area. The study of the Cambrian faunas of central Texas, Oklahoma, Wisconsin, and Minnesota in connection with the rocks containing them proves the absence of Lower and Middle Cambrian formations and faunas and the presence of a rather large Upper Cambrian fauna which has a wide geographic distribution³ and a stratigraphic range through about 1000 feet (305 m.) of sandstone, limestones, and shales. In Texas and Oklahoma there does not appear to be a marked physical boundary between the Cambrian and the Ordovician except by

¹ Smithsonian Misc. Coll., vol. 53, 1908, pp. 204, 205.

² *Idem*, vol. 57, 1913, p. 336.

³ Bull. U. S. Geol. Surv., No. 81, 1891, p. 235 for Texas; pp. 222-228 for Wisconsin, Iowa, and Minnesota.

Geol. Atlas United States, U. S. Geol. Surv., Tishomingo folio (No. 98), 1903, Text, p. 3.

Since my report of 1891 I have made large collections of fossils from the Middle Cambrian rocks of Idaho and British Columbia, and concluded both from stratigraphic and faunal reasons that there are no typical Middle Cambrian species in the Mississippian area and that so far as known the Cambrian transgression came in early Upper Cambrian time.

non-deposition of sediments, but in the Missouri and Wisconsin areas a distinct unconformity has been reported by Ulrich. It is interesting to note that in both Texas and Oklahoma barren limestone strata occur between the upper horizon of Cambrian fossils and the lowest reported horizon of Ordovician fossils.

There are a few species common to the Cordilleran and Mississippian Upper Cambrian formations which serve to prove that a connection existed between the seas in which the two series of sediments were deposited, or that there was a common source from which the faunas of the two areas were derived.

Croixian Formations and Faunas. It has been evident for several years that the various Cambrian formations of the upper Mississippi Valley that had been referred first to the Potsdam and then to the St. Croix sandstones needed revision in relation to their stratigraphic position and succession.

The original classification of Owen (1852) was superseded by the classification of the Minnesota Survey for the Minnesota sections, and for Wisconsin by the classification of the Geological Survey of Wisconsin.

The present provisional classification of the Upper Cambrian formations in the upper Mississippi Valley is as follows:¹

¹ Smithsonian Misc. Coll., vol. 57, 1914, p. 354.

Formations		Lithologic Characters
Canadian	Shakopee 60'	Dolomite.
Ozarkian	Oneota 110'	Dolomite.
	Madison 40'	Magnesian and calcareous sandstone.
	Mendota	Dolomite.
	Jordan (Winchell 1874) 60-80'	Heavy-bedded, soft, rather coarse-grained, yellowish sandstone.
Upper Cambrian (Croixian)	St. Lawrence (Winchell 1874) 120'	Soft, fine-grained brown, red, green or ash-colored sandstone often dolomitic near top. Yellow and ash-colored argillaceous-calcareous, thin-bedded rock near middle, and green sands interbedded with yellow sandstones in lower third.
	Franconia (Berkey 1898) 85'	A series of thin and thick-bedded, usually soft sandstones with much green material throughout or only in portions. The upper fifty feet often harder than the underlying beds and containing a considerable fauna, especially species of <i>Conaspis</i> . In many localities other fossiliferous beds occur in the central and lower portions.
	Dresbach (Winchell 1888) 100'	Massive-bedded, rather coarse-grained sandstone, with a thin bed of shale at the base and shaly sandstone near the middle. Fossils at the top and base, consisting almost entirely of shells of <i>Dicellomus</i> and <i>Lingulella</i> .
	Eau Claire (Ulrich MSS. About 100' 1914)	Mostly thin-bedded, in part shaly sandstone, with many fossiliferous layers, including Owen's Menomonee and Wooster's Eau Claire trilobite zones. Usually a coarse white friable sandstone with <i>Dicellomus</i> and <i>Lingulella</i> at the base. Numerous characteristic trilobites, <i>Crepicephalus iowensis</i> being one of the best of the guide fossils.
	Mt. Simon (Ulrich MSS 235' + 1914)	A series of coarse sandstones and grits resting on pre-Cambrian granite. About 225 feet are shown in the bluffs at Eau Claire and 50 feet of the base at Chippewa Falls, Wisconsin. Except <i>Scolithus</i> borings no fossils have been found.

Jordan Formation. As far as known, the Jordan sandstone as limited by Ulrich has not furnished any fossils. There is, however, a fauna that occurs in sandstones in the vicinity of Devils Lake, Sauk County, Wisconsin, that may belong at this horizon. It includes:

- Arenicolites woodi* Whitfield
- Finkelnburgia finkelnburgi* (Walcott)
- Syntrophia barabuensis* (A. Winchell)
- Straparollus* ? (*Ophileta*?) *primordialis* Winchell
- Dikelocephalus* cf. *limbatus* Hall
- Saukia* cf. *crassimarginata* (Whitfield)
- Saukia* cf. *pyrene* Walcott
- Osceolia* cf. *osceola* (Hall)
- Agraulos* ? sp. undt.
- Ptychaspis* sp. undt.
- Platycolpus barabuensis* (Whitfield)
- Platycolpus* cf. *eatoni* (Whitfield)
- Illænurur* sp. undt.
- Conaspis* cf. *anatina* (Hall)

St. Lawrence Formation. The fauna of the St. Lawrence formation as it occurs at a quarry near Osceola Mills, Polk County, Wisconsin, includes a large group of species from the upper sandstones of the formation:

- Lingulella mosia* (Hall)
- Lingulella mosia osceola* Walcott
- Lingulella winona* (Hall)
- Lingulella winona convexa* (Walcott)
- Billingsella coloradoensis* (Shumard)
- Finkelnburgia finkelnburgi* (Walcott)
- Finkelnburgia osceola* (Walcott)
- Finkelnburgia osceola corrugata* Walcott
- Syntrophia barabuensis* (A. Winchell)
- Hyalithes* ? *corrugatus* Walcott
- Spiroentalium osceola* Walcott
- Holopea sweeti* Whitfield
- Metoptoma* sp.

Platyceras ?

Owenella antiquata (Whitfield)

Murchisonia sp. undt.

Agnostus disparilis Hall

Ptychaspis ? sp.

Dikelocephalus ? *limbatus* Hall

Dikelocephalus minnesotensis Owen ?

Saukia leucosia Walcott

Saukia pyrene Walcott

Osceolia osceola (Hall)

Ptychoparia ? *binodosa* (Hall)

Ptychoparia sp.

Illænurus quadratus Hall

Triarthrella auroralis Hall

In the lower or arenaceo-calcareous beds *Dikelocephalus minnesotensis* has its greatest development. This subfauna includes:

Obolus (*Westonia*) *aurora* (Hall)

Obolus (*Westonia*) *stoneanus* (Whitfield)

Lingulella mosia (Hall)

Lingulella oweni (Walcott)

Lingulella winona (Hall)

Lingulella winona convexa (Walcott)

Finkelburgia osceola (Walcott)

Syntrophia primordialis (Whitfield)

Serpulites murchisoni Hall

Owenella antiquata (Whitfield)

Owenella vaticina (Hall)

Dikelocephalus minnesotensis Owen

Saukia crassimarginata (Whitfield)

Saukia lodensis (Whitfield)

Saukia pepinensis (Owen)

Calvinella spiniger (Hall)

Ptychoparia binodosa (Hall)

Triarthrella auroralis Hall

Ptychaspis n. sp.

Illænurus quadratus Hall

Illænurus n. sp.

Aglaspis eatoni Whitfield

Aglaspis barrandei Hall

Dendrograptus hallanus Prout. (Known from Osceola, Wisconsin, and Lake City, Minnesota.)

Franconia Formation. The fauna of the Franconia formation is quite distinct from that of the St. Lawrence formation and it includes only one representative of the Dikelocephalinæ in *Conokephalina misa* (Hall). The fauna includes:

Obolus matinalis Hall

Obolus mickwitzii Walcott

Obolus (*Westonia*) *aurora* (Hall)

Lingulella mosia (Hall)

Lingulella mosia osceola Walcott

Lingulella oweni (Walcott)

Lingulella phaon (Walcott)

Lingulella similis Walcott

Lingulella winona (Hall)

Lingulella winona convexa (Walcott)

Lingulella (*Lingulepis*) *acuminata* (Conrad)

Dicellomus politus (Hall)

Eoorthis ? *diablo* Walcott

Eoorthis remnicha (N. H. Winchell)

Eoorthis remnicha sulcata (Walcott)

Eoorthis remnicha winfieldensis (Walcott)

Eoorthis sp.

Otusia sandbergi N. H. Winchell

Billingsella coloradoensis (Shumard)

Finkelnburgia finkelnburgi (Walcott)

Finkelnburgia osceola (Walcott)

Syntrophia primordialis Whitfield

Syntrophia primordialis argia Walcott

Palæachmæa irvingi Whitfield

Eccyliomphalus n. sp.

Agnostus josepha Hall
Agnostus parilis Hall
Lonchocephalus hamulus Owen
Lonchocephalus wisconsinensis Owen
Ptychaspis granulosa (Owen)
Ptychaspis miniscansis (Owen)
Ptychaspis striata Whitfield
Chariocephalus whitfieldi Hall
Chariocephalus sp.
Conaspis anatina (Hall)
Conaspis bipunctata (Shumard)
Conaspis cryon (Hall)
Conaspis nasuta (Hall)
Conaspis oweni (Hall) ?
Conaspis patersoni (Hall)
Conaspis perseus (Hall)
Conaspis ? *shumardi* (Hall?)
Ptychoparia diademata (Hall)
Elliptocephalus ? *curtus* (Whitfield)
Conokephalina misa (Hall)

The *Hypseloconus* subfauna at Taylors Falls, Minnesota (Berkey, Amer. Geol., Vol. 21, 1898, pp. 270-292), which includes an interesting group of gastropods, appears to belong to the Franconia fauna.

Dresbach Formation. The fauna (other than *Dicellomus* and *Lingulella*) that has been referred to the Dresbach formation is not determined with sufficient definiteness to list it as from the Dresbach. The lower, shaly beds may carry about the same fauna as the Eau Claire beds.

Eau Claire Formation. This fauna is essentially Upper Cambrian in its facies. It does not contain the characteristic fauna of the Middle Cambrian of either the Cordilleran or Appalachian areas. It is marked by *Agraulos woosteri*, *Crepicephalus iowensis*, and *Crepicephalus texanus*.

The species in the collections of the United States National Museum are:

Worm borings

Obolus matinalis Hall

Obolus mickwitzii Walcott

Obolus namouna Walcott

Obolus rhea Walcott

Obolus (Westonia) aurora (Hall)

Lingulella mosia (Hall)

Lingulella phaon (Walcott)

Lingulella winona (Hall)

Lingulella winona convexa (Walcott)

Lingulella (Lingulepis) acuminata (Conrad)

Dicellomus pectenoides (Whitfield)

Dicellomus politus (Hall)

Billingsella coloradoensis (Shumard)

Pemphigaspis bullata Hall

Hyalithes primordialis Hall

Helcionella sp. undt.

Agnostus josepha Hall

Ptychoparia ? calymenoides Whitfield

Ptychoparia chippewaensis Owen

Ptychoparia optata Hall

Ptychoparia ? quadrata (Whitfield)

Crepicephalus iowensis Owen

Crepicephalus texanus Shumard

Lonchocephalus ? minor (Shumard)

Agraulos sp. undt.

Pagodia thea (Walcott)

Anomocare sp. undt.

Anomocarella onusta (Whitfield)

Anomocarella ? winona (Hall)

Anomocarella woosteri (Whitfield)

SOURCE OF CAMBRIAN FAUNAS OF CORDILLERAN AREA

The brief review given in the preceding pages of the succession of Cambrian formations and faunas leads to the conclusion that the early marine life of Cambrian time was developed in

waters outside of the present continental area and that the oldest Cambrian fauna first came from the Pacific into the Cordilleran sea and later from the Atlantic into the Appalachian sea. In addition to this I think we are justified in concluding that the evolution of the Cambrian fauna went on with little or no interruption in the Pacific basin waters and that the two marked changes in the succession of life resulting in the Middle and Upper Cambrian faunas originated from physical changes within the Cordilleran sea, rather than from any abrupt evolution within or without the sea. This conclusion is strengthened by the occurrence of faunas of the Middle and Upper Cambrian formations in western America which have the same general character and order of stratigraphic succession as those of eastern China.¹ This likeness would result from both areas being in free communication with the Pacific waters when a fauna of similar type extended along the shores of the northern Pacific Realm.

There are, however, limitations to the conclusion that the evolution of Cambrian life went on everywhere along the same lines as in the Pacific waters, as is shown by the presence of restricted local faunas such as the *Blackwelderia* subfauna of China² and the *Neolenus* subfauna of British Columbia.³

SUMMARY OF CAMBRIAN FAUNAS

An accurate summary of the Cambrian faunas of the world is exceedingly desirable, but unfortunately the Brachiopoda is the only one of the large groups which has been thoroughly studied in recent years.⁴ I am advancing the study of the trilobites, but it will be several years before it is completed.

Upper Cambrian. In America the Upper Cambrian fauna is characterized in the Cordilleran and Mississippian areas by

¹ Research in China, Carnegie Institution of Washington, Pub. No. 54, vol. 3, 1913. The Cambrian Faunas of China, pp. 54-58.

² *Idem*, p. 53.

³ Smithsonian Misc. Coll., vol. 53, 1908, pp. 209-211.

⁴ Monograph U. S. Geol. Surv., vol. 51, pts. 1, 2, 1912.

the presence of the genera *Linnarssonella*, *Syntrophia*, *Dikelocephalus*, *Saukia*, *Illænurus*, *Conaspis*, *Crepicephalus texanus* (Shumard), and *Aglaspis*.

As a whole the Upper Cambrian fauna is marked by the presence of brachiopods, the beginnings of an extensive gastropod fauna, and many small trilobites, also the larger *Dikelocephalinæ*.

Middle Cambrian. The Middle Cambrian fauna is large and varied and is usually readily identified by the presence of the genera *Micromitra*, *Acrothele*, *Nisusia*, *Billingsella*, *Olenoides*, *Dorypyge*, *Neolenus*, *Ogygopsis*, *Asaphiscus*, *Zacanthoides*, and *Bathyuriscus*.

The Middle Cambrian fauna has a great development of crustaceans, especially phyllopods, and also trilobites with large head and tail. There are also many brachiopods and pteropods and a few small gastropods.

Lower Cambrian. The Lower Cambrian fauna is especially characterized by the presence of *Olenellus*, *Mesonacis*, *Nevadia*, and other genera of the Mesonacidæ. Other genera are *Archæocyathus* and allied forms, and among the Brachiopoda *Kutorgina*, *Mickwitzia*, and *Obolella*.

Zacanthoides (few)

Crepicephalus (few)

The Lower Cambrian fauna is dominated by trilobites and simple, rather small, brachiopods, gastropods, and a number of pteropods.

Observations. The three subfaunas of the Cambrian are connected by many genera that occur in all three subfaunas, and a very few species that range from the upper formation of the Lower Cambrian into the base of the Middle Cambrian, and a few that pass from the Middle Cambrian to the Upper Cambrian.

LIMITATIONS OF PRESENT DATA

The brief review which I have given of the records of Cambrian time in the Cordilleran Province broadly outlines the

simplicity and complexity of the history of both the physical and biotic processes and events.

Antecedent conditions of Algonkian time laid the foundations for building the Cambrian system of sedimentation and preserving the record of life contained therein, and these conditions were of fundamental influence throughout Cambrian time. With such important factors assured it would seem to be a simple matter to interpret the record and write the history, but the actual conditions at present existing render it difficult. A generation or two of geologists and palæontologists will have come and gone before sufficient field research can be made from which to plot or map and record the observable phenomena. Today we have the records of much reconnaissance work, but almost none of intensive study of even limited districts.

Field work up to this time enables us to do little more than draw general conclusions to serve as a basis for further research.

Some of the problems for investigation now most apparent are suggested in the following notes.

UNSOLVED PROBLEMS

The incomplete outline here given of the constructive activities of Nature during Cambrian time in the Cordilleran area of North America has developed the view that in nearly every district in the Cordilleran area where the Cambrian formations now appear at the surface, there are local problems which demand detailed study especially in connection with areal mapping. In what I will state further, attention will be directed only to a few of the broader problems.

Incursion of Pacific Waters into Cordilleran Area. The inference drawn from the presence of the oldest Cambrian fauna and sediments in southwestern Nevada, that the Pacific waters had first penetrated into the Cordilleran area in that region is fairly well substantiated. But the question as to whether or not in late Cambrian time there were other openings

than the one indicated by Schuchert,¹ north of his Ensenada² positive element, is one of the problems that can be solved only by the finding of Cambrian faunas between the main Cordilleran geosyncline and the Pacific coast, or the discovery of a fauna that was positively derived from more northern waters.³ It would seem that if there was an opening toward the Arctic the waters of the Pacific would have entered and given a markedly different character to the fauna within this northern Cordilleran area. That the fauna of Lower Cambrian time which entered from the southwest was distributed far to the north is shown by the occurrence of similar species in southwestern Nevada and in British Columbia.

Existence of Land Deposits. The determination of the question as to whether or not there are continental or land deposits interbedded in the massive Cambrian formations, is one of great importance and it can be solved only by the examination of the formations deposited near the shore lines of the Cordilleran sea. We know at present that there are no sediments of continental character in the sections of central Nevada and what was probably the continuation of the central portions of the same sea northward into Utah and Idaho.

Search for such land deposits should be made about the Montana island or barrier of Cambrian time, and also wherever there is a promising area for study along the western margin of the Cambrian formations in the United States and British Columbia. This should be done with a view of ascertaining whether or no there are any traces of the non-marine Cambrian sediments of Lower and Middle Cambrian time deposited by rivers or winds on land areas or in bodies of fresh or brackish water on the areas adjoining the Cordilleran sea.

The absence of eruptive rocks of Cambrian age, and of salt and gypsum deposits favors the view that the Cambrian

¹ Schuchert, Bull. Geol. Soc. America, vol. 20, 1910, pl. 52.

² *Idem*, pls. 51, 52, and 53.

³ It may be that the upper *Olenellus* fauna of the Robson Peak District came in from the north. Both the brachiopods and trilobites suggest the same source of origin as similar forms occurring in northern Europe.

formations of the Cordilleran area are mainly of marine, sedimentary origin.

Coastal Deposits. By coastal or the shelf sea deposits I mean the deposits made along the coasts of the Pacific either along the open ocean or in bays or other bodies of water in immediate connection with the ocean during Cambrian time. As has been stated (pp. 167, 187) there are no known marine continental fringing or slope deposits or faunas laid down in late Algonkian time in the Pacific Realm or on or about any of the continents or islands of the world.

If the theory of Chamberlin and Salisbury on the cause of the disappearance of the coastal or fringing deposits is correct there is little hope of discovering them. Their conclusion is that "the theoretical continental fringe of sediments has been borne downward and thrust landward by each general deformation, and has crept outward and downward with each relaxation. The whole series is to be regarded as present in the continental shelf and the coast border tract, but as largely concealed by this combination of disturbing processes. When the great depth of the ocean basins at the edge of the continental shelf is considered, it is obvious that the volume of sediment required to build the shelf seaward is large in proportion to the extension of the shelf, and hence the fringing zone is not very broad."¹

One of the great problems to work out is the determination of these marine deposits and their contained life.

Changes toward the Close of the Lower Cambrian. There is evidence of a decided change in the character of the sediments and fauna at the close of the Lower Cambrian, but the cause of it is not so apparent unless it was a diastrophic movement that caused the gradual withdrawal of the marine waters. Possibly there may have been a climatic change influencing the temperature of the sea or it may have been brought about by the more or less filling up of the sea by sediments.

Cold Period at Close of Lower Cambrian and Middle Cambrian Time. As stated in the discussion of Glacial Deposits (pp. 184, 199), the probable existence of a cold period at or just

¹ Chamberlin and Salisbury, *Geology*, vol. 2, 1906, p. 529.

previous to the close of Lower Cambrian time is one of the problems to be investigated. Such research will require a detailed study of the Cambrian strata of this horizon throughout the Cordilleran region, and should also include the problems as to whether or not there was a cold period at the close of Middle Cambrian time. At present the evidence for either cold period is very slight.

Changes toward the Close of Upper Cambrian Time. The discovery in Missouri by Ulrich of a series of strata, several thousand feet thick and marked by a distinctive fauna,¹ between the Upper Cambrian and Canadian series, leads to the conclusion that there may be a similar break in the record of sedimentation and life in the Cordilleran area by non-deposition of sediments. However that may be, it is certain that the known records are so imperfect that satisfactory conclusions cannot be based on them. The entire subject of sedimentation and life following the close of the Cambrian in western America affords one of the interesting problems to be developed and settled by field and laboratory research.

Diastrophic Movements. The continuity and apparent conformity of the great Cambrian sections of central Nevada, western Utah, Alberta, and British Columbia prove a general uniformity of quiescent conditions during Cambrian time so far as the gradual subsidence of those portions of the Cordilleran geosyncline are concerned. Certainly there were here no mountain-making movements in this region at that time. The absence of Middle Cambrian formations in the Silver Peak District, Nevada, and in the Big Cottonwood Canyon section, Wahsatch Mountains, Utah, shows diastrophic movements elsewhere or warpings on the southwestern and eastern sides of the geosyncline which materially influenced the deposition of sediments. The strata of the Grand Canyon series of the Algonkian in Arizona were plexed and faulted prior to Middle Cambrian time but not noticeably metamorphosed. The tracing of the effect of these movements in other parts of the Cordilleran area is of importance, as also is the determination of the extent and

¹ Bull. Geol. Soc. America, vol. 22, 1911, pp. 281-680.

influence of the changes that brought about the incursion of the Upper Cambrian sea into the Mississippian region. This research will require thorough field work and study of the formations and faunas of Upper Cambrian time in the entire Cordilleran area.

Progenitors of the Cephalopods and Fishes of Post-Cambrian Time. With a fully developed cephalopod fauna near the base of the Ozarkian Eminence formation¹ and placogonoid fishes in the Middle Ordovician, I think it not improbable that progenitors of these two groups may ultimately be found in the Cordilleran Upper Cambrian rocks. No traces of them have been seen with the finely preserved Burgess shale Middle Cambrian fauna, but if a similar deposit can be found of late Upper Cambrian age it may be that the long-sought-for cephalopod and vertebrate life will be discovered. The one cephalopod reported in association with a fauna of Upper Cambrian age, *Cyrtoceras cambria* Walcott,² points to the Upper Cambrian as the horizon in which to search for the earliest forms of the Cephalopoda. That very delicate organisms may be preserved in a fossil state is proven by the presence of annelids, medusæ, and holothurians in the Burgess Middle Cambrian shale. With this in view, the great series of shales of the Upper Cambrian in British Columbia should be searched wherever it occurs.

Recurrent Faunas. In the Eureka District, Nevada, section, there is an apparent recurrence of the Upper Cambrian fauna of the Secret Canyon shale in the Dunderberg shale 1200 feet (365 m.) higher in the section (p. 214). This is a small but important problem to be settled by close collecting and study.

Relations of Cambrian Epochs and Faunas of the Cordilleran Area to Those Elsewhere on the North American Continent and to Those of Other Continents. This subject opens up several vital problems of the Cambrian. To solve them will require study, extended research among published records, and more

¹ Bull. Geol. Soc. America, vol. 22, 1911, p. 630.

² Carnegie Institution of Washington, Pub. No. 54, Research in China, vol. 3, 1913, p. 98.

or less field investigation. A few points have been incidentally touched upon in the preceding pages in passing, but as a whole a new and full study of the Cambrian system in America needs to be begun and carried forward for many years.

CHAPTER V

THE IGNEOUS GEOLOGY OF THE CORDILLERAS AND ITS PROBLEMS

WALDEMAR LINDGREN

INTRODUCTION

Of all geologic phenomena which fall under our observation, none are more striking, none compel the attention more, than those of igneous activity. Primeval man beheld them, trembling with fear, and prostrated himself before them, deeming them manifestations of some deity. In mythology and legends we find allusions to the breaking out of the subterranean fire. Since the dawn of science, when Pliny recorded the eruptions of Vesuvius, volcanoes have ever proved fascinating subjects of study.

As geologic science developed, we have become aware that the volcanoes, impressive as they are, form but one aspect of igneous action and that far below the surface processes go on in comparison to which the surface phenomena assume less importance. We have ascertained that immense quantities of fluid magma are forced up into the crust from abyssal depths without reaching the surface, and that these magmas, congealed, have been exposed by erosion. We have speculated broadly, though sometimes necessarily on the basis of slender premises, regarding the mechanics and sources of intrusion and volcanism. We have accumulated a vast amount of data regarding the composition of all classes of the igneous rocks. Now the time has come when we must fortify our speculation by the digesting and

logical arrangement of the data of petrography. Much has, indeed, been done along these lines, particularly by petrologists such as Rosenbusch, Iddings, Cross, Pirsson, Washington, Daly, Harker, Lacroix, and many others. Naturally some aspects remain which perhaps have not been adequately considered. Only comparatively lately have we been able to do full justice to the subject, since we have learned that the magma is not merely the specimens before us in a molten state, but a solution of molten rock and gases. The volatile constituents have escaped, but not without leaving some signs by which they may be traced. What we ordinarily examine is then only a part, of course the larger part, of the magma.

You have honored me by asking me to speak of "The Igneous Geology of the American Cordilleras and its Problems." It is a subject which assuredly does not suffer from too close limitation. The Cordilleras have for geological ages been the theatre of vast igneous manifestations which indeed are far from extinct at the present time. Here, if anywhere, a review should lead to definite results, because such a great amount of preliminary work has already been accomplished.

The American Cordilleras form but a part of that "Circle of Fire" which encompasses the Pacific, and it remains for the future to sum up the evidence for this whole region; its various provinces present widely differing aspects. The narrow belt along the west coast of South America contrasts, for instance, strongly with the broad and complicated zone of North America, and its petrology should perhaps be easier to interpret. In this review I shall have to confine myself to the northern part of the continent.

Here the task would be easy should it be limited to a statement of the problems. We want to ascertain the relations of the magmas—if any such relations exist—as to chemical and mineralogical composition. We also want to ascertain their place of origin, their differentiation, their mode of ascent, injection, and intrusion; and finally the relation of the *mise en place* of the magmas to the great stresses to which the crust has been subjected, and which have resulted in the building of

continents and mountain chains. I shall have to approach the subject from the side of definitely known data. It is the only way in which I could add anything that would help to solve these difficult problems.

The attention of petrographers has largely been directed to the Tertiary and Cretaceous igneous activity, but we must not forget that this is only a part of the history of the region. Since pre-Cambrian times, flows and intrusions have taken place in the North American Cordillera. Little attention has been given to the *petrologic history* of the Cordilleran igneous activity and the first part of this lecture will be entirely devoted to establishing this chronology and to drawing such conclusions from this as may seem warranted. The second and shorter part of the lecture will be devoted to the mechanics of intrusion and its probable relations to mountain-building processes.

Accounts of complete igneous history are available from some regions, for instance from Great Britain. These historical accounts show no progressive change in the character of the igneous rocks, although granites are perhaps more abundant in pre-Cambrian areas than elsewhere. Basalts and rhyolites of pre-Cambrian age and of all intermediate ages are known. The so-called alkali rocks are found in pre-Cambrian as well as in later formations, and if the leucite and nepheline basalts are largely confined to the Tertiary and the present, it is probably because these subaërial flows are thin and easily eroded. True granites, diorites, and gabbros are likewise known from all ages, and are probably now being intruded in many igneous districts. In formations of late age, erosion has rarely been deep enough to expose these intrusive bodies. Highly differentiated rocks like anorthosites are not uncommon in the oldest pre-Cambrian terranes. If all these variations in igneous rocks are produced by differentiation, we must conclude that these processes of cleaving in magmas have gone on since the most remote geological times.

As we shall see, the results of a chronological survey in the Cordilleran region do not fully conform with this law of uniformity. Certain differences in successive igneous periods

assuredly exist, and the wide area over which the rocks are spread give warning that those differences cannot be wholly accidental.

ROCKS OF PRE-CAMBRIAN AGE

We shall begin with the pre-Cambrian. In the Cordilleran region we are as yet unable to draw satisfactory division lines between the several series of sedimentary rocks and the names of Archæan and Algonkian have here little meaning. We may safely discard them and shall be better off without them. Nevertheless, certain parts of the pre-Cambrian with little altered sediments must be separated from the older rocks—in fact, they are, in the judgment of some observers, in part conformable with the Cambrian rocks. I allude to the Belt Series of Montana, Idaho, and British Columbia. With this is closely allied the Grand Canyon Series of Arizona and Utah, and probably certain quartzitic sandstones of the Uinta and the Wahsatch. We may refer to this—the latest period of the pre-Cambrian—as the *Beltian*.

Below the Beltian we find the most marked unconformity in the Cordilleran region. The lower, pre-Beltian rocks consist of a fundamental gneiss, on which rest sedimentary rocks as a rule highly altered. Finally, gneisses and sediments are broken by vast intrusions of granite. In comparison with the time scale adopted for the Lake Superior region, these highly altered sediments probably correspond to the various stages of the Huronian and Keewatin periods, while the Beltian deposits may correspond to the Keweenaw Series.

Previous to the Beltian, the gneisses, the highly altered sediments and the effusives were then broken on a large scale by intrusive rocks. By far the greater part of the pre-Beltian areas—probably 80 per cent—are now occupied by these intrusives. It is true that but a relatively small area of the whole Cordilleran region is occupied by pre-Beltian rocks, perhaps less than 10 per cent, and that in Mexico, California, Nevada, Utah, Idaho, Oregon, Washington, and British Colum-

bia they are almost entirely hidden from view. Nevertheless, the exposures in the eastern half are widely scattered and afford a fair estimate of the character of the rocks.

THE PRE-BELTIAN SEDIMENTARY ROCKS

These remnants of old sedimentary series, which cannot now be divided into separate periods, consist of quartzite, slate, and some dolomite and limestone, and are in most cases strongly metamorphosed. Some are muscovite-andalusite schists without semblance of bedding;¹ others are contorted clay slates and mica schists strongly injected by pegmatite;² others like those of the Encampment district, Wyoming,³ or the Needle Mountain group⁴ of southwestern Colorado consist of quartzite and conglomerate; the Shuswap Series of British Columbia is made up of an unusually thick aggregate of quartzite, slate, and a little limestone;⁵ still others, like the Cherry Creek group⁶ of Montana or the pre-Cambrian of southwestern Arizona,⁷ are composed of limestone, dolomite, mica schists, and amphibolites.

THE GNEISSES

There are also areas of typical gneiss, though comparatively small in extent, and not to be confused with the sometimes roughly schistose foliation of the later granite. These masses of gneiss are either embedded in later granite, as at Cripple Creek, Colorado, or lie below the clearly sedimentary rocks of

¹ Lindgren and Ransome, *Geology and Gold Deposits of the Cripple Creek District, Colo.*: Prof. Paper, U. S. Geol. Surv., No. 54, 1906.

² Spurr and Garrey, *Economic Geology of the Georgetown District, Colo.*: Prof. Paper, U. S. Geol. Surv., No. 63, 1908.

³ Spencer, A. C., Prof. Paper, U. S. Geol. Surv., No. 25, 1904.

⁴ Cross, Howe, Irving, and Emmons, *Geol. Atlas U. S.*, U. S. Geol. Surv., folio 131, Needle Mountains, 1905.

⁵ Daly, R. A., *Reconnaissance of the Shuswap Lakes and Vicinity*: Summary Rept. Geol. Surv., Canada, 1911.

⁶ Peale, A. C., *Geol. Atlas U. S.*, U. S. Geol. Surv., folio 24.

⁷ Banerft, H., *Bull. U. S. Geol. Surv.*, No. 451, 1911.

pre-Cambrian age. The origin is not always clear, but they are in most cases microcline-biotite gneisses with contorted or irregular schistosity and they represent the oldest pre-Cambrian rocks known. Such gneisses may have been derived from granite of far greater age than the great mass of pre-Beltian granites to be described later. As examples may be cited the rocks underneath the pre-Beltian sediments in the Needle Mountains quadrangle, Colorado (l. c.) or those underneath the series of dolomite and amphibolite near Parker, Arizona.¹ The gneisses of Mohave County,² Arizona, are clearly of intrusive origin, and are probably simply sheared modifications of the later granites. From southwestern Nevada, H. W. Turner has described granite and monzonite gneiss underlying pre-Beltian sedimentary schists.³

THE PRE-BELTIAN EFFUSIVE ROCKS

We note in the pre-Beltian not only an absence of the large gneiss areas, but also a lack of the Keewatin greenstone lavas, which occupy as much space in the Canadian Shield. Effusive rocks are very sparingly represented. There is a pre-Cambrian and probably pre-Beltian flow of rhyolite in the Franklin Range, near El Paso⁴ and dikes of rhyolitic porphyries have been described from northwestern New Mexico,⁵ and from the Neihart district, Montana.⁶ Possibly there are some effusive basic rocks in the complex of Chaffee County, Colorado, in the Irving greenstones of southwestern Colorado,⁷ in the Telluride region, and in the basal amphibolites below the quartzite in the Grand Encampment district.⁸ In a late publication, R. A. Daly

¹ Bancroft, H., *Op. cit.*

² Schrader, F. C., Bull. U. S. Geol. Surv., No. 397, 1909.

³ Bull. Geol. Soc. America, vol. 20, 1910, p. 230.

⁴ Richardson, G. B., Geol. Atlas U. S., U. S. Geol. Surv., folio 166.

⁵ Lindgren, Graton, and Gordon, Prof. Paper, U. S. Geol. Surv., No. 68, 1910, p. 136.

⁶ Weed, W. H., Geol. Atlas U. S., U. S. Geol. Surv., folio 56.

⁷ Cross, Howe, Irving, and Emmons, folio 131, Needle Mountains.

⁸ Spencer, A. C., Prof. Paper, U. S. Geol. Surv., No. 25, 1904.

describes pre-Beltian basalts in the Shuswap Series of British Columbia.¹ Areas of schist have been described from the Sherman quadrangle, Wyoming, which appear to contain highly altered basalts and rhyolites, associated with metamorphosed sedimentary rocks.

PRE-BELTIAN INTRUSIVE ROCKS

Intrusive rocks predominate strikingly. In nearly all districts there are minor masses of basic rocks like gabbro, diorite or diabase, sometimes schistose in part and converted to amphibolites. Such basic intrusives of gabbro are represented, for instance, in the Encampment district, Wyoming, where they intrude pre-Beltian sediments. A larger mass is described from central Colorado in Chaffee County,² and its rocks are mainly coarse gabbros. Many of these basic rocks are associated with pre-Beltian copper deposits. In the Sherman quadrangle, Wyoming, these smaller areas of basic rocks, including a considerable mass of anorthosite, are earlier than the great granitic batholiths. The basic rocks form a very small percentage of the total area of the pre-Beltian rocks.

The study of the older literature of these pre-Beltian areas is often trying to the patience, many authors confining themselves to the statement that the "crystallines" consist of "granite and schist." From many areas we have, however, more detailed accounts and from these we may deduce with confidence the conclusion that by far the largest part of the intrusives consist of granite, and that this granite, sometimes roughly schistose but much more commonly wholly massive, makes up at least 80 per cent of the pre-Beltian areas. This holds good in Wyoming, Colorado, New Mexico, Arizona, and also in the southeastern part of California and such scattered

¹ Reconnaissance of Shuswap Lakes and Vicinity: Summary Rept., 1911, Geol. Surv., Canada.

² Lindgren, W., Bull. U. S. Geol. Surv., No. 340, 1908, p. 160.

occurrences as are found in the Pacific States and Canada. The most northerly occurrence described is that of the Shuswap region, British Columbia. Much uncertainty as yet attaches to the pre-Beltian rocks of Yukon Territory and Alaska.

The prevailing rock is a reddish orthoclase granite with 73 per cent silica or more, and with more potash than soda. Microcline is the predominant feldspar, and both biotite and muscovite are ordinarily present, sometimes with a little hornblende. Accompanying these intrusions are pegmatites in abundance, cutting the granite or more commonly injecting the pre-Beltian sediments on a tremendous scale.

These vast intrusions of granite and pegmatite have not been repeated in the Cordilleras during later times, and this, I believe, is a conclusion of great importance.

The granites as far as examined commonly contain fluorite. Tourmaline is also plentiful in many districts, and especially in many pegmatite dikes, indicating that the principal volatile agents present were fluorine and boron, to which carbon dioxide and water should doubtless be added. These old magmas appear to have contained but little sulphur, chlorine, and phosphorus; sulphide ores of igneous affiliations are decidedly scarce in the granite areas. Though pegmatites are so common, they do not usually carry rare minerals except in the Black Hills, where minerals containing lithium, columbium, phosphorus, tungsten, beryllium, and tin occur in abundance. There are a few occurrences of such minerals in Colorado but they are scarce. It is probable that the tourmaline and lithium minerals from San Diego County, California, also occur in pre-Cambrian pegmatites.

Should we venture to assign an age to these vast pre-Beltian batholiths, on the time scale of the Lake Superior region, it is probable that they should be placed between the Keweenawan and the Huronian. As stated above, most of these granites are massive or have an imperfect schistosity.

A brief enumeration follows of the places where the granitic intrusions have been studied in detail.

From British Columbia, R. A. Daly describes a great series of pre-Beltian quartzose sediments intruded by enormous sheets of granite with pegmatites.¹ In Montana, the largest pre-Beltian areas are in the Three Forks and Livingston quadrangles,² but in both cases the description is unsatisfactory. Gneisses are said to prevail in the former, and gneisses and granites in the latter.

Only one small area of pre-Beltian rock, consisting of a microcline gneiss, is recorded from the Clearwater Mountains, Idaho.³ Much larger areas are described from Wyoming. The great granite batholith of the Big Horn Mountains⁴ outcrops over seventy miles by thirty miles and is only limited by overlapping Palæozoic rocks. It is predominantly red granite but in part goes over into quartz monzonite. Red massive granite is likewise present in large areas in the Wind River Mountains, in the Medicine Bow Range, and in the Casper Mountains. In the latter place,⁵ red granite appears as the most widespread rock, intruding serpentine. In the Sweetwater district at the foot of the Wind River Range is found a large pre-Cambrian schist area adjoined by "Archæan" granite.⁶ The most detailed description is that given by Darton, Blackwelder, and Siebenthal of the great batholith of the Laramie Range, which, as exposed underneath the covering strata, outcrops over an area thirty-five miles by thirteen miles in the Sherman quadrangle,⁷ and in comparison with which the schist and gneiss areas in the same vicinity are of small importance. The granite of the Sherman quadrangle extends southward through Colorado, and in fact the larger part of all the pre-Beltian exposures of the Front and Park ranges consist of this rock. It has been studied

¹ Reconnaissance of the Shuswap Lakes and Vicinity: Summary Rept., 1911, Geol. Surv., Canada, pp. 165-174.

² Geol. Atlas U. S., U. S. Geol. Surv., folios 1 and 24.

³ Lindgren, W., Prof. Paper, U. S. Geol. Surv., No. 27, 1904.

⁴ Darton, N. H., Prof. Paper, U. S. Geol. Surv., No. 51, 1906.

⁵ Diller, J. S., Bull. U. S. Geol. Surv., No. 470, p. 513, 1911.

⁶ Knight, W. C., Bull. Univ. Geol. Surv., Wyoming, June, 1901.

⁷ Geol. Atlas U. S., U. S. Geol. Surv., folio No. 173.

in the Georgetown quadrangle,¹ in the region of Monarch and Tomichi,² and in the Hahns Peak region.³

It is known from earlier work that similar granites occupy large areas in the Sawatch and Gore ranges in central Colorado. In more detail the granitic batholiths have been studied in the Pikes Peak⁴ and in the Castle Rock quadrangles,⁵ and from the latter areas a series of good analyses are available.⁶ Farther south the intrusive granites of the Wet Mountain and the Sangre de Cristo ranges have been described.⁷ The wide distribution of the intrusive granites in New Mexico throughout the length and width of the strata has been emphasized recently.⁸

In Arizona the pre-Cambrian areas are best exposed in the Catalina and Bradshaw mountains and in the region adjoining the Colorado River, but they are also found in smaller exposures in the eastern part. While sericite schists, amphibolites, limestone, and gneisses are present in some districts, yet the predominating rock is almost everywhere a reddish to gray granite, massive in most places, but sometimes roughly schistose.⁹

The pre-Beltian exposures in Oregon, Washington, Nevada, and Utah are insignificant. In California, adjoining the

¹ Spurr and Garrey, Prof. Paper, U. S. Geol. Surv., No. 63, 1908.

² Crawford, R. D., Bull. Colorado Geol. Surv., No. 4, 1913.

³ George, R. D., and Crawford, R. D., First Report, Colorado Geol. Surv., 1909.

⁴ Cross, Whitman, Geol. Atlas U. S., U. S. Geol. Surv., folio 7.

⁵ Finlay, G. I., U. S. folio in course of publication.

⁶ Clarke, F. W., Bull. U. S. Geol. Surv., No. 419, 1910.

⁷ Cross, Whitman, Geology of Silver Cliff and Rosita Hills: 17th Ann. Rept., U. S. Geol. Surv., part 2, 1896.

Patton, H. B., Geology of the Grayback Mining District: Bull. Colorado Geol. Surv., No. 2, 1909.

⁸ Lindgren, Graton, and Gordon, Prof. Paper, U. S. Geol. Surv., No. 68, 1910.

⁹ Ransome, F. L., Bisbee folio (No. 112), U. S. Geol. Surv.; Bull. U. S., Geol. Surv., No. 529, 1913, p. 179; Globe folio (No. 111), U. S. Geol. Surv.

Lindgren, W., Clifton folio (No. 129), U. S. Geol. Surv.

Jaggard and Palache, Bradshaw Mountains folio (No. 126), U. S. Geol. Surv.

Colorado River and possibly also in the San Bernardino and San Diego mountains, are granites and schists of great geological age. Granite has been found underlying Cambrian beds in San Bernardino County.¹ The scant knowledge of the crystalline rocks of the Mohave and Colorado deserts has been summarized by E. C. Harder.² From this it appears that the predominating rocks are schists and gneisses, the latter of igneous origin, but there seems to be less granite than in the region further east. At the Hedges Mountains in California,³ not far from Yuma, Arizona, granites with a strong development of pegmatites intrude schists which have the appearance of great geological age.

The dominant feature of the pre-Beltian in the Cordilleran region is thus the intrusion of great batholiths of granite, extending from the Canadian boundary to Mexico, the limits in both cases being defined by overlying younger series of rocks. This intrusion was practically the latest phase of the pre-Beltian and the irruption was followed by a long period of erosion, probably under desert conditions, which in most districts, degraded the ancient topography to a peneplain.

The intrusions were on such a vast scale as to make the earlier formations—sedimentary and igneous—appear of small importance. As far as can be seen, these intrusions were not dependent upon any structural line or on any coast line, but took place indiscriminately over the whole of the Cordilleran Belt. They were accompanied and followed by vast injections of pegmatite, which, however, seem to be more extensive in Colorado than elsewhere.

BELTIAN IGNEOUS ROCKS

A long period of quiescence followed the pre-Beltian intrusions. The thick sediments of the Beltian were deposited over large areas and these beds are, as might be expected, mainly of

¹ Darton, N. H., *Jour. Geol.*, vol. 15, pp. 470-475, 1907.

² Bull. U. S. Geol. Surv., No. 503, 1912.

³ Lindgren, W., unpublished notes.

quartzose character. At the very end of the Beltian period, renewed eruptions took place, but these are throughout of a basic character. The rocks are diabases or gabbros. They have, however, a marked tendency to differentiate into minor acidic facies such as quartz diabase, granophyre, and even granite.

When the Belt Series of Montana was first examined, the presence of such dikes of diabase or quartz diabase was not overlooked. Later, thick intrusive sheets of diabase and gabbro (the Moyie sills) were described from the Beltian of British Columbia by R. A. Daly,¹ and from the Purcell Range by S. J. Schofield.²

Similar sills of great persistence, though not as numerous, have been discovered in the Beltian of western Montana at Phillipsburg and in the Cœur d'Alene Mountains by F. C. Calkins.³

In British Columbia some doubt exists about the proper division line between the Cambrian and the Beltian. The unconformity is at best slight and it is possible that some of these intrusions took place in the earliest Cambrian.

Similar sills have been described from the Grand Canyon formation,⁴ which probably is the equivalent of the Beltian.

No one can review the literature of the pre-Beltian in Colorado and Wyoming without remarking the constantly recurring description of diabase dikes which form the latest pre-Cambrian intrusions. In the map accompanying the Big Horn report by N. H. Darton,⁵ these dikes have been plotted and are particularly striking; one of them is fourteen miles long and some dikes range up to 150 feet in width. None of them intersect the Cambrian formations which surround the granitic area.

¹ Rosenbusch Festschrift, 1906.

Am. Jour. Sci., (4), vol. 20, pp. 186-197.

² The Geology of East Kootenay, B. C.: Doctor's thesis, Institute of Technology, Boston, Mass., 1912.

³ Prof. Paper, U. S. Geol. Surv., No. 78, 1913; Bull. U. S. Geol. Surv., No. 540, 1914, p. 174.

⁴ Noble, L. F., Am. Jour. Sci., (4), vol. 29, 1910.

⁵ Prof. Paper, U. S. Geol. Surv., No. 51, 1906, p. 18.

We have thus good evidence of a widespread intrusion of diabase and gabbro in the latest Beltian or very earliest Cambrian. No doubt extensive surface flows of basalt were poured out over the land areas of pre-Cambrian time, but these basalts have been removed by erosion.

Apparently, these basic intrusions are related to no structural lines nor to any coast line.

The following series of igneous activity is thus established in pre-Cambrian time.

Pre-Beltian	{	Granitic gneisses (oldest); restricted areas.
		Surface lavas and tufts; restricted areas.
		Granitic intrusions, now gneisses; small areas.
		Basic intrusions; small areas.
		Granitic intrusions; very large areas.
		Pegmatitic intrusions; large areas.

Beltian: Diabase intrusions probably with basalt flows; small areas.

PALÆOZOIC IGNEOUS ROCKS

From the beginning of the Palæozoic the records are better preserved, and we begin to discern a certain dependence of the igneous activity on the coast line of the Pacific, which later is destined to still greater emphasis. Few eruptions took place during the whole of the Palæozoic in the part of the Cordilleran region in the United States east of Longitude 115° or 120°.

Cambrian, Ordovician, and Silurian igneous rocks are very scarce, even along the Pacific coast. From the Taylorsville district in northern California, J. S. Diller¹ describes a pre-Silurian rhyolite, the age of which is confirmed by Silurian conglomerates carrying the same rock. The same author has mapped an altered andesite near Redding, California,² as Devonian or older, but the rhyolite of the same age from the same quadrangle is held by L. C. Graton to be a Jurassic intrusive. H. W. Turner mentions a probably Cambrian basalt as well as definite interbedded lenses of altered rhyolite in the

¹ Bull. U. S. Geol. Surv., No. 335, 1908.

² Redding folio (No. 138), U. S. Geol. Surv.

Ordovician strata of Silver Peak quadrangle in western Nevada.¹ A chloritic and vesicular diabase is, according to F. B. Weeks and V. C. Heikes, intercalated as a lava flow in the Ordovician Series near Pocatello, Idaho.² In Alaska the igneous rocks of early Palæozoic age are more abundant. It is believed by Prindle that some greenstones in the Tatalina group in the White Mountains may be of Ordovician age.³

“Pre-Devonian” schists and gneisses in part derived from basic and acidic (in part rhyolites) rocks are distributed in the Yukon and Atlin regions of Yukon Territory (Mt. Stevens group),⁴ and in Alaska (Birch Creek Series).⁵ No definite statement can be given of the age and mode of eruption of these.⁶

Igneous areas, definitely known to be of Devonian age, occur in Alaska. In the central region on the Yukon the rocks are basaltic flows of considerable extent, known as the Rampart Series.⁷ They are interstratified with sediments and limestone and also contain some flows of rhyolite.⁸ In southeastern Alaska flows of greenstone and beds of tuffs are found in the upper (Chichagof Island) part of the Devonian strata which here are developed in great thickness.⁹ Tuffs are also found in the lower Devonian beds.

Much more important are the igneous rocks of Carboniferous and Permian age. They are confined to the Pacific coast from central California to Alaska, and consist exclusively of flows or tuffs of basalt, diabase, and basic andesite, interbedded with sediments. The distribution of these basic rocks approximately

¹ Bull. Geol. Soc. America, vol. 20, 1910, p. 253.

² Bull. U. S. Geol. Surv., No. 340, 1908, p. 180.

³ Prindle, L. M., Bull. U. S. Geol. Surv., No. 525, 1913, p. 52.

⁴ Cairnes, D. D., Mem. Geol. Surv., Canada, No. 37, 1913, p. 48.

⁵ Prindle, L. M., *Op. cit.*, p. 35.

⁶ McConnell, R. G., The Klondike Region: Ann. Rept., Geol. Surv., Canada, vol. 12, new series, 1899, p. 18A.

⁷ Spurr, J. E., Geology of the Yukon Gold District, Alaska: 18th Ann. Rept., U. S. Geol. Surv., part 3, 1898, pp. 155-169.

⁸ Eakin, H. M., Bull. U. S. Geol. Surv., No. 535, 1913.

⁹ Wright, F. E. and C. W., Bull. U. S. Geol. Surv., No. 347, 1908.

coincides with the belt in which the Carboniferous strata have suffered metamorphism and in which limestones form the smaller part of the sediments. In extent they rarely compare with the Triassic and Jurassic lavas.

Such altered andesites occur in the western foothills of the Sierra Nevada,¹ and in the Taylorsville district² at the northern end of the range. Near Redding heavy flows of the Bass Mountains diabase are intercalated in the sandstones and shales of the Bragden formation³ (Mississippian).

In southern Oregon the Carboniferous basic effusive rocks appear in increased volume, especially in the Gold Hill and Applegate districts.⁴ In smaller amounts these greenstones are found in the Blue Mountains of Oregon,⁵ in the Cascade Range of Washington (Hawkins formation),⁶ and in Stevens and Ferry counties⁷ in northern Washington, in all cases embedded in more or less altered form in partly metamorphosed slates.

Similar rocks (Wedder formation) are described from southwest British Columbia in R. A. Daly's section⁸ along the boundary line.

At various places in Alaska, British Columbia, and Yukon Territory we meet the same series of Carboniferous flow rocks, and tuffs. The so-called Vancouver Series of rocks has lately been found to belong mainly to the Trias and Jura. But in southeastern Alaska a period of volcanic activity ensued, resembling that of the Devonian, though it was of much longer duration. The products of these volcanoes are now represented by altered greenstones and tuffs, and have with the interstrati-

¹ Turner, H. W., Downieville: folio (No. 37), U. S. Geol. Surv.

Ransome, F. L., Mother lode district: folio (No. 63), U. S. Geol. Surv.

² Diller, J. S., Bull. U. S. Geol. Surv., No. 353, 1908.

³ Diller, J. S., Redding folio (No. 138), U. S. Geol. Surv.

⁴ Diller, J. S., Bull. U. S. Geol. Surv., No. 546, 1914, p. 19.

⁵ Lindgren, W., 22d Ann. Rept., U. S. Geol. Surv., 1901, part 1, pp. 551-776.

⁶ Smith, George Otis, Mt. Stuart, folio (No. 106), U. S. Geol. Surv.

⁷ Bancroft, H., Bull. U. S. Geol. Surv., No. 550, 1914.

⁸ In course of publication by Geol. Surv., Canada.

fied slate beds a thickness of about 4000 feet. They are shown in the Juneau district and in the Chichagof and Prince of Wales islands.¹ Similar Carboniferous volcanics are described from the Wheaton² and White Horse districts, Yukon Territory, and the Atlin district, British Columbia.³ The rocks are greenstones and tuffs with some associated intrusives of diorite and diabase, and they are referred to as the Perkins group.

In the interior of British Columbia, in the Phoenix district just north of the international boundary line, are a series of Carboniferous beds, known as the Knob Hill, Atwood, and Rawhide formations, all of which contain tuffs and meta-andesites; their Carboniferous age is not, however, established beyond doubt.⁴ Some of the basic volcanics at Rossland, British Columbia, belong to the same age. Describing the volcanic rocks of the Eagle River region of southeastern Alaska, A. Knopf⁵ states that the volcanic greenstones of the Carboniferous differ markedly from the younger volcanic greenstones, in that they consist of andesites and even more salic lavas, while the Mesozoic effusives are highly pyroxenic lavas.

Farther to the northeast in central Alaska, the intensity of the Carboniferous eruptions appears to have subsided. Tuffs and flows are reported from few places and those mainly in the Copper River and Upper Tanana basins. From the former region, W. C. Mendenhall describes the Mankomen Series of Permian age, which contain much volcanic material. The lavas of the Chitina and White rivers are probably of Mesozoic age.

Summary. Almost the whole of the igneous activity of the Palæozoic is concentrated along the Pacific coast and is mainly represented by basic or medium basic effusives, poured out during sedimentation, in part submarine. Rhyolites are entirely subordinate and reported from few localities. The effusive belt

¹ Wright, F. E. and C. W., Bull. U. S. Geol. Surv., No. 347, 1908.

Spencer, A. C., Bull. U. S. Geol. Surv., No. 287, 1906.

² Cairnes, D. D., Mem. Geol. Surv., Canada, No. 31, 1912.

³ Cairnes, D. D., Mem. Geol. Surv., Canada, No. 37, 1913.

⁴ LeRoy, O. E., Mem. Geol. Surv., Canada, No. 21, 1912.

⁵ Bull. U. S. Geol. Surv., No. 502, 1912, p. 18.

extends from central California to southeastern Alaska; the greatest eruptions took place in the latter region.

THE TRIASSIC AND JURASSIC EFFUSIVES

General. With the dawn of the Mesozoic there was ushered in a period of intense volcanic activity. As during the Palæozoic, this was almost wholly restricted to the border of the Pacific, west of Longitude 115° in the United States, to the western Cordillera in Canada and to southeastern and southern Alaska. The eruptions were, however, much more widespread and intense than those in the Palæozoic era.

It is not always easy to separate strictly the Triassic from the Jurassic effusives.

Triassic Effusives. Thick sheets of Upper Triassic basic greenstones with tuffs are intercalated in the sedimentary rocks of the northern Sierra Nevada,¹ well up towards the summit region. The horizon is in the uppermost Triassic and lowest Jurassic. More extensive were, however, the eruptions of a more easterly belt in California, Nevada, and Oregon, and they differ from the preceding and immediately succeeding igneous epochs in that a great succession of andesites and rhyolites were erupted, the earliest of such great differentiated groups.

From the Inyo Range, Adolph Knopf² has described at least 4500 feet of andesites belonging to the Upper Triassic, and overlying limestones and slates of marine origin. Farther north, in the Humboldt Range of Nevada, F. L. Ransome³ has found that the Lower Trias (Koipato Series) of the Fortieth Parallel Survey contains an abundance of volcanic flows, mostly rhyolites but also some andesites. Both kinds of flows are also to some extent present in the upper part of the Triassic (Star Peak Series).

¹ Lindgren, W., Colfax folio (No. 66); and Turner, H. W., Downieville folio (No. 37), U. S. Geol. Surv.

² Bull. U. S. Geol. Surv., No. 540, 1914, p. 91.

³ Bull. U. S. Geol. Surv., No. 414, 1909.

Still farther north along longitude 117° , the marine Trias is exposed in eastern Oregon¹ along the Snake River. The exact stratigraphic position is not known, but basalts, rhyolites, and andesites are associated in a thick series with marine limestone and shale.

The Triassic eruptions probably continued all along the Pacific coast northward from Oregon, but they have not been found in Washington. On Vancouver Island they may be present, but cannot as yet be differentiated from the Jurassic rocks. A short distance north of the boundary we meet the Nicola Series² of 4000 feet or more of Triassic basaltic rocks associated with some sediments. The series which was first described by G. M. Dawson has been metamorphosed almost as much as the underlying Carboniferous sediments. These volcanics have been more recently examined by Charles Camsell³ in the Tulameen district, British Columbia. This geologist states that the rocks consist of andesites, porphyrites, and diabases, and regards them as submarine eruptions. Some of the Rossland, British Columbia, basic volcanics are also believed to be of Triassic age.

On the east side of the Strait of Georgia are found Triassic marine sediments underlain and interbedded with heavy masses of andesite and basalts, collectively called greenstones.⁴ They are grouped under the names of Valdes and Parson Bay formations and have been metamorphosed by the Coast Range intrusives. No Triassic volcanics have been recognized in southeastern Alaska in the Yukon Territory and in the interior of Alaska.

In southern Alaska, between White River and Cook Inlet, thick beds of greenstones and tuffs occur in various formations. In many cases the age is uncertain—whether late Palæozoic or Triassic—and some beds seem to lie between the two periods.

¹ Lindgren, W., 22d Ann. Rept., U. S. Geol. Surv., part 2, 1901, p. 581.

² Daly, R. A., Summary of a Reconnaissance of the Shuswap Lakes and Vicinity: Summary Rept., 1911, Geol. Surv., Canada, Reprint No. 1218a.

³ Mem. Geol. Surv., Canada, No. 26, 1913, p. 39.

⁴ Bancroft, J. A., Mem. Geol. Surv., Canada, No. 23, 1913, pp. 68-77.

In the White River region,¹ the Carboniferous contains tuffs, thick flows of basic lavas, and pyroclastics of possibly Triassic age.

In the Nizina district on the Chitina River, the 4000 feet thick diabase of the Nicolai greenstone formation immediately underlies the Triassic Chitistone limestone. Farther west similar rocks are shown to exist in the headwaters of Susitna and Gulkana rivers,² and south of the Alaska Range. The Trias is here well developed, but in the Alaska Peninsula little volcanic material seems to have been recognized in the series.

Summary of Triassic Eruptions. Along the whole Pacific coast from Inyo County, California, to the Alaska Range, effusive rocks are found associated with marine Triassic sediments. Generally they are of very basic character, but in California, Nevada, and Oregon a well-differentiated series of andesites and rhyolites are present. To a considerable extent the flows are submarine and all of them were poured out near the old shore line. No intrusive rocks are known.

Jurassic Effusives. The Jurassic lava flows were of even greater volume than those of the Trias and follow the same lines of distribution along the Pacific coast. Greenstones of basic character predominate but many of the rocks are less altered than the eruptives of greater age.

The most southerly³ belt of eruptives begins along the foothills of the Sierra Nevada,⁴ and extends up to its northerly end.⁵ The rocks represent enormous ejectionments of a series of

¹ Moffit and Knopf, Bull. U. S. Geol. Surv., No. 417, 1910, p. 16.

² Moffit, F. H., Bull. U. S. Geol. Surv., No. 498, 1912.

³ Surface flows of old rhyolites and andesites of pre-Chico age are reported from San Diego County, California, and the vicinity of Ensenada, Lower California. It is not certain whether they are of Cretaceous or Jurassic age. (W. Lindgren, Proc. California Acad. Sci., (2), vol. 1, part 1, 1888.)

⁴ Lindgren and Turner, Gold Belt folios, U. S. Geol. Surv.

Turner, H. W., Further Contributions, etc., 17th Ann. Rept., U. S. Geol. Surv., part 1, 1896.

⁵ Diller, J. S., Bull. U. S. Geol. Surv., No. 353, 1908.

volcanoes of late Jurassic time comprising diabase, basalts, augite, and andesites, more rarely gabbros and thick masses of tuffs; quartzose rocks analogous to dacites occur in small volume. Along certain lines the igneous rocks are deeply altered to greenstones and amphibolites, and in some places erosion has exposed basic intrusives.

Farther north near Redding, California,¹ Diller describes Jurassic andesites. Jurassic greenstones are also found in southeastern Oregon, particularly near Galice.² In the Cascade Range of Washington, Jurassic volcanics appear to be absent, as far as the exposures below the Tertiary lavas permit examination.

In British Columbia, the igneous activity became intense during the Jurassic. From Vancouver Island, C. H. Clapp³ describes extraordinarily thick masses of basalts, diabases, meta-andesites, and "augite porphyrites" belonging to the Vancouver and the Sicker Series, the former possibly in part of Upper Triassic age.

On the mainland opposite Vancouver Island, no Jurassic volcanics are found, but heavy flows of basic andesites and tuffs of Middle Jurassic age have recently been found in the Queen Charlotte Islands.⁴

Mesozoic andesites and basalts believed to be Jurassic are reported from Prince of Wales Island.⁵ Farther north in the Juneau gold belt, a broad belt of highly basic "augite-melaphyres" follows the coast from Berners Bay to Douglas Island.⁶

Farther north and somewhat away from the coast, Jurassic to Cretaceous basic volcanics have been reported from the Atlin

¹ Redding folio (No. 138), U. S. Geol. Surv.

² Diller, J. S., Bull. U. S. Geol. Surv., No. 546, 1914.

³ Mem. Geol. Surv., Canada, No. 36, 1913; Mem. Geol. Surv., Canada, No. 13, 1912.

⁴ MacKenzie, J. D., Results not yet published.

⁵ Wright, F. E. and C. W., Bull. U. S. Geol. Surv., No. 347.

⁶ Knopf, Adolph, Bull. U. S. Geol. Surv., No. 502, 1912; No. 446, 1911.

and Wheaton districts¹ under the names of the Laberge and Chieftain Hill Series.

Farther west, in southern Alaska, the Jurassic is believed to be represented by the Orca greenstones,² but no Triassic or Jurassic lavas are known from the Alaska Peninsula.³

Summary of Jurassic Eruptions. The Jurassic effusives and tuffs follow the Pacific coast line with few interruptions from central California to southern Alaska. They are throughout of basic composition and often consist of rocks termed augite melaphyres, or augite porphyrites or diabase porphyrites; in part these are altered to massive or schistose amphibolites. They present great similarity to the Triassic lavas but are more basic on the whole. The rocks are commonly highly sodic and in many potash is present only in traces. The eruptions were in part submarine, in part they issued from volcanoes placed along the shore line.

JURASSIC-CRETACEOUS INTRUSIONS

General Features. We now come to the most striking phenomenon of the whole igneous history of the Cordilleran region. Intensive folding had corrugated the Palæozoic and the Mesozoic sediments and lava flows and in part they have been converted into schists. Mountain ranges already outlined during the movements at the end of the Carboniferous now became strongly accentuated. At this time—at the end of the Jurassic or the beginning of the Cretaceous—intrusions began on a large scale along the coast, accompanied by a marked uplift; magmas in great volume were intruded, forming the great chain of batholiths now exposed by erosion all along the Pacific from Lower California to the Alaska Peninsula.

In comparison with this intrusion, all later and earlier igneous phenomena—save the pre-Beltian—fade into insignificance.

¹ Cairnes, D. D., Mem. Geol. Surv., Canada, No. 37, 1913; No. 31, 1912.

² Grant and Higgins, Bull. U. S. Geol. Surv., No. 443, 1910.

Capps and Johnson, Bull. U. S. Geol. Surv., No. 542, 1913, pp. 86-124.

³ Atwood, W. W., Bull. U. S. Geol. Surv., No. 467, 1911.

A glance at the geological map of North America reveals the main geographic features of these intrusions.

The magma crystallized as a coarse granitic rock but its average composition is not that of a granite but a granodiorite and large areas have the characteristics of quartz monzonite or quartz diorite. The rocks are uniformly gray or whitish. Hornblende and biotite are usually present, as well as quartz, andesine, and orthoclase. Microcline is absent or subordinate. The silica averages about 66 per cent, the lime 3 to 4 per cent. The rocks are either predominantly sodic or carry about equal quantities of soda and potash. Pegmatites are, speaking broadly, absent, compared to the great pegmatitization of pre-Cambrian intrusives. Where they are present, soda pegmatites prevail. Aplites are more plentiful, often they are soda aplites and in places complementary basic dikes like minette or vogesite appear. A considerable amount of titanite is almost characteristic of the granular rocks. Boron and fluorine minerals are rare. The mineralizers present in greatest abundance were chlorine and sulphur, the former indicated by the abundance of scapolite in many contact zones, the latter by the great and widespread mineralization by sulphides, which has been caused particularly by the smaller satellitic intrusions.

The batholiths are not homogeneous bodies but consist of a great number of separate intrusions; some of them are, however, of gigantic dimensions. In the western foothills of the Sierra Nevada in California smaller intrusions appear which are often of quartz diorite, diorite, gabbro, or granodiorite. The main mass is of granodiorite or quartz monzonite; and near the summit region, especially in the Sierra Nevada, we find smaller intrusions of almost normal granites high in silica and with predominating potash.

Distribution. The intrusions begin in Lower California,¹ where, however, the age is not definitely fixed. The rocks are quartz diorites near the coast and granodiorites with about 16 per cent orthoclase near the summit.

¹ Lindgren, W., Proc. California Acad. Sci., (2), vol. 1, part 2, 1888.

The rocks in southern California are imperfectly known. The quartz diorites and granodiorites continue across the boundary line and intrude Carboniferous rocks in San Diego County, and Triassic rocks near Riverside. In the San Gabriel Range,¹ normal granodiorites prevail with some quartz monzonites and granites. The batholith appears in full development along the whole length of the Sierra Nevada. The introductory notes portray the general conditions in this belt.²

The batholith of the Sierra Nevada is 400 miles long and has a maximum width of eighty miles. It breaks through sediments of latest Jurassic age. In northern California the main part of the batholith is covered by Tertiary volcanics, but near Redding,³ minor areas of quartz diorites and alaskite porphyry (keratophyre) are known. Earlier than these, but belonging to the same series of intrusions, are basic rocks like serpentine and peridotite, and the latter are also well developed in southern Oregon at the foot of the Cascade Range.

The next appearance of the batholith underneath the Tertiary lavas is in northwestern Washington, where George Otis Smith describes rather large areas of granodiorite intruded in peridotite, both of late Jurassic or Cretaceous age.⁴

Along the international boundary the batholithic masses are split into many bodies and spread over a width of 350 miles.

¹ Arnold and Strong, *Bul. Geol. Soc. America*, vol. 16, 1904, pp. 183-204.

² Turner and Lindgren, *U. S. Geol. Surv., folios Downieville (37), Bidwell Bar (43), Colfax (66), Truckee (39), Pyramid Peak (31), Placerville (3), Sacramento (5), Big Trees (51), Sonora (41), Smartsville (18), Jackson (11)*.

Turner, H. W., 17th Ann. Rept., *U. S. Geol. Surv.*, part 1, 1896, pp. 521-762.

Iddings, J. P., *Igneous Rocks*, vol. 2, 1913 (Collection of Analyses).

Lindgren, W., *Am. Jour. Sci.*, (4), vol. 3, 1897, pp. 301-314.

³ Diller, J. S., Redding folio (No. 138), *U. S. Geol. Surv., Bull. U. S. Geol. Surv.*, No. 546, 1914.

⁴ Mount Stuart folio (No. 106), *U. S. Geol. Surv.*

Weaver, C. E., *Bulls. Washington Geol. Surv.*, Nos. 6 and 7, 1911 and 1912.

R. A. Daly¹ here distinguishes twelve bodies. The earliest are granodiorites and of Jurassic age. The later are classed as granites, largely rich in soda and not like the pre-Cambrian granites, and a Miocene age is assigned to these; the evidence of this is not wholly convincing and they may well be late Cretaceous. The Jurassic granodiorites, in contrast to those of the Sierra Nevada and the Coast Range further north are often sheared and gneissoid.

North of the boundary the great Coast Range batholith begins and extends without break for 1100 miles, with a greatest width of 120 miles, into the southern part of Yukon Territory. It is probably the greatest single intrusive mass known. Many smaller bodies are intruded in the schists along the immediate coast line. Here, as elsewhere, the batholith is made up of a great number of separate and interlocking intrusions.

On Vancouver Island,² large masses of diorite, quartz diorite, and granodiorite are intruded and are of Jurassic or early Cretaceous age. On the mainland opposite the island,³ quartz diorite, granodiorite, and granite are the dominant rocks, the first named being the most prevalent type. From here north to its end in Yukon Territory, the batholith seems to be largely composed of quartz diorite with many dikes of soda pegmatite.⁴ Near Berners Bay and Eagle River the diorite is in part gneissoid.

The age of this batholith in Alaska and British Columbia is probably early Cretaceous. F. E. and C. W. Wright prefer to assign to it a Middle Jurassic age.⁵

In Alaska, where the Coast Cordillera bends sharply westward, the batholith breaks up in numerous smaller and some larger areas. In the Yukon-Tanana region, granitic rocks and those

¹ Bull. Geol. Soc. America, vol. 17, 1906, pp. 329-376.

² Clapp, C. H., Mem. Geol. Surv., Canada, No. 13, 1912.

³ Baneroft, J. A., Mem. Geol. Surv., Canada, No. 23, 1912.

⁴ Wright, F. E. and C. W., Bull. U. S. Geol. Surv., No. 347, 1908.

Spencer, A. C., Bull. U. S. Geol. Surv., No. 287, 1906.

Knopf, Adolph, Bull. U. S. Geol. Surv., No. 446, 1911.

⁵ *Op. cit.*

of intermediate composition are most common and some of the granites have been transformed into gneisses. The areas are abundant in the eastern part of this region but towards the west the exposures are less prominent. L. M. Prindle believes that the intrusives underlie a large part of the region.¹ Biotite granites predominate in the Fairbanks district. In the Alaska Range² and the Cook Inlet region are large intrusive areas ranging from granite and quartz monzonite to granodiorite and diorite, Mount McKinley being the centre of one of the largest masses. Quartz diorite and biotite granite are the most abundant. The age of all of these Alaskan intrusives is considered to be Cretaceous.

Still farther west along the southern coast of the Alaska Peninsula³ are several smaller areas of granitic rocks considered to be of Middle or Lower Jurassic age. Numerous areas of pre-Cretaceous and post-Palaeozoic biotite granites with an unusual train of pegmatite dikes, occasionally also tourmaline and cassiterite, occur in the Palaeozoic schists of the Seward Peninsula.⁴

Summary of Jurassic-Cretaceous Intrusion. Broadly speaking the coast batholiths were intruded from the middle of the Jurassic to the end of the Cretaceous, though a few minor intrusions of Eocene, or even Miocene age may be found. The bulk of the intrusion probably falls in the earliest Cretaceous.

The intrusions seem to have begun on the west side by irruption of basic magma—peridotites, pyroxenites, and gabbro—and gradually extended eastward, while the composition became more acidic and finally granitic. In any separate intrusion the same succession holds good, so that we find basic material near the walls and in embayments, while the great masses range from quartz monzonite to quartz diorite.

¹ Bull. U. S. Geol. Surv., No. 525 (Fairbanks Quadrangle), 1913.

² Brooks and Prindle, Prof. Paper, U. S. Geol. Surv., No. 70, 1911, p. 153.

³ Atwood, W. W., Bull. U. S. Geol. Surv., No. 467, 1911.

⁴ Moffit, F. H., Bull. 533, 1913; Smith, P. S., Bull. 433, 1910; Knopf, Adolph, Bull. 358, 1908; U. S. Geol. Surv.

THE CRETACEOUS COAST RANGE INTRUSIVES

The Coast Range of California has, since the early Cretaceous, been subject to repeated upward and downward movements and is tremendously dissected by complex faulting of recent and Tertiary age.

The pre-San Franciscan¹ quartz diorites of the Coast Range exposed in small areas from Tejon Pass to Marin County are of doubtful age. Some hold them to be Palæozoic intrusions, while others consider them Mesozoic precursors of the batholith of the Sierra Nevada.

The most characteristic of the igneous rocks of the Coast Ranges are basic intrusives including diabase, diabase porphyries, basalts, gabbro, pyroxenites, peridotites, and serpentine,² which in irregular masses occupy much space. They are intruded in the San Franciscan Series (Jurassic ? early Cretaceous ?) and also in the Knoxville Cretaceous, but do not reach the Chico Cretaceous. The intrusions, therefore, are post-Jurassic and earlier than the middle of the Cretaceous. The San Franciscan also contains some interbedded basic volcanics. The relations of these basic intrusives to the main batholith are not definitely ascertained. In mode of eruption they are entirely different. Probably they were, in the main, later than the batholithic masses.

THE CRETACEOUS PERIOD

Pacific Coast. After the great batholithic intrusions and the basic intrusions of the Coast Range, the igneous activity along the Pacific coast slackened, and we find in fact extremely few igneous rocks interbedded in sediments of late Cretaceous age.

¹ The sandstones and cherts of the San Franciscan formation are probably of Jurassic age. They occupy large areas in the Coast Range of California.

² Lawson, A. C., San Francisco folio (No. 193), U. S. Geol. Surv., 1913. Branner, J. C., Santa Cruz folio (No. 163), 1909.

Fairbanks, H. W., San Luis folio (No. 101), 1905.

In California, Oregon, Washington, Vancouver Island, Queen Charlotte Islands, and Alaska, the Cretaceous record is one of quiet sedimentation. The same absence of Cretaceous igneous rocks applies to the larger part of the interior and the whole of the southern part of the Cordilleras, including Mexico.

Eastern Cordilleras. In contrast to this, lavas now began to break out along what was to be the eastern edge of the Cordilleras, in Alberta and Montana, in a region exempt since the Beltian from igneous disturbances. This is the first manifestation of the forces which were to create the Laramide system of ranges, at the close of the Cretaceous. The first outbreaks took place in Alberta near Crowsnest Pass,¹ where tuffs of analcite basalts occur in the Fort Benton Series of the Upper Cretaceous.

A large area of "andesite," probably of late Cretaceous age, is exposed between Butte and Helena, in Montana, and the Boulder batholith, mentioned in the next paragraph, is intrusive into this flow rock. The "andesite" has affiliations with dacite and latite and shows in its chemical composition undoubted relationship with the intrusive rock.

LATE CRETACEOUS OR EARLY EOCENE

The batholithic intrusions of the Pacific coast gradually spread eastward. In many cases the time of intrusion is in doubt, owing to the absence of Cretaceous strata over a large part of the interior. The two largest masses are known as the Idaho² and the Boulder³ batholith. The former covers an area of about 22,000 square miles and its main mass is a quartz-biotite monzonite, though it has many marginal facies of granodiorite, etc.

The Boulder batholith in Montana has an area of about 1000 square miles and a composition similar to the former, but carries

¹ Knight, C. W., Canadian Record of Science, Montreal, vol. 9, 1905, pp. 265-278.

MacKenzie, J. D., Geol. Surv., Canada. Museum Bulletin, 1914.

² Umpleby, J. B., Bull. U. S. Geol. Surv., No. 539, 1913.

W. Lindgren, 20th Ann. Rept., U. S. Geol. Surv., Part III, pp. 65-256, 1900; Prof. Paper 27, U. S. Geol. Surv., 1904.

³ Knopf, Adolph, Bull. U. S. Geol. Surv., No. 527, 1913.

both biotite and hornblende. The age of both is regarded as late Cretaceous or possibly earliest Eocene.

There are very many smaller batholiths, stocks and laccoliths scattered through Montana, Nevada, Colorado, Utah, New Mexico, and Arizona; they are almost always quartz monzonites or granodiorites, in places grading into more acid alaskites, and are often intruded in late Cretaceous beds. On the other hand, the Miocene lavas cover their eroded outcrops. Wherever they intrude the Cretaceous beds, a laccolithic development follows.

In Montana many smaller satellitic intrusions surround the Boulder batholith,¹ and in the Front Ranges are sheets and laccoliths of about the same age. Some of these rocks are of the alkaline type.²

In western Colorado a group of laccoliths which in general are granodiorite porphyries have been described by W. Cross.³ Another belt of small intrusive stocks, sheets, and dikes extends from Leadville to Boulder County and is on the whole of quartz monzonitic type, although there are many highly acidic and some alkaline facies.⁴ In New Mexico⁵ about fourteen small stocks have been found intrusive in the uppermost Cretaceous and lower strata. A few of them are gabbros or diorites but the majority are intermediate between diorite and granite.

In Arizona the same conditions prevail, for instance at Clifton,⁶ where rocks ranging from diorite porphyry to granite porphyry are intruded in Cretaceous and lower strata, at

¹ Barrell, J., Prof. Paper, U. S. Geol. Surv., No. 57, 1907 (Marysville).

Calkins, F. C., Prof. Paper, U. S. Geol. Surv., No. 78, 1913 (Phillipsburg).

² Weed and Pirsson, Bull. U. S. Geol. Surv., No. 139, 1896; 20th Ann. Rept., U. S. Geol. Surv., part 3, 1899 (Castle Mts.); 18th Ann. Rept., U. S. Geol. Surv., part 3, 1897 (Little Belt Mts.).

³ The Laccolithic Mountain Groups: 14th Ann. Rept., U. S., Geol. Surv., 1895.

⁴ Summary in F. L. Ransome, Geology and Ore Deposits of the Breckenridge District: Prof. Paper, U. S. Geol. Surv., No. 75, 1911.

⁵ Lindgren, Graton, and Gordon, Prof. Paper, U. S. Geol. Surv., No. 68, 1910.

⁶ Lindgren, W., Prof. Paper, U. S. Geol. Surv., No. 43, 1905.

Globe,¹ Bisbee,² Silver Bell,³ Bradshaw Mountains,⁴ Harqua Hala,⁵ and Wallapai Mountains,⁶ and many other places. In the latter three cases the age of the intrusives is uncertain. At Bisbee granite porphyry was intruded previously to the early Cretaceous, and many of the Arizona intrusives may be of earlier age than those farther north.

In Utah a series of minor intrusions of monzonitic character, such as those of Park City and Little Cottonwood⁷ in the Wasatch Mountains and the San Francisco⁸ district, Utah, may belong to the earliest Tertiary. In the San Francisco district, the intrusion of granodiorite and quartz monzonite is accompanied by flows of andesites, latites, and rhyolites and is in fact a stock intruded in an old volcano.

There are many more such areas in Utah. Still more abundant are these small intrusions in Nevada⁹ and eastern California, but here the intrusions appear to be older and but little later in age than the great California batholith. Exact dates are difficult to fix, owing to the absence of Cretaceous beds, but near Winnemucca large intrusions of granodiorite occur in Jurassic strata.¹⁰

EOCENE ERUPTIONS

With the Eocene the great Tertiary Series of effusives begins which in the Miocene was destined to extend over the whole of the Cordilleran region.

In California, both in the present Coast Range and along the foot of the Sierra Nevada, the Eocene was a period of quiet sedimentation without volcanic activity. Farther north, diabase and basalt flows were erupted along the coast and along the

¹ Ransome, F. L., Prof. Paper, U. S. Geol. Surv., No. 12, 1903.

² Ransome, F. L., Prof. Paper, U. S. Geol. Surv., No. 21, 1904.

³ Stewart, C. A., Trans. Am. Inst. Min. Eng., vol. 43, 1913, pp. 240-290.

⁴ Jaggar and Palache, Geol. Atlas U. S., U. S. Geol. Surv., folio 126, 1905.

⁵ Baneroff, H., Bull. U. S. Geol. Surv., No. 550, 1914.

⁶ Schrader, F. C., Bull. U. S. Geol. Surv., No. 397, 1909.

⁷ Boutwell, J. M., Prof. Paper, U. S. Geol. Surv., No. 77, 1912.

⁸ Butler, B. S., Prof. Paper, U. S. Geol. Surv., No. 80, 1913.

⁹ Ball, S. H., Bull. U. S. Geol. Surv., No. 308, 1908.

¹⁰ Lindgren, W., unpublished notes.

foot of the Cascade Range in the Eocene¹ of Oregon and of Washington.²

On the east side of the Sierra Nevada, rhyolite and basalt with some andesite broke out in heavy flows. Probably there are also in this region smaller intrusions of monzonite.³ Similar eruptions of basalt and rhyolite are recorded in considerable volumes from the eastern slope of the Cascade Range.⁴ Continuing northward, basalts and a little rhyolite are recorded from the extreme southeast of Alaska.⁵ Basalts and andesites of probably Eocene age are described by C. C. Camsell from the Tulameen district, British Columbia⁶ (Cedar Creek volcanic series).

Still farther north in Alaska, Eocene volcanics are known, but do not seem to be abundant. The Kenai formation represents a long period of quiet sedimentation. Eocene basalts and andesite are known from the Porcupine district, from the White River, and from the Alaska Peninsula;⁷ probably the volcanics of the Wrangell Range began their activity in the Eocene. In the interior of Alaska few eruptions took place during the Tertiary.

We return now to the interior of the Cordilleran region in the United States east of longitude 117°. Eocene surface flows are here much less abundant than those of Middle Tertiary age.

In the sediments of the great Eocene lakes which covered so large areas in Wyoming, Colorado, and Utah, and in northwestern New Mexico, there are but few beds of tuffs or volcanic flows. Some rhyolitic tuff is mentioned by A. C. Veatch⁸ from

¹ Diller, J. S., Roseburg and Coos Bay folios (Nos. 49, 73), U. S. Geol. Surv.

² Arnold and Hannibal, *The Marine Tertiary Stratigraphy of the North Pacific Coast of America*: Am. Phil. Soc., vol. 52, No. 212, 1913.

³ Ball, S. H., Bull. U. S. Geol. Surv., No. 408, 1908.

Ransome, F. L., Prof. Paper, U. S. Geol. Surv., No. 66, 1909 (Goldfield).

⁴ Smith, George Otis, and Calkins, F. C., Snoqualmie folio (No. 139), U. S. Geol. Surv.

⁵ Wright, F. E. and C. W., Bull. U. S. Geol. Surv., No. 347, 1908.

⁶ Mem. Geol. Surv., Canada, No. 26, 1913.

⁷ Palache, Charles, *Harriman Expedition*, vol. 4, 1904, pp. 74-79.

⁸ Prof. Paper, U. S. Geol. Surv., No. 56, 1907, p. 50.

southwestern Wyoming. Beds of rhyolitic volcanic ash of considerable extent are found in the Brule formation of Nebraska, but this is probably of Oligocene age.

Andesitic tuffs and flows are found in abundance, however, in the Denver beds in Colorado, which are now considered Eocene. Another centre of Eocene eruptions was in central Montana, near Livingston and the Crazy Mountains. It has already been stated (page 260) that the surface eruptions here began in Cretaceous time and they continued up Fort Union (Eocene formation). Probably many intrusions in the front of the main ranges of Montana were of Eocene age and it is possible that here as well as at many points farther south in the Rocky Mountains the intrusions were accompanied by surface eruptions which now have been eroded.

In the San Juan region in southwestern Colorado, the great series of surface flows began during this period with eruptions of andesites.

In the Yellowstone National Park and adjacent region, igneous activity began at the end of the Laramie with the intrusion of laccoliths and sills of andesitic and dacitic magmas, and with the extrusion of tuffs and breccias of andesite and dacite. In Eocene time minor volcanoes of andesite and basalt were built up. In their eroded cores were intruded stocks of gabbro, diorite, and quartz diorite.¹

At many other places in the interior of the Cordilleran region the eruptions probably began during the Eocene.

MIocene AND PLIOCENE ERUPTIONS

During the Miocene and the Pliocene the volcanism reached its maximum in the Cordilleras, and the eruptions, by far pre-vaillingly of surface flows, are so complex that it is difficult to give a brief summary of them. The eruptions were not, however, equally distributed, for we note their absence over certain conspicuous areas, for instance over the greater part of the Plateau region and the Eocene plateaus in Utah, Wyoming,

¹ Iddings, J. P., *Igneous Rocks*, vol. 2, 1913, p. 415.

and Colorado, and over the larger part of British Columbia, Yukon Territory, and northern Alaska. They are sparsely distributed over the entire Front Ranges of the Rocky Mountains and along the Pacific coast line.

The great volcanic areas are: 1. The Mexican Plateau; 2. The Arizona-New Mexico field; 3. The San Juan region; 4. The Great Basin region, continued into Arizona; 5. The Yellowstone Park area; 6. The Columbia River field; 7. The Sierra Nevada and Cascade belt; 8. The British Columbia field on Okanogan and Fraser rivers; 9. The Queen Charlotte Islands; 10. The Wrangell Mountains and adjacent areas; 11. The Alaska Peninsula and the Aleutian chain. Outside of these are many smaller areas.

These regions constitute the greatest lava areas of the world, the Columbia River field alone occupying 200,000 to 250,000 square miles, with a thickness of flows ranging up to 4000 feet and representing a volume of at least 30,000 cubic miles or a cube with sides of about 30 miles. This volume, then, records the volume transferred in this region from the interior of the earth to the surface.

The Miocene-Pliocene lavas consist largely of characteristically differentiated flows of andesite, dacite, latite, rhyolite, and basalt. The andesites are really intermediate rocks with considerable potash, and the rhyolites are rich in soda. On the whole the entire series bears marks of affinity with the granodioritic magmas of the coast batholiths.

There are also some large basaltic areas in which the relationship mentioned is not so apparent.

AREAL REVIEW OF MIOCENE-PLIOCENE LAVAS

The Mexican Plateau is covered by thick flows of andesite, rhyolite and dacite with subordinate basalt.¹

¹ Ordoñez, E., Boletín del Instituto Geológico de México, Nos. 4, 5, 6, 1897.

Hovey, E. O., Bull. Am. Mus. Nat. Hist., 23, 1907, p. 401.

Weed, W. H., Trans. Am. Inst. Min. Eng., vol. 32, 1902, p. 396 and p. 444.

Along the Pacific coast there are large volcanic areas in the southern half of Lower California, but they are little known. In California the volcanic areas along the coast are small, but eruptions of rhyolite, andesite, basalts and basic intrusives are known and the Miocene Monterey Series contains much rhyolitic tuff. Farther north is the Pliocene andesite area of Lake County. In Oregon along the coast are few Neocene eruptions, but farther north in Washington, the Miocene and Pliocene contain basalts and tuffs.

Along the summit of the Sierra Nevada, a series of volcanoes were active in Miocene-Pliocene times, which flooded the slopes first with minor rhyolite flows, later with large volumes of andesite, the eruptions closing in the late Pliocene with smaller masses of basalt.¹ The rhyolites contain much soda and the andesites at least 2 per cent of potash. The silica in the andesites is not lower than 58 per cent. They are practically flow equivalents of the granodiorite but contain slightly less silica.²

The volcanoes of the Cascade Range probably began their activity in Eocene times and the latest eruptions were in the late Quaternary. The period of greatest activity probably fell in the Miocene and Pliocene. The bulk of the eruptions consists of andesites, though some rhyolite and basalt are present. The Lassen Peak³ andesites are practically equivalents of the granodiorites and are generally called dacites.⁴

Farther north, in Oregon and Washington, andesites are strongly developed and together with dacites build the greater part of the range. In British Columbia, Tertiary volcanics are very sparingly represented along the Coast Range, but on the Queen Charlotte Islands are dikes and sills of andesitic rocks and heavy flows of basalt, all probably of Middle Tertiary age.⁵

Along the coast of southern Alaska, the andesites of the

¹ Lindgren, W., Prof. Paper, U. S. Geol. Surv., No. 73, 1911.

² For analyses see J. P. Iddings, *Igneous Rocks*, vol. 2, p. 441.

³ Diller, J. S., Lassen Peak folio (No. 15), U. S. Geol. Surv., 1895.

⁴ Diller, J. S., and Patton, H. B., Prof. Paper, U. S. Geol. Surv., No. 3, 1902.

⁵ MacKenzie, J. D., Oral information.

Wrangell Range volcanoes and the volcanoes extending from Cook Inlet to the end of the Aleutian chains were in operation during the latter part of the Tertiary.¹

The eruptive masses of the interior of the continent belong to several more or less distinct regions. We have first to consider the great areas of the Columbia River lavas in Oregon, Washington, Idaho, and northern Nevada.

Along the margins of this enormous basaltic field—at the foot of the Cascades² and in John Day Basins³—are exposed basalts, andesites, and rhyolites of Eocene age. The Columbia River basalts themselves are of Miocene age and along their southern margin, in Idaho⁴ and Nevada, they are underlain or interbedded with heavy rhyolite flows of the same age.

In British Columbia the continuation of the great depression of the Columbia River lavas is represented by the lava fields of Okanogan and Fraser rivers. The rocks are regarded as Miocene and consist of a series of andesites, latites, and dacites with some alkaline facies.⁵ G. M. Dawson⁶ states that rocks of the earlier Miocene epoch were chiefly andesites, while in the later Miocene epoch great sheets of basalts were extruded.

South of the Columbia River lava extends the Great Basin with its manifold volcanic manifestation difficult to summarize in a few words.

In western Nevada, andesites, dacites, and rhyolites predominate. F. L. Ransome⁷ has established the succession at

¹ Brooks, A. H., Prof. Paper, U. S. Geol. Surv., No. 45, 1906, pp. 250, 270, 1911, 52.

² Smith, George Otis, folios 86, 106, 139 (Ellensburg, Mt. Stuart, Snoqualmie), U. S. Geol. Surv.

³ Merriam, J. C., and Sinclair, W. J., Bull. Geol. Dept., Univ. California, vol. 5, 1907, p. 173.

⁴ Lindgren, W., and Drake, N. F., Silver City folio (No. 104), U. S. Geol. Surv.

⁵ LeRoy, O. E., The Geology and Ore Deposits of Phoenix, B. C.: Mem. Geol. Surv., Canada, No. 21, 1912.

⁶ Bull. Geol. Soc. America, vol. 12, 1901, p. 81.

⁷ Prof. Paper, U. S. Geol. Surv., No. 66, 1909, p. 105.

Goldfield; it is complicated with many repetitions. Farther south, rhyolites and basalts predominate.¹ In northeastern Nevada according to the results of the Fortieth Parallel Survey, recently summarized by W. H. Emmons,² rhyolites predominate. The eruptions probably began in early Miocene times and the general succession established is (1) rhyolite, (2) andesite, and (3) basalt. The basalts are regarded as Pliocene.

The eruptives of the Great Basin continue southward into California and Arizona along the Colorado River,³ the principal flows being rhyolite, andesite, and trachyte. The basalts are of small volume.

In east-central Arizona, the basalt flows of the Mogollon Mesa, extending into New Mexico, are the most prominent feature. Where examined along the southern margin,⁴ the eruption seems to have taken place from central vents. There were several repetitions of rhyolite and basalt.

The volcanic rocks of Arizona are continued into New Mexico⁵ and have a wide distribution in the western part of the state. The general succession of the heavy flows is (1) rhyolite; (2) andesite and latite; (3) rhyolite; (4) basalt, the latter probably of Pliocene or even Quaternary age.

In Colorado we have first the remarkable volcanic complex of the San Juan region.⁶ Here the first outbursts are placed in the Eocene, but they continued through the Miocene and the Pliocene. The flows were erupted from central vents.

¹ Ball, S. H., Bull. U. S. Geol. Surv., No. 308, 1907.

Spurr, J. E., Bull. U. S. Geol. Surv., No. 208, 1903, p. 147.

Summary by B. S. Butler in Prof. Paper, U. S. Geol. Surv., No. 80, 1913, pp. 64-70.

² Bull. U. S. Geol. Surv., No. 408, 1910, p. 34.

³ Schrader, F. C., Bull. U. S. Geol. Surv., No. 397, 1909.

⁴ Lindgren, W., Clifton folio (No. 129), U. S. Geol. Surv., 1905.

⁵ Lindgren, Graton, and Gordon, Prof. Paper, U. S. Geol. Surv., No. 68, 1910, p. 42.

⁶ Folio 57 (Telluride), 120 (Silverton), 130 (Rico), 171 (Engineer Mountain), 153 (Omay), U. S. Geol. Surv.

For summary see Whitman Cross in Bull. U. S. Geol. Surv., No. 478, 1911, pp. 18-22.

The earliest members consist of andesitic tuffs of the San Juan Series, with a greatest thickness of 3000 feet. These are covered by the Silverton Series of rhyolite, andesite, and latite, the Potosi Series of latite and rhyolite, and the Hinsdale Series which contains rocks ranging from rhyolite to basalt. Normal basalts are subordinate in the San Juan region and the enormous complexity of eruptions makes futile the establishment of a simple succession. Towards the close of the volcanic activity, quartz monzonite porphyries were intruded into the older lavas and sediments as sheets and stocks.

North and east of the San Juan region in Colorado are a number of smaller volcanic vents. Some of these yielded andesite lavas only; others chiefly lavas of rhyolitic types¹ like Silver Cliff and Rosita Hills. A rarer type, represented by the Miocene volcano of Cripple Creek,² yielded lavas of alkaline type.

In Utah were several volcanoes of the type of central vents, which were active in Tertiary times and yielded rhyolite and andesite lavas, often with intrusions of quartz monzonitic or granodioritic type. Those located at Tintic and San Francisco are good examples (see references on p. 262), but there are many others. The exact time of eruption can rarely be established.

In southern Utah is the volcanic complex of the Tushar Range and vicinity,³ here are widely distributed flows of dacites, covered by rhyolites. Small bodies of monzonites are intruded in the volcanoes. Another large area of volcanic flows, mainly andesite, lies along the boundary of Nevada and southern Utah.

North of Utah two main volcanic areas of Miocene age stand

¹ Cross, Whitman, 17th Ann. Rept., U. S. Geol. Surv., part 2, 1896, pp. 263-403.

² Cross, Whitman, Pikes Peak folio (No. 7), U. S. Geol. Surv.

Lindgren, W., and Ransome, F. L., Petrography by L. C. Graton: Prof. Paper, U. S. Geol. Surv., No. 54, 1906.

³ Dutton, C. E., Geology of the High Plateaus of Utah: U. S. Geogr. and Geol. Surv., 1880, p. 184.

Butler, B. S., Bull. U. S. Geol. Surv., No. 511, 1912, pp. 12-16.

out prominently. One of them is in central Idaho and its lavas cover the Idaho batholith. Andesites and latites began the series; these were followed by rhyolitic and andesitic tuffs; basalt closed the succession.¹

The second great center of Miocene activity is in the Yellowstone National Park region.² Here the eruptions had already begun during the Eocene but they continued in enormous volume during the Miocene and Pliocene. The early Miocene succession shows andesitic breccias followed by some rhyolite and basalt and succeeded by heavy beds of andesite breccia.

The eruptions were closed by unusually heavy flows of rhyolite, intercalated with basalt, and on top of this rhyolite lies a thinner sheet of Quaternary basalt. Granodiorite porphyry is intrusive in the Miocene flows.

LATE PLIOCENE AND QUATERNARY VOLCANOES

We have now come down to the most recent periods. It remains to consider the late Pliocene and the Quaternary; it is impossible to draw a sharp line between these two periods in the Cordilleran region.

During the late Pliocene the last andesitic eruptions took place in the Coast Ranges and the Sierra Nevada of California and in western Nevada. The Cascades from Shasta to Mount Baker poured out their andesite floods in full force (with some basalts)—as did no doubt the Alaskan and Aleutian volcanoes. Throughout Mexico, andesites, dacites, rhyolites, and basalts continued to be erupted. In the rest of the Cordilleras in the United States, the basalts are almost the only igneous rocks of the period, and they were erupted from many fissures and small cones.

¹ Umpleby, J. B., *Bulls. U. S. Geol. Surv.*, Nos. 528 and 539.

² Hague, A., and Iddings, J. P., *Yellowstone National Park folio* (No. 30), *U. S. Geol. Surv.*

Iddings, J. P., *Igneous Rocks*, vol. 2, 1913, pp. 350, 415.

The most prominent areas of Pliocene basalts are those of the Snake River Plains,¹ and of the San Luis Valley² in southern Colorado, and the Rio Grande Valley³ of New Mexico. Numerous basaltic vents of that age are also found in Nevada and Arizona.⁴

Finally we take a last general review of igneous activity in the Quaternary ranging down to the present time.

Scattered Quaternary basalt flows are found in the Coast Range⁵ of California and along the Sierra Nevada, particularly along the eastern slope. A string of almost recent small basalt cones and a few small rhyolitic craters⁶ follow the eastern scarp of the Sierra Nevada; abundant andesites were erupted along the Cascades. Some dacite flows in the Lassen Peak region⁷ date from a hundred years back. In 1914 Lassen Peak resumed its rôle of an active volcano by numerous eruptions of dacitic fragmentary material.

The andesite eruptions of the Cascades which began in the Miocene have persisted to recent time and the Alaskan and Aleutian volcanoes are still emitting such lavas and dust in abundance. Equally active during the Quaternary were the andesitic volcanoes of the Mexican chain, from Colima to Orizaba.

In the eastern part of the Cordilleran region no eruptions are recorded in Canada, in Wyoming, Montana, and Colorado. Otherwise, the Quaternary eruptions are widely scattered in the central Cordilleran region from Washington to Mexico.

¹ Lindgren, W., and Drake, N. F., Boise and Nampa folios (Nos. 45, 103), U. S. Geol. Surv.

Lindgren, W., 20th Ann. Rept., U. S. Geol. Surv., part 3, 1900, p. 99.

Russell, I. C., Bull. U. S. Geol. Surv., No. 199, 1902.

² Siebenthal, C. E., Water-Supply Paper: U. S. Geol. Surv., No. 240, 1910.

³ Lindgren, Graton, and Gordon, Prof. Paper, U. S. Geol. Surv., No. 68, 1910.

⁴ Lee, W. T., Bull. U. S. Geol. Surv., No. 352, 1908.

⁵ Becker, G. F., Mon. U. S. Geol. Surv., No. 13, 1888.

⁶ Russell, I. C., 8th Ann. Rept., U. S. Geol. Surv., part 1, 1889, pp. 261-394.

⁷ Diller, J. S., Lassen Peak folio (No. 15), U. S. Geol. Surv., 1885.

They produced basalt only and they originated from a vast number of separated vents, each of which often yielded but a small mass of ejecta. None took place within historic times. In eastern Washington and in eastern Oregon, in the Snake River Valley of Idaho,¹ in Nevada, and in Utah there are many of these small vents. Continuing south from the Snake River Valley, basalt cones are found in the Salt Lake Basin;² they thickly dot some of the high plateaus of southern Utah³ and some of the plateaus overlooking the Colorado River.⁴ South of that river these remarkable basaltic dots are scattered in the vicinity of the San Francisco Mountains,⁵ which form a group of cones of dacite eruptions of Pliocene age, and isolated position.

South of the San Luis Valley in Colorado,⁶ which is occupied by a large area of Pliocene basalt, a broad belt of small Quaternary basalt eruptions begins and continues through New Mexico,⁷ in part with alkaline facies, down to the international boundary.⁸ Some of these craters are well preserved; the flows are scoriaceous and fresh. Quaternary basalts are also described from western Arizona and northern Mexico.

There exists a long space in British Columbia and Alberta, from the international boundary line up towards Yukon Territory, from which the Quaternary basalts appear to be absent. But in Yukon Territory and in the plateau region of Alaska comparatively small flows have been observed in many places.

¹ Russell, I. C., Bull. U. S. Geol. Surv., No. 199, 1902.

² Gilbert, G. K., Mon. U. S. Geol. Surv., No. 1, 1890.

³ Dutton, C. E., Rept. Geology High Plateaus of Utah, 1880.

⁴ Dutton, C. E., Mon. U. S. Geol. Surv., No. 2, 1882.

⁵ Robinson, H. H., Prof. Paper, U. S. Geol. Surv., No. 76, 1913.

⁶ Siebenthal, C. E., l. c.

⁷ Darton, N. H., Bull. U. S. Geol. Surv., No. 435, 1910.

Lindgren, Graton, and Gordon, Prof. Paper, U. S. Geol. Surv., No. 63, 1910.

⁸ Lee, W. T., The Acton Craters: Bull. Geol. Soc. America, vol. 18, 1908, pp. 211-220.

QUANTITATIVE RELATIONS OF TERTIARY EFFUSIVES

Regarding the quantitative relation of the various rocks it is difficult to pass judgment. Along the western part of the eruptive zone, along the Cascades and the Sierra Nevada, andesites predominate beyond question. They also occupy large areas in San Juan County, Colorado, and in the ranges east of the Yellowstone National Park. They are plentiful in the Great Basin, and in the volcanic areas of Arizona and New Mexico; but in the Great Basin their volume is exceeded by the rhyolites, and in the two latter states by the basalts. Basalts of ages ranging from Eocene to Pliocene cover thousands of square miles within the region of the Columbia River and northern Nevada. A large part of the Columbia River lava, especially along the southern margin, is, however, underlain by rhyolite, and in Nevada rhyolite is the most abundant lava. On the whole, basalt is probably the most widely spread of the Tertiary effusives.

As stated above, the larger part of the rhyolites contains much soda, and the so-called andesites are abnormally rich in potash, making them the equivalents of the granodiorites and monzonites or quartz monzonites, especially as many of them evidently contain free quartz; they are thus in large part dacites and latites.

SUCCESSION OF TERTIARY EFFUSIVES

The succession of the various rocks has been studied in many districts with somewhat discordant results. Richthofen's conclusion, announced at an early date, was that the eruptions in Nevada began with andesite, which later was followed by trachyte, rhyolite, and basalt in the order given. Since that time our knowledge has increased greatly and the subject has been studied by Iddings, Cross, Spurr, Ransome, Ball, and others. Iddings¹ believes that the eruptions begin in general by intermediate rocks, changing later to rhyolite and basalt.

¹ *Igneous Rocks*, vol. 1.

Spurr,¹ on the other hand, arrives at the conclusion that in a broad way the eruptions in the Great Basin began by rhyolite, followed by andesite, later rhyolite, later andesite, and finally basalt. Ransome² doubts the general applicability of Spurr's succession.

In many districts where apparently a complete cycle is preserved, rhyolite was certainly the first erupted lava. However, comparing the data available,³ it does not seem possible to formulate a law which will hold in all cases. At many places in Arizona and the Great Basin, rhyolites have for instance been repeated from three to five times, alternating with basalts and andesites, and as stated before the andesites are entirely absent in some districts. Almost all recorded successions agree, however, in one point, namely, that the eruptions close with the outpouring of basalts.

Petrologists are of the opinion that this rapidly changing succession of rocks of different kinds is caused by the deep-seated differentiation of a magma of intermediate character. If this is true, there seems to have been the least differentiation along the lines of the Cascades and the Sierra Nevada, while the magmas in the basins farther east are more thoroughly differentiated. This was long ago emphasized by Iddings.

PROVINCE OF ALKALINE ROCKS⁴

There remains to mention the remarkable province of the alkaline rocks of the Rocky Mountain region; it occupies an interrupted and irregular belt extending from Alberta, Canada, down into New Mexico and Texas and probably even into

¹ Jour. Geol., vol. 8, 1900, p. 643.

² Prof. Paper, No. 66, U. S. Geol. Surv., 1909, p. 105.

³ Daly, R. A., *Igneous Rocks and their Origin*, 1904, Appendix B.

⁴ I would define alkaline rocks as those which combine a high percentage of alkalis (generally 10 per cent or more of potash plus soda) with the presence of feldspathoids such as nephelite, leucite, analcite, sodalite, etc. In a few rather exceptional rocks belonging in this class, the sum of the alkalis falls below 10 per cent.

eastern Mexico. Representatives of alkaline rocks are found as far east as the Black Hills and as far west as the La Sal Mountains in southeastern Utah. These alkaline rocks nowhere occupy large areas but usually appear as isolated intrusive masses or lava flows. In time, their eruption ranges from the Colorado Cretaceous almost to the Recent, for there are basaltic flows and well-preserved craters of such rocks in northern New Mexico.¹ Nearly always they occur in connection with monzonite or quartz monzonites, which are the predominating rocks, and they should, I believe, be regarded as products of differentiation of such rocks, which resulted in increased alkalies and alumina, generally also in decreased silica. There seems to be little foundation for the view that considers these alkaline rocks as restricted to a special province, for we have representatives of this class, both along the coast² and in the islands of the Pacific, as has recently been pointed out by Professor Daly. There appears to be no good reason why these alkaline rocks should not be considered as having split from monzonites by differentiation, as indeed is plainly shown in Pirsson and Weed's account of the relations at Yogo Peak.³ The conditions at Georgetown and Idaho Springs described by Ball⁴ point decidedly in the same direction, for here we find that a long series of early Tertiary intrusives, of general quartz monzonitic affiliations, goes over into dikes of bostonite and alkali syenites at the extreme northeastern end of the belt. Similar views have lately been expressed by C. H. Smyth, Jr.,⁵

¹ Lee, W. T., Oral information.

² The following occurrences are known: (1) The (Miocene?) Kruger alkali syenites, described by R. A. Daly, from the boundary between British Columbia and Washington; (2) Nephelin syenites, etc., from the Boundary district and from the Rossland district, British Columbia; (3) the teschenites, described by H. W. Fairbanks, from San Luis, California; (4) the leucite basanite from Bullfrog, described by F. L. Ransome and W. H. Emmons; (5) leucite basalt from Tres Virgenes volcano (Lower California).

³ 20th Ann. Rept., U. S. Geol. Surv., part 3, 1900, pp. 494, 504.

⁴ Prof. Paper, U. S. Geol. Surv., No. 63, 1908.

⁵ Am. Jour. Sci., (4), vol. 36, pp. 33-46.

who also, with good reason, attributes an important rôle to the "mineralizers" in effecting the differentiation.

At any rate, I find it difficult to agree with R. A. Daly, who sees in the alkaline rocks the result of absorption of limestone from sedimentary strata, believing as I do that the larger part of the differentiation took place at great depth far beyond the influence of sedimentary rock. It is not to be denied that some alkaline types *may* result from assimilation of limestone.

The alkaline rocks appear under all conditions as to mode of eruptions: coarse granular, porphyritic, and glassy. They are of all ages from Cretaceous to Quaternary, and have no relation to the great limestone beds. If they had, would we not be sure to find them in the great Palæozoic geosyncline of eastern Nevada and western Utah?

On the contrary, they follow a broad but ill-defined belt along the Rocky Mountains, extending north and south, and this alone suffices to disprove their connection with limestone. Furthermore, the alkaline rocks always contain chlorine and nearly always fluorine, often in considerable amounts. They are also relatively rich in strontium, zirconium, and rare earths. Is it likely that they have received these substances from limestone? The association of telluride and fluorite deposits with many alkaline rocks is also a significant fact.

Neither can I accept Harker's broad division into Atlantic and Pacific types of igneous rocks as far as the Cordilleran region is concerned. His diagram¹ indicating an alkali percentage increasing with the distance from the Rocky Mountain divide is probably not a valid generalization. We have, for instance, in the La Sal Mountains of laccoliths in southeastern Utah, far on the west side of the Rocky Mountain Ranges, rocks averaging very high in alkalis. Iddings's law that the highly differentiated rocks are usually the last of a series evidently does not hold in the case of the alkaline rocks, for, as we have seen, they constitute the very earliest recorded eruptions in the Rocky Mountain region.

¹ *Natural History of Igneous Rocks*, 1909, p. 95.

Under certain conditions—unknown at present—granodiorite and monzonitic magmas have then, I believe, the property of separating, by differentiation, small quantities of alkaline melts.

CONCLUSIONS

We have now completed our rapid review of igneous activity in the Cordilleran region. Broadly speaking, we have ascertained the following succession:

1. Pre-Cambrian granitic and batholithic intrusions of acidic potassium magmas with large amount of pegmatite, probably invading the whole Cordilleran region.

2. The Beltian or Cambrian diabase and gabbro intrusions. These intrusions are most marked in the northern part of the United States, and in the adjacent parts of Canada where the Beltian is strongly developed.

3. The Devonian to Jurassic era of basic surface flows. Only smaller amounts of acidic rocks are associated with these and the magma was rich in soda. The eruptions closely followed the Pacific coast from California to Alaska, but at times the activity reached western Nevada and eastern British Columbia. This series of eruptions preceded or accompanied the Jurassic epoch of mountain building.

4. The early Cretaceous era of basic or ultra-basic intrusions following the Coast Ranges in California and Oregon.

5. The great era of granodioritic or quartz monzonitic magmas originating along the Pacific coast and spreading eastward to the front of the Rocky Mountains. These eruptions cover a time interval from the latest Jurassic and the earliest Cretaceous down to the present, and comprise batholiths and surface flows of great magnitude. In the intrusive bodies some differentiation took place, but it was far less marked than in the lavas which separated into rhyolites, andesites, and basalts. The alkaline rocks are regarded as a differentiated facies of the quartz monzonites. Of the close relationship of the intrusives of this era, there can be little question.

In Quaternary time the andesitic and dacitic eruptions continued, though not without pauses, along the main line of the western Cordillera from Alaska through the Cascades down to Central America.

6. The era of basaltic effusions. Beginning in the Eocene and attaining their maximum in the Miocene, the basalts were poured out in enormous volume in the northwestern part of the United States. While many basalt flows of the interior may be interpreted as differentiation products of granodioritic magmas, this explanation hardly fits these large eruptive areas. Practically all of the latest Pliocene and the Quaternary eruptions were of basalt and they were widely scattered over the whole Cordilleran region, though in few places of great volume.

The conditions outlined above, even with the broadest allowance for processes of differentiation, seem to call for magma basins, or magma beds, of several kinds.

The pre-Cambrian intrusions which represent vast quantities of granitic-pegmatitic magma, transported from the depths to the surface, evidently require a large reservoir of acidic magma which had only been differentiated to a slight degree.

The subsequent eruptions along the Pacific coast, ranging in time from Cambrian to Jurassic, produced basic magmas both as flows and intrusions. Differentiation into acidic types took place only exceptionally. All these eruptions probably came from a reservoir of basic magmas similar to those now erupted in abundance in the islands of the Pacific Ocean.

Probably we should add to this the early Cretaceous irruptions of the Coast Range of California, the Miocene Columbia River basalt of Washington and Oregon, and the basaltic fields of Arizona and Idaho.

The late Mesozoic and Tertiary eruptions of quartz monzonitic magma with all its differentiation products clearly demand another basin of an intermediate composition, decidedly different from the preceding reservoirs. Erupted with the least differentiation along the main chains of the western coast, it appears in the Middle Tertiary in full force in large areas of the

Cordilleran belt. The absence of true granite and pegmatite is striking.

The history of the Cordilleran igneous activity would, therefore, broadly speaking, call for at least three magma basins of primary importance, one acidic, the second basic, and the third intermediate, in composition.

How shall these be placed? General considerations agreeing with common views of layering of the earth would place them in order of decreasing acidity, the basaltic zone being situated at depths of many miles. Quite generally, we know, do the basaltic and the intermediate magmas break through the acidic older rocks. This view, at least, does not seem contradictory to the evidence.

It would, however, seem to stand in direct opposition to the planetesimal hypothesis.

The quartz monzonitic magma seems to have been particularly subject to differentiation when erupted as surface flows. The intrusives differentiated but little during their *mis en place*, but we find minor intrusions of acidic or basic or alkaline granular rocks accompanying the prevailing type.

The effusives, are, on the other hand, strongly differentiated into andesite, basalts, and rhyolites. This statement is of course made on the assumption that the rhyolite and basalt and andesite of the interior basins are really such differentiation products. The circumstantial evidence of this is strong, but with all our discussions nobody has yet proved the exact *modus operandi* nor indicated why the differentiation of lavas should be different from that of intrusives. One fact deserves mention: In many dissected volcanoes which erupted basalts, rhyolites, and andesites, central intrusive masses have been disclosed, but these are not gabbros or diabases or granites but rocks of quartz monzonitic or granodioritic composition.

Some petrologists believe that differentiation was effected in the vents through which the magmas reached the surface, but without assuming openings of improbable dimensions it is difficult to agree to this view.

R. A. Daly¹ holds that there are but two layers, one acidic and the other basaltic. The same author regards the granodioritic intrusive magmas (for instance those of the Pacific coast) as syntectics caused by the melting of granites and sediments during the ascension of the magmas of the basaltic substratum.

This ingenious explanation cannot be accepted. In the first place, the sediments may be fairly neglected; their remelting would have about as much influence on the composition of the coast batholith as a whole as a wheelbarrow of limestone would have on the basalts of the Kilauea basin. In the second place, it does not seem possible that an intrusive body of the comparatively uniform composition which, for instance, the coast batholith of British Columbia has, could be a syntectic of magmas from two widely separated layers of the earth's crust. At some places at least, the magmas from the basaltic substratum would have reached the surface. This has not happened, judging by the absence of basic rocks from the main mass. Wherever such are present they are differentiation products, mostly marginal facies, and they were among the earliest products of intrusion.

MODE OF ERUPTION

General Features. Only brief time remains to state some principal problems regarding the manner in which the magmas of the Cordilleras reached the surface.

Petrologists distinguish justly two modes of volcanicity:² Fissure eruptions and central eruptions, the first prevailing when the crust movement is mainly vertical, producing plateaus or depressions, and the second characteristic of areas under the influence of horizontal, mountain-building pressure. In the Cordilleras it may not always be easy to separate these two modes, but in a broad way the distinction holds. It seems also to be true that volcanism often begins in geosynclinal basins and that the rocks intercalated in the strata under such conditions

¹ *Igneous Rocks and their Origin*, 1914.

² Harker, Alfred, *The Nature of Igneous Rocks*, 1909, p. 39.

are mainly of basic character. Sometimes, as in the Columbia River lava field, we have extensive fissure eruptions, accompanied by depression but not followed by mountain-building thrusts. At other times, for instance, during the Jurassic, the basic eruptions in a geosyncline along the coast were the precursors of intense intrusions. Some connection seems to exist between the two, and Daly¹ in fact assumes that volcanism in geosynclines usually initiates a series of igneous phenomena.

There is no fundamental difference between volcanic and intrusive action. Both are closely connected. Intrusive bodies of large size are often found in the cores of eroded volcanoes; intrusion may, however, take place without effusion. The differences are probably in part due to the free connection with the surface and to consequent intense gas action.² Furthermore, the phenomena of effusion are far more rapid than those of intrusion. In intrusion large masses of magma are slowly forced up with accompanying deformation of the crust. In effusion lavas are rapidly forced out from comparatively small explosive vents, usually without creating great tectonic disturbances.

Causes of Igneous Action. The question of the origin of igneous action is by far too large to be discussed here. In a general way I believe that the impetus to eruption is given by orogenic stresses which finally disturb the equilibria in portions of the earth situated miles below the surface. A solid and rigid crust is postulated, roughly divided in an acidic, an intermediate, and a basic shell. In some places the pressure will be relieved, resulting in melting and expansion, which in itself will produce a rise of the magma. With its rise into the cooler part of the crust the expansive forces will steadily increase and finally the magma will be forced up into the zone of fracture.

The fundamental fact in the Cordilleran region is that the igneous activity began along the present Pacific coast line and gradually extended eastward. The initial stresses primarily causing the rise of the magma and secondarily the deformation

¹ *Igneous Rocks and their Origin*, 1914, p. 188.

² Daly, R. A., *Op. cit.*, p. 288.

of the sediments, therefore, came from the Pacific side. They were abyssal, extending to depths of many miles.

This explanation accords in the main with that given by Daly. I quote one of his conclusions:¹ "The location and alignment of mountain ranges, the location and alignment of geosynclinals, the final development of igneous batholiths and satellitic injections, all are interdependent and related to special zones of powerful abyssal injection from the substratum."

Intrusive Action. The mode of intrusion has been a subject of wide discussion and I can barely touch upon it. We have heard much of late of the "stoping theory," strongly advocated among others by R. A. Daly. According to this theory, the intrusive masses rise passively, simply by blocks being detached from the roof. These sink and assimilate in the magma, thereby forcing up an equivalent quantity of magma.

I believe fully in stoping as a concomitant of intrusive action, and the conception of Lane and Daly of the "blowpiping" action of the liberated gases on the roof appears to be a particularly happy idea. It is well possible that blocks are detached from the roof during intrusion, sink down and become assimilated in the magma. Towards the end of intrusive activity, when equilibrium begins to be established and yet the gas action is intense, it may well be that stoping is a very important mode of action. But that this passive rise is the only or even the principal factor, is impossible to believe.

Everywhere intrusions correspond to uplifts, and the evidence, it seems to me, is entirely favorable to simultaneous uplift and intrusion. In my view there is no difference between laccoliths and batholiths as to pressure exerted. In both cases there is strong hydrostatic pressure derived mainly, I believe, from the stresses which builded the Cordilleras. In the laccolith no proof of this is necessary. But laccoliths, sheets, and batholiths are often inseparably connected. A beautiful case came under my observation at Clifton, Arizona, where a stock of quartz monzonite breaks across pre-Cambrian granite and in part also

¹ *Op. cit.*, p. 193.

across the Palæozoic but sending out thin sheets in the latter. The same intrusive mass when reaching the pliable Cretaceous strata turns into a heavy laccolithic sheet and lifts the super-incumbent sediments.

Sean, if you will, the recent monographs dealing with intruded stocks at Park City,¹ Phillipsburg,² Frisco,³ and other places where sediments are intruded, and you will always find mention of doming more or less strongly marked and of the contacts frequently following the bedding planes. The evidence cannot be overlooked. To Professor Barrell we owe the best argument for the stoping hypothesis, but even at Marysville there was a decided doming and its dependence upon the batholith is very evident.

By far the clearest and most incontrovertible evidence of the mechanism of batholithic intrusion we find in the Sierra Nevada, clearly recorded in the Gold Belt folios of the United States Geological Survey. Everywhere the strata bend around the intrusive masses. Even in the large batholith of the High Sierra this is evident by the strata following the general trend of the contacts. The sedimentary rocks have been pushed aside bodily to accommodate the slowly rising intrusive. Practically no schistosity has been developed by pressure from the intrusive and the effect of bending is, therefore, by no means secondary. These conditions are best shown in the smaller batholiths at the western foot of the Sierra. I would refer to the Sonora intrusion⁴ where the limestone bends around the intrusive mass in

¹ Boutwell, J. M., Prof. Paper, U. S. Geol. Surv., No. 77, pp. 96-98. "The intrusives in making their way to their present positions, tore away portions of lower formations and floated them up for thousands of feet." "The compressive stress exerted (by the intrusion) on the sediments was very great. . . . The Clayton Peak mass doubtless domed the overlying Triassic and Jurassic sediments. . . . The invasions of the Carboniferous formations by the diorite porphyry magma . . . would seem to have been accomplished under very high pressure and naturally produced corresponding deformation."

² Calkins, F. C., Prof. Paper, U. S. Geol. Surv., No. 78, pp. 98 and 108.

³ Butler, B. S., Prof. Paper, U. S. Geol. Surv., No. 80, p. 70.

⁴ Turner and Ransome, Sonora folio (No. 41), U. S. Geol. Surv.

a particularly convincing manner; to the small stock¹ at Don Pedro Bar in the same vicinity; to the Nevada City batholith;² to the batholith of soda granite in the Colfax quadrangle;³ to the main contact in the same quadrangle; and to the intrusive masses in the Bidwell Bar quadrangle.⁴

The batholithic magma was then under strong hydrostatic pressure, strong enough to laterally deform the adjacent rocks. Wherever a roof is visible as at Park City, Utah, Marysville, Montana, Frisco, Utah, and Phillipsburg, Montana, doming is observed.

Laccoliths are simply offshoots of batholiths and under the same hydrostatic pressure, strong enough to lift up thousands of feet of superincumbent strata. Can we doubt that uplift was one of the consequences of batholithic intrusion? Is it not also probable that large areas of elevation in the Cordilleras are underlain by concealed batholiths?

Extrusive Action. It is not easy to separate strictly fissure eruptions from those of central vents, for within the large areas of lava probably mainly erupted from fissures are many central vents around which smaller volcanic cones were built up. In southeastern Arizona many of the widespread flows originated from such vents.

¹ Turner, H. W., Jackson folio (No. 11), U. S. Geol. Surv.

² Lindgren, W., Nevada City and Grass Valley folio (No. 29), U. S. Geol. Surv.

³ Lindgren, W., Colfax folio (No. 66), U. S. Geol. Surv.

⁴ Turner, H. W., Bidwell Bar folio (No. 43), U. S. Geol. Surv.

Daly reproduces Turner's diagram of the intrusions in the Bidwell Bar quadrangle in his book on *The Igneous Rocks and their Origin*, p. 302, but entirely misapprehends Turner's meaning. Turner distinctly states that the phenomena shown are not peripheral cleavage or schistosity induced by intrusions, but that the bending was produced by the pressure of the intrusion. In very few places in the Sierra Nevada has peripheral schistosity been developed by intrusion. One such case is mentioned in folio 39 [Truckee] north of Snow Mountain. It is true that cross cutting is found in all batholiths, and wherever the propelling force ceased but blow-piping and stoping continued, there may be but little conformity to structure. But these conditions in no way invalidate the conclusions already reached.

A better line of division might be established between the volcanic eruptions which mainly consist of basalt and rhyolite and those in which andesitic rocks largely enter. The former include the Columbia River lavas, many fields in Nevada and those of central and eastern Arizona. These eruptions go over into the type of latest Pliocene and of Quaternary age, in which only basalts were poured out. It seems probable that these eruptions are not connected with the granodioritic magmas but are of more deep-seated origin.

The second division embraces the volcanoes of the Sierra Nevada, the Cascades, innumerable vents in Nevada, the Yellowstone Park region and the San Juan country in southwestern Colorado. All these yield predominant andesite with considerable rhyolite and minor masses of basalt and it seems fair to advance the hypothesis that they are caused by explosive action from the magmas of older granodioritic or quartz monzonitic batholiths, which have had time to differentiate in their upper gas-charged "cupolas," or from satellitic intrusions of such batholiths. Wherever we find local intrusions in such volcanoes they appear to be of magma of intermediate composition. It seems to me there can be little doubt that such deep-seated batholithic masses underlie large parts of the Cordilleras.

EPILOGUE

Looking back upon the complicated history of igneous activity in the Cordilleran region, the definite unfolding of the series of events is impressive: The earliest granitic intrusions differ strikingly from the later igneous activity; following these general batholithic intrusions, seemingly independent of structural lines, we meet geosynclinal basaltic magmas, also without relation to present mountain ranges. Still later other basic magmas break out along the structural line of the Pacific coast and are again followed by intrusions of intermediate magmas gradually spreading eastward. These were finally succeeded by volcanic differentiation products of intermediate magmas and locally by basaltic geosynclinal eruptions.

It seems to me that the study we have just completed strongly tends to support the hypothesis that the outer crust of the earth consists of zones in which with depth the basic constituents of the magma gradually increase.

In comparing the igneous history of the Cordilleran region with that of other parts of the globe, strongly marked differences are apparent. This would suggest that the outer shell of the earth is not everywhere of the same uniform composition, but that in some places the acidic, in others the intermediate layers may be lacking in full development.

OUTLINE MAP SHOWING PRINCIPAL OROGRAPHIC TRENDS OF THE NORTH AMERICAN CORDILLERA

By F. L. RANSOME

CHAPTER VI

THE TERTIARY OROGENY OF THE NORTH AMERICAN CORDILLERA AND ITS PROBLEMS¹

F. L. RANSOME

INTRODUCTION

The vast, complex, and wonderfully diversified mountain region known as the North American Cordillera extends in a slightly sigmoid curve from Bering Strait to the Isthmus of Tehuantepec, a distance of about 4500 miles. Along most of its course this enormous highland mass overlooks to the east the broad stretches of the interior plains and on the west opposes its bulk directly to the waves of the Pacific. Its greatest width, 1000 miles, coincides nearly with the 40th parallel of latitude or is measured with sufficient exactness for general descriptive purposes by the distance between Denver and San Francisco. The average width is probably between 500 and 600 miles.

The Cordilleran region is by far the highest and roughest portion of the continent. Its general elevation, lofty peaks, deep canyons, broad plateaus, and long lines of cliffs are all expressive of the fact that in this province orogenic or mountain-making processes have been far more active in late geologic time than in other parts of North America. It is the purpose of the present address to tell in part the story of this activity, to discriminate between the movements of Mesozoic or older time and those which, beginning with the great post-Cretaceous or Laramide revolution, have continued to the present; more

¹ Published by permission of the Director of the U. S. Geological Survey.

especially shall it be my endeavor to describe these younger movements, to sketch broadly their results in the existing topography, and to indicate some of the problems that invite future study in this rich geologic field.

A strictly logical form of presentation would require either that there be laid before you first a picture of conditions in the Cordilleran region at the end of Cretaceous time, and that the various steps leading up to the structural and topographic features of the present day be reviewed in chronological order; or else, that a full description of existing forms be made the starting point for retrogressively uncovering the events of the past. I have preferred rigid adherence to neither course, proposing, at the risk of repeating what may be familiar to some of you, to sketch very briefly the essential tectonic and topographic features of the province, with a view to presenting not so much a picture, as a useful outline diagram, of the North American Cordillera. With that in mind, we may then consider the origin of those features and some of the problems connected with their development.

I am fully sensible that personal experience equips me to speak of small parts only of a very large region, and that it is mainly from the work of other observers that important general conclusions are to be drawn. Nevertheless, even slight first-hand knowledge of a field adds so greatly to the value of any broad discussion of its geological literature that I am inclined to give this factor considerable weight and consequently to pass as lightly as possible over the consideration of remote or little studied portions of the Cordillera, in order that closer attention may be given to the complex and better-known section within our own country.

Over large areas of the Cordillera the geologic structure is yet to be elucidated. Nevertheless, the literature on the western part of our continent is more voluminous than anyone who has not attempted to review it can realize, while the tectonic problems involved are so intricate and invite the attention into so many unexplored paths that it is manifestly impossible that the very comprehensive subject which has been assigned to me

should be treated on this occasion in other than a general, although I hope suggestive, way.

Throughout this paper there is implied the broad concept of Suess that the great primary earth movements are centripetal in character and that actual uplift of large areas of the earth's surface rarely occurs. It is impossible, however, to determine in most instances whether an apparently uplifted area is really farther from the earth's center than before, or whether it has merely been left as a horst, or residual mass, by the subsidence of adjoining land areas or of the sea. In order that familiar modes of expression may not be fettered by continual qualification, I shall use *uplift* and *subsidence*, unless otherwise stated, in merely relative senses.

MAJOR DIVISIONS OF THE CORDILLERA

The Cordillera as a whole, although a well-defined topographic and structural unit, is composed of many constituent parts and is divisible into provinces distinguished in the main by marked differences in form, structure, material, and geologic history.

Any complex mountain system is susceptible of division in various ways. The distinctions may be based on topography, on trend, on geologic structure, on contemporaneity of origin, on kind of deformation, or on other characteristics. Some groupings may depend largely on theoretical considerations, while others may be founded upon features so obvious as to receive ready and general recognition. Among the more theoretical divisions of the North American Cordillera may be mentioned, for example, that of Suess, who carries his Asiatic System (which, it will be remembered, includes the Appalachians) through Alaska and along the Rocky Mountains to northern New Mexico; who regards as part of the Andean chain the Coast Ranges of California, as far north as the Klamath Mountains; and who groups as the Intermediate Mountains (*Zwischengebirge*) all of the remaining portion of the Cordillera. The classification adopted in the present paper is essentially topographic and geographic, although not rigidly so

in every detail; for it was soon found that in attempting to classify mountain groups a guiding principle leads to more satisfactory results than does the arbitrary application of a rule.

Topographically, a threefold longitudinal division has been recognized by most observers throughout the greater part of the North American Cordillera, although writers are far from agreement as regards the designations for these primary units. Named in order from east to west, there may be distinguished first, following Dana, the Laramide System, second, the Intermontane Belt, and third, the Pacific System. From Alaska to western Texas the Laramide System includes what are popularly called and are often officially designated the Rocky Mountains. South of the Rio Grande it is represented by the Mexican Plateau and its marginal ranges. The commonly accepted nomenclature fails, however, to recognize a fact that has been particularly emphasized by R. T. Hill,¹ namely, that, between the ranges to the north and the Mexican Plateau to the south, there intervenes the lofty plateau region drained mainly by the Colorado but in part also by the Rio Grande. The Laramide System should, therefore, be considered as divisible into three great provinces, which from north to south may be designated (1) the Rocky Mountains, (2) the Colorado Plateaus, and (3) the Mexican Plateau.

The name Rocky Mountains was first applied to a single range in northern Montana and some geographers have sought to retain this application as against the generally accepted, broader, although rather indefinite, usage now current. Daly² has distinguished as the "Rocky Mountain System" the original

¹ The geographic and geologic features, and their relation to the mineral products of Mexico: *Trans. Am. Inst. Min. Eng.*, vol. 32, pp. 163-178, 1902.

Physical geography of the Texas region: *Topog. Atlas U. S., U. S. Geol. Surv.*, folio No. 3, p. 4, 1900.

Reconnaissance notes on the geology of the Trans-Pecos (Texas) province and related adjacent areas of the Cordilleran region: *Bull. U. S. Geol. Surv.*, No. — (in press).

² Daly, R. A., Nomenclature of the North American Cordillera between the 47th and 53d parallels of latitude: *Geograph. Jour.*, vol. 27, pp. 586-606, 1906.

Rocky Mountains and "their orographic continuations north and south." This usage, while it extends the original application of the name, includes so much less than is commonly implied by the familiar designation *Rocky Mountains* as to impair its usefulness and raise doubt of its survival. *Rocky Mountains* as used in the present address applies to the whole of that part of the Laramide System which extends from Bering Sea to the southern ends of the Wasatch Range in Utah and of the San Juan and Sangre de Cristo mountains in Colorado. The name is thus made to include the Purcell, Selkirk, and Gold or Columbia ranges, in British Columbia, all of which Dawson grouped with his Interior Plateau, and the Flathead, Cabinet, Bitterroot, Mission, Salmon River, Uinta, Wasatch, and other ranges in the United States, which lie west of Daly's "Rocky Mountain System."

The Colorado Plateaus are, like the Rocky Mountains, bounded on the east by the Great Plains. On the north they terminate rather irregularly against the Sangre de Cristo, San Juan, Uinta, and Wasatch mountains. On the west this province sweeps boldly out to the Grand Wash Cliffs at the mouth of the Grand Cañon. Thence its boundary coincides with the line of cliffs and plateau remnants that extend south-eastward through Arizona, New Mexico, and Trans-Pecos, Texas, to the vicinity of Pecos station on the Texas and Pacific Railway.

The great Mexican Plateau is defined along its eastern and western sides by the eastern and western Sierra Madre and particularly by the sharp descent on both sides to the foothills and plains of the *tierra caliente*. On the north its distinction from the Colorado Plateaus is less definite, and there is perhaps some question whether the line separating the Mexican Plateau province from the Intermontane Belt in southern Arizona should be a rather arbitrary northward continuation of a boundary which has real significance farther south, or should bend east, as I have drawn it, to meet the boundary of the Colorado Plateaus near El Paso. The mountains and valleys of southeastern Arizona and of southwestern New Mexico are

so closely allied in form and trend to those of southwest Arizona as to suggest that all belong to a single province.

The Intermontane Belt is also susceptible of transverse division into provinces. North of the boundary line between British Columbia and the United States extends what Daly¹ has called the *Belt of Interior Plateaus*, modifying slightly Dawson's² original name, *The Interior Plateau*. Brooks³ has referred to the same feature as the *Central Plateau Region*. To distinguish this province from other plateaus to the south, it may be here designated *The Northern Interior Plateau*. In my delimitation of this area (see accompanying map), I have included the Cassiar Mountains with the Laramide System. Following Keele,⁴ moreover, I have indicated the axis of the Mackenzie Range as curving gently westward from Fort Liard toward the junction of the Yukon and Porcupine rivers, instead of drawing it, as has sometimes been done, in a more northerly direction to meet the east end of the Endicott Range, near the mouth of the Mackenzie River. The geography and geology of this northern region are, however, still comparatively little known and these interpretations may not be final.

Near the International Boundary the plateau character of the Intermontane Belt becomes very obscure, and, according to Daly,⁵ the Belt of Interior Plateaus terminates a few miles south of the boundary at the north base of the Colville Mountains, a small and comparatively low member of this Columbia System which includes the Gold Ranges of Dawson and others. It is questionable whether the orographically unimportant Colville Mountains should be regarded as constituting an interruption of the Intermontane Belt. I prefer to consider

¹ *Op. cit.*, p. 594.

² Dawson, G. M., Physical and geological features of that portion of the Rocky Mountains between latitudes 49° and 51° 30': *Ann. Rept. Geol. Surv., Canada*, for 1885, 1886.

³ Brooks, A. H., Geography and geology of Alaska: Prof. Paper, U. S. Geol. Surv., No. 45, plate 3, 1906.

⁴ Keele, Joseph. A reconnaissance across the Mackenzie Mountains: *Geol. Surv., Canada*, Pub. No. 1097, 1910.

⁵ *Op. cit.*, p. 588.

them as a part of that belt rather than as a member of the Laramide System. This interpretation would make the south end of the Northern Interior Plateau coincide closely with the courses of the Columbia and Spokane rivers, near latitude 48°.

South of that latitude stretches the great lava-flooded region which Powell named the *Columbia Plateaus* and which Daly has called the *Columbia Lava Plain*. This feature is worthy to be considered as the second great division of the Intermontane Belt. Its southern boundary may be taken as a curved line which follows in general the divide that separates the headwaters of the Columbia from the Great Basin.

The third division of the Intermontane Belt comprises the Great Basin (in which fall most of Nevada and portions of Oregon, California, and Utah) together with the Sonoran Province of Arizona and Mexico. Physiographically, as Hill¹ has pointed out, the Sonoran Province is apparently the southern continuation of the Great Basin. The fact that part of the area is a closed basin while the other part drains to the sea, is not in itself a distinction of prime importance from the topographic or geologic point of view. Consequently, the third division will be referred to as the Nevada-Sonoran region. An appropriate physiographic term would be preferable to the non-committal *region* but no sufficiently expressive word has been hit upon. The province designated by Powell as the *Basin Ranges* includes much more than the *Nevada-Sonoran Region*. He extended it across southwestern New Mexico into Texas and over the great Mexican Plateau, although he suggested that "the region east of the Colorado may ultimately be distinguished by another name: *Sierra Madre* would be appropriate."² The name *Great Basin* is well established in usage for that part of the Nevada-Sonoran Province which has no outlet to the sea.

¹ Hill, R. T., The geographic and geologic features and their relation to the mineral products of Mexico: Trans. Am. Inst. Min. Eng., vol. 32, p. 163, 1902.

² Powell, J. W., Physiographic regions of the United States: in the volume *The Physiography of the United States*, Nat. Geog. Soc. and Amer. Book Co., p. 95, 1896.

The province here designated the Pacific System separates the Intermontane Belt from the Pacific and includes what Powell called the "Pacific Mountains," a name which Spencer,¹ following a suggestion from Mr. Alfred H. Brooks, modified to the "Pacific Mountain System." Daly² has objected that "the large view of the Cordillera assuredly claims the word 'Pacific' for its own, and cannot allow in logic that 'Pacific Mountain System' shall mean anything less than the entire group of mountains." He thus regards *Pacific System* as synonymous with *Cordillera*. He may be right; but there is at least something to be said for other opinions, and as *Pacific System* in its application to the coastal chains has become fairly well established, that usage is here followed.

The Pacific System, unlike the other great longitudinal divisions, is not separable into sharply contrasting segments. There are some notable changes in trend, as in Alaska, at Vancouver, and in southern California, but these, with the possible exception of the last, scarcely afford a basis for divisions of the same order as have been made in the other provinces. Between the various ranges of this system, there are some fundamental differences, but the structural and topographic units involved are generally smaller and topographically less distinct than those which we have thus far been considering.

Before the subdivisions of the larger Cordilleran units are described, attention may be called briefly to three great transverse lines which are probably of broad tectonic significance, although their interpretation is as yet far from clear. On the north is the notable westward bend of the Cordillera marked by the Endicott Range along the Arctic Ocean and the Alaska and Aleutian ranges along the Pacific, constituting the feature that Suess has termed *Shaarung* and his English translator *syntaxis*. Another transverse line is that defined by (1) the break in the continuity of the Laramide System in central Wyoming, (2) the south end of the Wasatch Range,

¹ Spencer, A. C., *Pacific Mountain System* in British Columbia and Alaska: Bull. Geol. Soc. America, vol. 14, p. 117, 1903.

² *Op. cit.*, p. 592.

(3) the northwest edge of the Colorado Plateaus, (4) the south end of the Sierra Nevada, and (5) the notable change of trend of the coastal ranges between the Mohave Desert and Point Conception. It may also be worthy of note that the Black Hills of South Dakota lie on the same line. This great line or zone, which may conveniently be referred to as the *Wyoming lineament*,¹ runs nearly northeast and southwest. In the Laramide System it separates Powell's divisions of the Stony Mountains from the Park Rangés. A third line coincides in general with the same features in the Pacific System as have just been mentioned, with the southwest boundary of the Colorado Plateaus and with the valley of the Rio Grande. It is along this general line that the uplifted masses of Paleozoic rocks of the Colorado Plateau province, as in the Franklin Mountains near El Paso, look out to the south over the Cretaceous terrane of the Mexican Plateau. Mr. R. T. Hill has called attention to this feature in several of his papers and points out that in the Trans-Pecos region it coincides with a zone of faulting which is older than the north-south faults to which the bolder topographic features are due. The entire, rather vaguely defined and perhaps in part imaginary, zone from the Pacific to the Gulf of Mexico may be called the *Texas lineament*.

SUBDIVISIONS, TOPOGRAPHY, AND STRUCTURE OF THE SEVERAL PROVINCES

LARAMIDE SYSTEM

ROCKY MOUNTAINS

Northern Division. The Endicott Range, the northernmost member of the Rocky Mountains, extends in a nearly east-west direction across northern Alaska. It is as yet little known. According to Schrader,² the mountains in the vicinity of the 152d meridian rise rapidly from the rolling Koyukuk country

¹ For this use of *lineament*, see Hobbs, W. H., *Lineaments of the Atlantic border region*: Bull. Geol. Soc. America, vol. 15, p. 485, footnote, 1904.

² Schrader, F. C., *Geological section of the Rocky Mountains in northern Alaska*: Bull. Geol. Soc. America, vol. 13, pp. 233-252, 1902.

to the south, through a belt of foothills, and attain an elevation of about 6000 feet. The general uniformity of summit levels suggests a much dissected plateau. On its northern versant the range descends rather abruptly to the edge of the gentle Arctic slope which meets the mountains at an elevation of about 2500 feet. The relation is thus similar, as Schrader points out, to that between the Rocky Mountains and the Great Plains, farther south.

From the eastern end of the Endicott Mountains the descriptions of McConnell,¹ Keele,² and Camsell³ appear to indicate a rather low and interrupted orographic connection with the Mackenzie Range, which Keele characterizes as a well-defined crescentic mass, about 300 miles in maximum width, extending from the Liard River on the southeast to the lowland between the Yukon and Porcupine rivers on the northwest. According to McConnell, the mountains which separate the headwaters of the Porcupine from the Mackenzie drainage are only about 2800 feet in elevation near Rat River portage. The Mackenzie Range, to portions of which the names Selwyn Range and Ogilvie Range have been applied, rises to elevations between 7000 and 8000 feet.

South of the gap in the Rocky Mountains now occupied by the Liard River and the headwaters of the Pelly, the Laramide System has two distinct longitudinal members separated by the remarkable valley which Dawson⁴ appears to have been the first to describe and which Daly⁵ has proposed to name the *Rocky*

¹ McConnell, R. G., Report on an exploration in the Yukon and Mackenzie basins: Ann. Rept., Geol. Surv., Canada, 1888-1889, vol. 4, Rept. D, 1890.

² Keele, Joseph, Report on the upper Stewart River region, Yukon: *Ibid.*, vol. 16, Rept. C., 1906; A reconnaissance across the Mackenzie Mountains: *Ibid.*, Pub. No. 1097, 1910.

³ Camsell, C., Report on the Peel River and its tributaries, Yukon and Mackenzie: *Ibid.*, vol. 16, Rept. CC, 1906.

⁴ Dawson, G. M., Preliminary report on the physical and geological features of that portion of the Rocky Mountains between latitudes 49° and 51° 30': Ann. Rept., Geol. Surv., Canada, 1885, vol. 1, p. 28b, 1886.

⁵ Daly, R. A., The nomenclature of the North American Cordillera between the 47th and 53d parallels of latitude: Geograph. Jour., vol. 27, p. 596, 1906.

Mountain Trench. This depression is known to extend from Flathead Lake, Montana, to the Liard River in northern British Columbia, a distance of 1000 miles. Future work may show it to continue even farther into the little known north. It is occupied successively from north to south by Kachika (or Tochieca), Finlay, Parsnip, and Fraser rivers, by Canoe Creek and by Columbia and Kootenai rivers. According to McConnell,¹ "its width varies from two to fifteen miles and it is everywhere enclosed, except for some distance along the west bank of the Parsnip, by mountain ranges varying in height from 3000 to 6000 feet or more above the valley. The width of the valley does not depend on the size of the stream which occupies it at any particular place. It is fully as wide along the smaller streams and at the watersheds which separate the different streams, as along great rivers like the Columbia and Finlay. The average height of the bottom of the valley above sea is about 2300 feet, and the variation in height is about 1000 feet."

The origin of the Rocky Mountain Trench has not yet been fully explained. It is clearly pre-glacial. Dawson considered that it was in existence in late Tertiary time and was excavated by a river flowing to the south. I shall refer again to the latter supposition farther on. Schofield² has even suggested that the Purcell Range was built before the eastern front range and that the two ranges are structurally separated by the trench. At present, attention may be directed to the importance of the trench merely as a physiographic boundary between the two mountain groups.

In British Columbia the Rocky Mountain Trench separates the main eastern range, for which unfortunately there is no generally accepted name other than the variously used *Rocky Mountains*, from a group of mountains which in the northern United States and in southern British Columbia includes the Flathead, Cabinet, and Cœur d'Alene (or Bitterroot) moun-

¹ McConnell, R. G., Report on an exploration of the Finlay and Omineca rivers: Ann. Rept. Geol. Surv., Canada, vol. 7, p. 18C, 1896.

² Guide Book No. 9, 12th Inter. Geol. Congress, pp. 54-55, 1913.

tains, and the Purcell, Selkirk, and Columbia ranges. Farther north, the Cariboo, Omineca, and Cassiar ranges also lie west of the Rocky Mountain Trench. The name *Gold Ranges* has been applied to all of the ranges mentioned as lying west of the trench in Canada and, with the singular termination, to a part of the Columbia Range. Daly has advocated the use of *Columbia System* as more appropriate than *Gold Ranges* for the broader usage. Considerable confusion exists also in the application of the name *Selkirk*, which is sometimes used in a broad sense as inclusive of the Purcell Range and even of the Columbia Range. The Purcell Range is separated from the Selkirk Range proper by the feature which Daly has named the Purcell Trench. This depression is of the same kind as the Rocky Mountain Trench and is older than the present drainage. It is occupied in part by Cœur d'Alene and Pend d'Oreille lakes, by Kootenai River and Kootenai Lake, by Duncan River, and, finally, is followed by Beaver River to its mouth, near Donald, where the Purcell and Rocky Mountain trenches join. The Selkirk Range is bounded on the west, according to Daly, by the south-flowing Columbia, from the point where it leaves the Rocky Mountain Trench to that where it enters the Columbia Lava Plain. This depression, occupied by the Columbia and by the Arrow Lakes, Daly has called the Selkirk Valley. Thus, in British Columbia, each of the three eastern mountain divisions is bounded on the west by a trench or valley of the same name. The fact that these remarkable linear depressions converge northward is difficult to account for if, as Dawson supposed, the Rocky Mountain Trench was excavated by a southward-flowing stream.

South of latitude 48° or Flathead Lake, the Rocky Mountain Trench apparently loses its identity, although Calkins¹ has suggested that "its rôle as a boundary between mountain groups of the first rank is taken up by a zone of low land occupied by Flathead Lake, part of Flathead River, and Jocko Creek, and, south of the region here considered, by Bitterroot River." The

¹ Calkins, F. C., A geological reconnaissance in northern Idaho and northwestern Montana: Bull. U. S. Geol. Surv., No. 384, p. 11, 1909.

main Rocky Mountain crest continues southward as the Big Belt Mountains, east of Helena, and as the Bridger Range farther south. In this part of Montana, however, the Little Belt, Crazy, Highwood, and other outlying mountain masses detract from the contrast, elsewhere so notable, between the front of the Laramide System and the Great Plains. From the south end of the Bridger Range on Yellowstone River, the principal crest is represented by the Snowy Mountains southeast of Livingston, the Absaroka Range along the eastern side of the Yellowstone Park, and the Wind River Range in west-central Wyoming. The mountain front, however, along this part of the Laramide System is shifted 100 miles to the east by the existence of the Bighorn Range. The Laramie Range in southeastern Wyoming carries the front still farther east; but this range lies south of the Wyoming lineament and belongs in the Park Range subdivision, which will be considered later.

West of the main Rocky Mountain crest in Montana and Idaho the most important range is the Bitterroot, with a length, including what are sometimes called the Cœur d'Alene Mountains, of about 350 miles. Between the Bitterroot Range and the eastern crest of the Laramide System are many short ranges, among which may be mentioned the Flathead, Galton, Cabinet, Mission, Swan, Anaconda, Jefferson, Madison, and Gallatin ranges. Southwest of the Bitterroot Range is the irregular group of the Salmon River Mountains, comprising the Sawtooth and other short ranges. The Salmon River Mountains continue northward with no real line of separation, into the Clearwater Mountains, which, in turn, are very closely connected on the east with the main Bitterroot Range.

Near the western boundary of Wyoming the lofty Teton Range is continued southward from Yellowstone Park by the southeast end of the Snake River Range, which sends a spur into Idaho toward the Bitterroots, and by the Wyoming Range. A little farther west the overlapping Salt and Sublette ranges, with the Bear River Plateau, carry the general line of north-south uplift to the southwest corner of the state, where it disappears in front of the great east-west fold of the Uinta Range.

That fold in turn ends at the west in the north-south structure of the Wasatch Range.

Having thus rapidly reviewed the names and positions of the principal constituent ranges of the Rocky Mountains, from the transverse depression of the Liard and Pelly rivers on the north to the transverse depression of the Green and North Platte rivers on the south, I shall now very briefly present such ascertained structural features of the various ranges as have a direct bearing on their Tertiary tectonic history. Among the various facts ascertainable about any range, those are of present concern which may help to answer the following questions: (1) What structural elements of the range were antecedent to the post-Cretaceous deformation? (2) What general conditions of sedimentation preceded that deformation? (3) What was the character of the Laramide deformation? and (4) To what extent was this character determined or influenced by the antecedent factors mentioned?

In the Endicott Mountains, Schrader's sections indicate that rather open folds, accompanied by some faults, give place along the northern front of the range to a zone of much more vigorous deformation, the folds there being overturned to the north and cut by numerous faults. It is possible that future work may show the overturned folds to be connected with important overthrusts. The deformation is in part post-Cretaceous, but there are suggestions of earlier folding. Schrader's section describes only sedimentary rocks, ranging in probable age from Silurian to Upper Cretaceous, as involved in the mountain structure.

The Mackenzie Range consists of crystalline metamorphic rocks, probably pre-Cambrian to Cretaceous, with comparatively small masses of intrusive rocks. The structure, as described by Keele, "is characterized by folding, generally on a broad scale, which has thrown the strata into a series of anticlines and synclines; but the folding is sometimes close, and in certain cases the folds appear to be overturned and overthrust." The same explorer suggests that the mountains appear "to consist of two ranges, an older western range,

against the eastern edge of which a newer range has been piled."¹

For the long stretch of the Rocky Mountain front ranges from the Liard River south to the vicinity of Yellow Head Pass, where the Grand Trunk Railway crosses the divide west of Edmonton, a distance of over 500 miles, the geological information is so meager and indefinite that it may for present purposes be disregarded. All that is known indicates that the structure of these mountains is not very different from that of the same ranges farther south.

McEvoy's² report on the Yellow Head Pass route, published in 1900, contains few structural details and suggests, rather than describes, the existence of overthrusting along the mountain front. Dowling,³ describing the same section, is more explicit, although his descriptions are brief. He states (Guide Book No. 9) that "the first or outer range of the Rocky Mountains stands out prominently on the western side of Brule Lake and the structure there displayed is that of an overthrust block of Devonian limestone superposed on Lower Cretaceous." According to him, the main overthrust mass differs from the Rocky Mountain structure farther south in that the major faults are more widely spaced and the blocks, instead of being cut by numerous minor faults, exhibit sharp folding. These folds are said to pass into faults to the south. The rocks of this part of the range comprise sediments ranging from Upper Cambrian to Lower Cretaceous, all apparently conformable. The Cretaceous of the mountains is the pre-Dakota coal-bearing Kootenai formation. The rocks under the main overthrust comprise, in descending order, the Pierre and Belly River formations of the Upper Cretaceous of the Canadian Great

¹ *Op. cit.*, p. 13.

² McEvoy, J., Report on the geology and natural resources of the country traversed by the Yellow Head Pass route from Edmonton to the Tête Jaune Cache: Ann. Rept., Geol. Surv., vol. 11, Rept. D, 1900.

³ Dowling, D. B., Coal fields of Jasper Park, Alberta: Summary Rept., Geol. Surv. Canada for 1910, pp. 150-168, 1911; Guide Book No. 9, 12th Inter. Geol. Congress, p. 137, 1913.

Plains section. These beds, much folded and faulted, are exposed in a belt of foothills along the mountain front. Dowling states (Summary Report, p. 157) that the Laramide revolution followed the deposition of the Tertiary rocks in Alberta, but does not offer any evidence for so sweeping an assertion.

West of the Rocky Mountain Trench in this latitude, $52^{\circ} 30'$, here occupied by the Fraser River, is the northern end of the pre-Cambrian Shuswap group of the Selkirk Range.

About seventy miles south of Yellow Head Pass, between the Brazeau and North Saskatchewan rivers, a Cretaceous coal basin, about ten miles wide, between the main Rocky Mountain front and the outlying Bighorn Range, has been described by Malloch.¹ Incidentally he characterizes the front range and the Bighorn Range as huge fault blocks, thrust to the northeast so that Devonian beds have overridden Jurassic and Cretaceous sediments. In this basin the Kootenai formation of the Lower Cretaceous and the Jurassic Fernie shale have been brought to the surface by folding below the plane of overthrust.

About eighty-five miles southeast of the Bighorn coal basin the Rocky Mountains are crossed by the main line of the Canadian Pacific between Calgary and Revelstoke, and it was along this section, near latitude 51° , that McConnell² first described the great overthrust faults which have since proved to be so important a feature of Rocky Mountain structure. McConnell states that in latitude 51° , the Rocky Mountains are divisible on a structural basis into two parts, one lying east and the other west of the west base of the Sawback Range, which lies northwest of Banff and east of the upper Bow Valley. In McConnell's words (p. 31), "The region east of this line has been broken by a number of parallel or nearly parallel longitudinal fractures into a series of oblong orographic blocks, and these tilted and shoved one over the other into the form of a

¹ Malloch, G. S., Bighorn coal basin, Alberta: Mem. Geol. Surv., Canada, No. 9-E, 1911.

² McConnell, R. G., Report on the geological structure of a portion of the Rocky Mountains: Ann. Rept., Geol. Surv., Canada, 1886, vol. 2, 1887.

westerly-dipping compound monocline." In the section examined, he recognized seven principal faults and six blocks. The faulted region is now about twenty-five miles wide, but McConnell estimates that before the faulting the same rocks occupied a belt over fifty miles wide. In some blocks there are overturned folds, but these are said to be subordinate features of the structure.

Dowling¹ states that the eastern scarps in many places show remnants of anticlines, broken through along the crest, and suggests that the faults were developed from overturned folds. One of the largest thrusts is that along the east front of the range where Cambrian beds have overridden the Cretaceous (Belly River) for a distance of seven miles, with a vertical displacement of over 15,000 feet.

It is rather difficult to get from the published descriptions a clear conception of the dip of the Canadian overthrusts. McConnell's cross-sections indicate that the first great thrust, along the edge of the Great Plains, varies in dip between 10° and 60° and undulates in gentle folds. On the other hand, the thrusts farther west are represented on McConnell's section and on the one published in the Guide Book of the Twelfth International Congress (Guide Book No. 8) as having dips of 45° or more.

The section of the front ranges between the Sawback Range and the Columbia River, or Rocky Mountain Trench, is characterized on the whole by rather open synclines and anticlines with some overturned folds and a few normal faults of large displacement. As a whole the western division is greatly uplifted relatively to the eastern division, the prevailing rocks being pre-Devonian, largely Cambrian or older; whereas the rocks of the eastern fault-blocks range from Devonian to Lower Cretaceous.

West of the Rocky Mountain Trench the main line of the Canadian Pacific skirts the northern end of the Purcell Range, passing from the Rocky Mountain Trench into the Purcell

¹ Dowling, D. B., Guide Book No. 8, 12th Inter. Geol. Congress, part 1, p. 86, 1913.

Trench. According to Daly,¹ this part of the Rocky Mountain Trench coincides with a great longitudinal fault which has dropped the Cambrian and younger Paleozoic formations of the front ranges against the pre-Cambrian (Belt) rocks of the Purcell Range. Daly believes that this fault "dates from the Laramide (post-Laramie and pre-Eocene) revolution." The vertical displacement he estimates must be at least 5700 meters.

The Purcell Range is characterized by Daly² "as essentially a mass of Beltian strata folded with comparative regularity. The Cordilleran strike (here N. 30° W.) is generally well preserved throughout the whole area covered in this part of the Purcell System, as it is in the much broader section mapped at the International Boundary, far to the south. However, the folds show local disorder; they were accompanied by subordinate fractures and, when closely appressed, by mashing and by the development of slaty cleavage."

The Purcell Trench near its northern end has been eroded along the crest of an anticline in the Cougar formation of the Belt Series, according to Daly, whereas near the International Boundary the trench has been eroded along a fault. In his cross-section, Daly shows a fault along the anticline near the north end of the trench, but does not refer to this feature in his text.

West of the northern end of the Purcell Trench, the Selkirk Range is broadly synclinal. The axis of the principal fold, crossed by the railway at Rogers Pass, lies near the eastern border of the mass, so that in the western part of the range, rocks emerge which are older than any known in the Purcell or front ranges, and finally, east of Revelstoke and the Selkirk Valley, there is exposed a broad area of the crystalline pre-Beltian Shuswap rocks. The whole of the Selkirk and Purcell ranges are in fact a synclinorium, along the east limb of which the rocks older than the upper beds of the Cougar formation have been dropped out of sight by the great fault along the Rocky Mountain Trench. The Selkirk Valley, occupied by the

¹ Guide Book No. 8, 12th Inter. Geol. Congress, part 2, p. 202, 1913.

² *Op. cit.*, p. 204.

Columbia River and separating the Selkirk Range from the Columbia Range, is, in this part of its course, believed by Daly to mark the position of a longitudinal fault of unknown but possibly considerable displacement, with downthrow on the eastern side.

The Columbia Range, the westernmost unit of the Rocky Mountains in the latitude 51° , consists entirely of the Shuswap Series of the Canadian geologists. The line of separation between these mountains and the Belt of Interior Plateaus is crossed by the Canadian Pacific near Sicamous, or Shuswap Lake.¹ The structural features of the Shuswap terrane, which consists of metamorphosed sediments cut by various granitic rocks, are for the most part older than the Belt sediments. The dips are generally low and the rocks, according to Daly, have, notwithstanding their greater age, undergone less deformation than adjacent Paleozoic strata. He concludes that the "earth-shell which has here transmitted the mountain-building thrust had a depth of only a few kilometers; and that this shell was sheared over its basement of Shuswap rocks."² Inasmuch, however, as we know neither the structure of the Paleozoic beds which once arched over the Shuswap area, nor the structure of the Shuswap rocks which now are buried under the folded and faulted younger rocks in adjacent areas, Daly's suggested explanation appears to need some supporting evidence.

The general history of the Rocky Mountains in latitude 51° has been concisely summed up by Daly.³ Before the deposition of the Belt sediments, the Shuswap rocks possibly were arched into a broad geanticline trending about N. 70° E. From this time until the Mississippian epoch the zone now occupied by the Pacific System and the Belt of Interior Plateaus (the Western Geosynclinal Belt of Daly) is conceived to have been land, while the zone of the Laramide System (the Rocky Mountain Geosynclinal of Daly) was subsiding and continued to subside and receive sediment to the close of the Paleozoic.

¹ Daly, R. A., *Op. cit.*, p. 224.

² *Op. cit.*, p. 153.

³ Daly, R. A., *Op. cit.*, p. 157.

Daly believes that there was a broad upwarping at the close of the Paleozoic and that the western half of the Rocky Mountain prism of deposition was out of water and being eroded through Mesozoic time. It is not yet known how far the western half of the Rocky Mountain zone in this latitude was mountain-built during the late Jurassic or early Cretaceous revolution that affected so profoundly the Western Geosyncline. The deposition of the thick Cretaceous sediments along the Rocky Mountain geosyncline was terminated by the Laramide revolution. According to the estimates of the Canadian geologists the sediments along the Rocky Mountain zone, exclusive of the Shuswap group, had attained the extraordinary thickness of at least 96,000 feet, or over eighteen miles, at the close of the Cretaceous.

South of Bow River and the main transcontinental line of the Canadian Pacific, Cairnes¹ by his study of the Moose Mountain coal field has incidentally supplied additional information on the structure of the Rocky Mountain front ranges. His map and cross-sections show that the Cretaceous beds in front of the basal overthrust have been much crumpled and faulted, and that even the underlying Paleozoic rocks under the foothill belt have participated in this deformation, Moose Mountain being a slightly overturned short anticline, by the erosion of which the Paleozoic rocks are now exposed at the surface. In consequence of this vigorous folding in the foothill belt, Cairnes was able to recognize for the first time in the Great Plains region, the presence of the Kootenai formation of the Lower Cretaceous, which had hitherto been known only to the west of the Rocky Mountain front. This discovery was important in showing that there was no land barrier in Kootenai time along the present line of the Rocky Mountains. According to Cairnes, the Kootenai thins to the eastward.

Still farther south, the section across the Rocky Mountains traversed by the Crownest branch of the Canadian Pacific Railway has been briefly and not very satisfactorily described

¹ Cairnes, D. D., Moose Mountain district of southern Alberta: Geol. Surv., Canada, Pub. No. 968, 1907.

in Guide Book No. 9 of the Twelfth International Geological Congress. Beyond the statement that Crownest Mountain is an isolated remnant of "almost horizontal beds of Paleozoic limestone which have overridden Cretaceous sandstones of the Allison Creek formation along a great thrust plane" (page 34), there is scarcely a reference to the most interesting and most important large structural features of the section.¹

In the United States, Willis² has described and discussed the structure of the Rocky Mountain front in northern Montana with admirable clearness. The Livingston, which is the main front range of the Rocky Mountains in southern British Columbia, falls away and loses its identity near McDonald Lake, its place, with reference to the Great Plains, being taken by the Lewis Range, about eight miles farther east. This range, according to Willis, rises from the plains a few miles north of the International Boundary and continues southeast to the vicinity of Helena, Montana. Its total length is thus about 175 miles. It is perhaps open to question whether the distinction here made between the Lewis and Livingston ranges has more than local significance. Some geographers would probably prefer to consider the Lewis and Livingston ranges as a single orographic unit.

The Lewis and Livingston ranges are composed of argillites, limestones, and quartzites, which have a total thickness of over 12,500 feet and are all classed as Algonkian by Willis. These beds have been folded into a broad syncline, whose axis trends N. 25° W., and the whole mass has been thrust eastward over the Cretaceous beds of the Great Plains for a distance of seven or more miles. The thrust surface is of low general inclination, the maximum dip being estimated at less than 8°, and is undulating or warped in form. It is assumed by Willis on the basis of all available evidence that "(a) The thrust surface

¹ Unfortunately R. A. Daly's report on the Geology of the North American Cordillera at the Forty-ninth Parallel (Geol. Surv., Canada, Mem. No. 38) is not available at the date of writing.—F. L. R.

² Willis, Bailey, *Stratigraphy and structure, Lewis and Livingston ranges, Mont.*: Bull. Geol. Soc. America, vol. 13, pp. 305-352, 1902.

coincides essentially with the bedding of the Algonkian Series. (b) It coincides essentially with the highest peneplain on the Cretaceous rocks. (c) The antecedent structures of the Lewis thrust were determined by conditions of deposition."

The probable sequence of events as worked out by Mr. Willis are as follows:

1. The deposition of Dakota and Benton sediments east of a shore line which lay not many miles west of the present limit of the plains in this latitude. The deposition was accompanied by subsidence of the sea bottom off-shore and uplift of the adjacent land. (2) The development of the initial anticline thus formed into a more pronounced arch, by compressive stresses during the post-Laramie revolution. (3) Erosion of the crest of this fold and the cutting of the Blackfoot peneplain in early Tertiary time, and (4) Renewed compression in mid-Tertiary time with rupture of the weakened anticline followed by overthrust faulting. (5) The development in Miocene or possibly Pliocene time of a north-northwest-south-southwest normal fault between the Livingston and Galton ranges, with downthrow to the west. The vertical displacement on this fault probably amounts to thousands of feet. Mr. Willis, however, points out that the geologic dates assigned by him to the principal events depend upon certain hypotheses which as yet are unverified and that the thrust may possibly have taken place in late Cretaceous time.

Between the Livingston Range on the east and the Purcell Trench on the west lie parts of Montana and Idaho of whose structure as a whole we have only reconnaissance knowledge. The rocks, as shown by Walcott¹ and by Calkins,² are almost entirely sediments belonging to the great Belt Series of the Algonkian. Their total thickness has been estimated by Dr. Walcott at 37,000 feet.

"The region is characterized structurally more by faulting

¹ Walcott, C. D., Algonkian formations of northwestern Montana: Bull. Geol. Soc. America, vol. 17, pp. 1-28, 1906.

² Calkins, F. C., A geological reconnaissance in northern Idaho and northwestern Montana: Bull. U. S. Geol. Surv., No. 384, 1909.

than by folding. Very few folds in the region can be traced for great distances, but a number of faults, some of which are of enormous throw, have been followed for many miles. The blocks between the faults are generally much tilted, and steep dips persist in places for long distances across the strike.''¹ The great faults are mostly steep and the majority of them are probably normal. They range in trend from north to nearly west and are for the most part strike faults. With few exceptions the downthrow is to the southwest, the beds in the fault blocks dipping to the northeast. The Cœur d'Alene district in northern Idaho² shows much greater complexity of structure than is characteristic of the general region.

South of latitude 47° the Big Belt and Bridger ranges, between the Missouri and Yellowstone rivers, constitute the main Cordilleran front, which here rises less abruptly than elsewhere from the Great Plains province, owing to the presence of the Little Belt, Crazy, Highwood, Big Snowy, and other outlying mountain masses. The Little Belt Mountains have been described³ as a broad flat-topped anticline with slight overturning of the folds along its northern and eastern sides. The Crazy Mountains are essentially igneous stocks. The Big Belt Range has been briefly described by Davis⁴ as an oval anticline with steep dips and granitic intrusions. Little is known of its structural details.

According to the same geologist the crest of the Bridger Range, south of the Big Belt Mountains, is formed of thick Carboniferous limestone, strongly overturned to the east, so as to dip from 60° to 70° to the west, and overlies the disturbed Mesozoic beds along the east base of the range. Peale states

¹ Calkins, F. C., *Op. cit.*, p. 52.

² Ransome, F. L., and Calkins, F. C., *Geology and ore deposits of the Cœur d'Alene district, Idaho*: Prof. Paper, U. S. Geol. Surv., No. 62, 1908.

³ Weed, W. H., *Little Belt folio*, Geol. Atlas U. S., U. S. Geol. Surv., No. 56, 1899.

Calvert, W. R., *Geology of the Lewistown coal field, Montana*: Bull. U. S. Geol. Surv., No. 390, p. 46, 1909.

⁴ Davis, W. M., *Relation of the coals of Montana to the older rocks*: Tenth Census, vol. 15, Mining Industries, pp. 705-706, 1886.

that the "Bridger Range represents the eastern slope of a long anticlinal uplift which is overthrown at the south end, where schists and gneisses rest upon inverted Paleozoic structure."¹

West of the front ranges in west-central Montana and central Idaho, the orographic structure is complicated by the intrusion of the Boulder batholith² of Montana and the superficially much larger batholith of central Idaho, which may well be called the Idaho batholith. Both masses are mainly quartz monzonite and in the 150 miles of territory separating them occur smaller areas of similar rock, so that it appears probable, as Knopf³ has suggested, that all are in reality parts of a single great batholith. The Boulder batholith⁴ is exposed over an area of about 1100 square miles and the Idaho batholith over 2100 square miles. Weed considers the Boulder batholith as Miocene, while Knopf, who found probable Eocene beds resting on the quartz monzonite, regards it as late Cretaceous. According to Emmons and Calkins,⁵ the batholithic intrusions of the Phillipsburg district, west of Helena, cut the Colorado formation and are of "Tertiary or, at the earliest, of very late Cretaceous age." The age of the Idaho batholith has been less definitely determined, but Lindgren⁶ shows that it is probably post-Triassic.

In the Marysville district, Montana, which lies a few miles

¹ Peale, A. C., *Livingston folio*, Geol. Atlas U. S., U. S. Geol. Surv., No. 1, 1894.

² Since this address was delivered, a paper has appeared in which Prof. A. C. Lawson suggests that the so-called Boulder batholith is probably a laccolith. (Is the Boulder "Batholith" a laccolith? *Bull. Dept. Geol., University California*, vol. 8, pp. 1-15, 1914.)

³ Knopf, Adolph, *Ore deposits of the Helena mining region, Montana*: *Bull. U. S. Geol. Surv.*, No. 527, p. 34, 1913.

Knopf, Adolph, *Op. cit.*, p. 29.

⁴ Weed, W. H., *Granite rocks of Butte, Montana, and vicinity*: *Jour. Geology*, vol. 7, p. 737, 1899. Also, *Geology and ore deposits of the Butte district, Montana*: *Prof. Paper, U. S. Geol. Surv.*, No. 74, pp. 28-29, 1912.

⁵ *Geology and ore deposits of the Phillipsburg quadrangle, Montana*: *Prof. Paper, U. S. Geol. Surv.*, No. 78, p. 83, 1913.

⁶ Lindgren, W., *A geological reconnaissance across the Bitterroot Range and Clearwater Mountains in Montana and Idaho*: *Prof. Paper, U. S. Geol. Surv.*, No. 27, pp. 26-27, 1904.

north of the main area of the Boulder batholith, Barrell¹ states that towards the close of the Cretaceous or the opening of the Tertiary, the strata were folded, with the production of great "domes and arches." The elevation of the domes was accomplished in part by marginal faulting. This deformation was followed, according to Barrell, by the intrusion of a batholithic mass which is probably an outlying part of the Boulder batholith. He concludes that the folding was accompanied by strong compressive stresses whose effects are visible in mashing, brecciation, and some thrust faulting. Thrust faults, however, are not described as prominent structural features. Normal faults, later than the compression and folding, are numerous and of various ages. After the intrusion of the batholith, followed by prolonged erosion, there appears to have been some revival of mountain-making movements in the Miocene or Pliocene, characterized by faulting, tilting, and warping, associated with volcanic outbursts.

In the Phillipsburg district, Montana, a few miles northwest of Butte, the stratigraphic sequence from the Belt Series of the Algonkian to the Colorado formation of the Upper Cretaceous lacks representation only in the Ordovician and Triassic periods. The beds have undergone vigorous deformation by folding and faulting, the general structural trends being nearly north and south, and have been invaded by batholithic masses. The intricate structure has been worked out with skill and patience by Mr. Calkins,² who states that "the effects of deformation are chiefly to be seen in the pre-Tertiary rocks, which have been very complexly faulted and folded, the folds involving the Cretaceous and older rocks being locally overturned or even recumbent, and some faults having throws of several thousand feet. The great unconformity between the Tertiary and pre-Tertiary rocks is partly proved by the relatively slight deforma-

¹ Barrell, Joseph, *Geology of the Marysville mining district, Montana*: Prof. Paper, U. S. Geol. Surv., No. 57, p. 24, 1907.

² Emmons, W. H., and Calkins, F. C., *Geology and ore deposits of the Phillipsburg quadrangle, Montana*: Prof. Paper, U. S. Geol. Surv., No. 78, 1913.

tion of the Tertiary beds, which, however, have been tilted and faulted to some extent. The principal effect of igneous activity has been the intrusion of irregular or dome-like masses of magma which have crystallized as granular rocks belonging to the diorite, granite, and intermediate families."¹ In the development of the structure of the region, faulting has been more prominent than folding. A great zone of thrust faulting crosses the quadrangle from north to south, along which Algonkian rocks on the west have been thrust in general over younger Paleozoic and Jurassic rocks to the east. "This zone of thrust faulting offers a striking exception to the general rule that the faults are subsequent to the folds, for it has been folded and has been dislocated by normal faults to nearly the same extent as the rock strata, and is therefore one of the oldest tectonic features of the quadrangle."² In some places the thrust surface is described as not only folded but as actually overturned. Mr. Calkins considers it probable that the Phillipsburg thrust zone is the southern continuation of the great thrust along the east base of the Lewis Range. These two localities, however, are nearly 150 miles apart, and the Lewis thrust, to join with that at Phillipsburg, would have to swing over the Lewis Range instead of keeping along its base, or else would have to turn sharply west past Helena. While the two thrusts probably have a close genetic relation, further geologic work is necessary to establish their identity.

About fifty miles west of Phillipsburg lies the section of the Bitterroot Range studied by Lindgren.³ This part of the range is carved mainly from the Idaho batholith and the chief structural feature of interest in connection with the present inquiry is a remarkable fault described by Lindgren along the east side of the mountains. On that side of the range a zone of gneissic and schistose structure in the batholith and an associated parallel topographic surface which dips from 15° to 26° east are interpreted by Professor Lindgren as having

¹ Emmons and Calkins, *Op. cit.*, p. 31.

² Emmons and Calkins, *Op. cit.*, p. 146.

³ *Op. cit.*

resulted from a great normal fault whereby the Bitterroot Range was elevated and the rocks under the Bitterroot Valley were depressed. The dip slip on this fault is estimated as probably at least 20,000 feet. The dislocation is supposed to have taken place in early Tertiary time, after the development of the surface of erosion which is indicated by the general uniformity of crests throughout the mountain masses of central Idaho. In the low angle of dip and in the profound metamorphism indicated by the conversion of the quartz monzonite into gneiss and schist, this is certainly a very remarkable normal fault, and it invites further investigation.

South of the area studied by Lindgren a reconnaissance by Umpleby,¹ mainly in Lemhi County, Idaho, supplies the latest geological information. The sedimentary rocks, ranging from Algonkian to Carboniferous, are folded and much faulted, but the region apparently contains no large overthrusts. An old erosion surface, supposedly Eocene, was elevated in pre-Miocene time and has been deformed by moderate folding and faulting in post-Miocene time.

Near the southern base of the Salmon River Mountains, in the Wood River region, recent work by Prof. L. G. Westgate on the Hailey quadrangle, not yet completed, indicates that a thick series of rocks probably ranging from Algonkian to Carboniferous have been vigorously deformed by folding and faulting. Some of the folds have been overturned and overthrust to the east. The structural details, however, have not yet been fully worked out.

In the Yellowstone region, the Jefferson, Madison, and Gallatin ranges exhibit strong post-Cretaceous folding and faulting but the structure is irregular, has not yet been studied in detail, and disappears to the south under the Yellowstone volcanic plateau. This lofty tableland, with an average elevation of about 8000 feet, is the characteristic topographic feature of the National Park. Its lavas appear to have been erupted throughout the Tertiary, their accumulation being

¹ Umpleby, J. B., *Geology and ore deposits of Lemhi County, Idaho*: Bull. U. S. Geol. Surv., No. 528, 1913.

accompanied by subsidence. Along the east side of the park, the rugged Absaroka Range, also of volcanic material, has been piled upon the Mesozoic and older rocks, effectually concealing their structure.

On the west side of the Bighorn Basin or east base of the Absaroka Range, Fisher¹ has described and pictured the "Wasatch conglomerate" lying with striking angular unconformity on "Laramie sandstone." More recent work has shown, however, that the "Wasatch" of Mr. Fisher at the locality illustrated is really Wind River² and that his "Laramie" at the same place is true Fort Union, or basal Eocene.³ This would indicate that the major uplift of the mountains enclosing the Bighorn Basin took place within early Eocene time.

South of the Yellowstone volcanic plateau, the Teton, Snake River, Hoback, Gros Ventre, and Wind River ranges have as yet received only reconnaissance examination. In 1910, Blackwelder⁴ made a rapid examination of the ranges mentioned with special reference to the occurrence of phosphate rock, and this has been followed by detailed geologic work which he has not yet completed. Of the geologic structure of the Snake River Range, little is known except that the rocks are much folded and faulted. The rugged Teton Range, according to Professor Blackwelder, has been carved from a monoclinal block with gentle dip to the west and a great fault scarp along its eastern front. Structurally, therefore, it appears to be in sharp contrast with the Snake River Range. The Hoback Range is described by Blackwelder as closely folded, with important normal faults, especially along its flanks. "The Gros Ventre Range is a broad, somewhat complex anticlinal uplift with steep dips and local faults on the southwest and gently inclined

¹ Fisher, C. A., Geology and water resources of the Bighorn Basin: Prof. Paper, U. S. Geol. Surv., No. 53, p. 33, and plate X-B, 1906.

² Sinclair, W. J., and Granger, W., Notes on the Tertiary deposits of the Bighorn Basin: Bull. Am. Mus. Nat. Hist., vol. 31, pp. 60-61, 1912.

³ Hewett, D. F., oral communication. See also Sinclair and Granger, *loc. cit.*

⁴ Blackwelder, Eliot, A reconnaissance of the phosphate deposits in western Wyoming: Bull. U. S. Geol. Surv., No. 470, pp. 452-481, 1911.

strata interrupted by low asymmetrical folds along the northeast side.”¹

“The Wind River Range,” says Blackwelder, “is a broad, low, somewhat broken anticline with northwest-southeast trend. Along the north slope the general northeasterly dip is interrupted by several low but sharp asymmetrical anticlines which, as in the Gros Ventre Range, are always over-steepened toward the southwest. On the south side the older rocks are said to be largely concealed by Tertiary sediments and thick deposits of glacial drift. Around the head of Green River, in the southwestern part of the range, and perhaps farther south-eastward, the ancient metamorphic rocks are overthrust upon the Paleozoic strata, which are there complexly folded and faulted.”²

In a paper now in press, Blackwelder³ states that on Roaring Fork, in the northwestern part of the Wind River Range, conglomerate beds, which he would refer to the basal part of the Wind River if that formation in Wyoming were not everywhere nearly horizontal, are overturned and dip 45° into the mountains under overthrust pre-Cambrian. He concludes that if not Wasatch, the conglomerate is probably Fort Union.

Northeast of the region examined by Professor Blackwelder are the Owl Creek Mountains, which, with the Bridger Range (to be distinguished from the range of the same name in Montana), join the Absaroka or Shoshone Range to the Bighorn Range and separate the Bighorn Basin on the north from the Wind River Basin on the south. According to Darton,⁴ the Owl Creek Range is a deeply eroded, rather complex anticlinal uplift with some faults of large throw. In general the dip of the beds is steeper on the south limb of the anticline than on the north.

¹ Blackwelder, *Op. cit.*, p. 467.

² Blackwelder, *Op. cit.*, pp. 471-472.

³ Blackwelder, E., *Stratigraphy of the Wind River Mountains, Wyoming*: Bull. U. S. Geol. Surv., No. — (in press).

⁴ Darton, N. H., *Geology of the Owl Creek Mountains*: Senate Doc. 219, 59th Cong., 1st Sess., 48, pp. 11-13, 1906.

The Bighorn Range, which has also been studied by Darton,¹ is an anticline which, on the northeast side, rises very sharply from the nearly horizontal strata of the plains. There are minor folds and some important normal faults along the flanks of the anticline, one of the faults having a throw of about 9000 feet. A steep overthrust, with a displacement of about 1500 feet is described by Darton on the west side of the range. This fault has a length of about two miles and apparently is a local and minor feature in the general structure.

Inasmuch as the Kingsbury conglomerate, formerly considered by Darton as of late Cretaceous age, but now known to be a member of the early Eocene Fort Union formation,² contains pebbles of beds down to and including the Cambrian, there must have been uplift and extensive erosion in early Eocene time. The principal mountain-making deformation took place then and according to Darton these uplifts were truncated and the larger features of the present topography outlined during the Eocene.

In southwestern Wyoming, southeastern Idaho, and northeastern Utah, west and southwest of the Teton Range, is a region containing a number of comparatively short uplifts, including the Wyoming, Salt River, Caribou, Blackfoot, Preuss, and Bear River ranges. Of this whole region, Gale and Richards state: "The structure . . . is that of a closely compressed, overfolded, and overthrust faulted complex, which is in great part difficult of interpretation. The major structures have a north-south trend, and the direction of the overthrust is universally from the west. The compressive forces have been of such intensity that they have produced many overturned and recumbent folds and overthrust faults, carrying the older hard-rock formations up and over younger strata and contorting and crumpling the beds of the underlying flanks."³ A number

¹ Darton, N. H., *Geology of the Bighorn Mountains*: Prof. Paper, U. S. Geol. Surv., No. 51, 1906.

² Gale, H. S., and Wegeman, C. H., *The Buffalo coal field, Wyoming*: Bull. U. S. Geol. Surv., No. 381, p. 143, 1910.

³ Gale, H. S., and Richards, R. W., *Preliminary report on the phosphate deposits in southeastern Idaho and adjacent parts of Wyoming and Utah*: Bull. U. S. Geol. Surv., No. 430, p. 482, 1910.

of thrust surfaces have been recognized. The easternmost one is the Darby thrust, mapped by Schultz¹ along the east flank of the Wyoming Range and with a horizontal displacement which Richards and Mansfield² have estimated at three miles.

West of this thrust is the great Absaroka thrust, first observed by Peale,³ who, however, shows it in his sections as an approximately vertical fault and apparently did not recognize it as an overthrust. Veatch⁴ describes it as "an enormous thrust fault, in which the thrust has come from the west." The dip as shown in Mr. Veatch's sections is in general steeper than 45°, and the stratigraphic throw is estimated to be from 15,000 to 20,000 feet. By the subsequent work of Schultz,⁵ the Absaroka thrust has been traced northward along the east base of the Salt River Range, to Snake River, so that its total length is probably at least 150 miles. West of the Absaroka fault other thrusts have been recognized close to the western boundary of Wyoming, especially the Crawford thrust east of the Bear River Plateau,⁶ possibly the fault at Cokeville, although this has been described as a normal fault,⁷ and perhaps the fault near Afton, west of the Salt River Range.⁸

Still farther west, in Idaho and Utah, is the great Bannock overthrust which has been studied by Richards and Mansfield.⁹ They show that various dislocations which previously have been considered as separate faults are probably parts of a single overthrust extending from Idaho Falls in Idaho to a point midway between Evanston and Ogden in Utah, or a distance in a

¹ Schultz, A. R., Coal fields in a portion of central Uinta County, Wyoming: Bull. U. S. Geol. Surv., No. 316, plate 13, 1907.

² Richards, R. W., and Mansfield, G. R., The Bannock overthrust: Jour. Geology, vol. 20, p. 705, 1912.

³ Peale, A. C., 11th Ann. Rept., Geol. Geog. Surv., Territories for 1877, p. 536, plate 53, 1879.

⁴ Veatch, A. C., Geography and Geology of a portion of southwestern Wyoming: Prof. Paper, U. S. Geol. Surv., No. 56, p. 109, 1907.

⁵ *Op. cit.*, plate 13.

⁶ Veatch, *Op. cit.*, p. 112; Gale and Richards, *Op. cit.*, p. 514.

⁷ Gale and Richards, *Op. cit.*, p. 506.

⁸ Peale, *Op. cit.*, p. 546.

⁹ *Op. cit.*, pp. 681-709.

straight line of more than 150 miles. The trace of the fault is remarkably sinuous, extending from the north along the Blackfoot and Preuss ranges to the vicinity of Montpelier, thence looping northwest and again continuing southward along the east base of the Bear River Range (west of Bear Lake) into the Randolph quadrangle, where it has been studied by G. B. Richardson.¹ The horizontal displacement is estimated by Messrs. Richards and Mansfield at not less than twelve miles, and the maximum vertical displacement at from 8500 to 12,000 feet. The thrust surface as a whole dips west at a low angle but has been thrown into gentle folds, the deformation apparently being less than in the Phillipsburg region. The Bannock thrust has cut the Beekwith formation, of which the larger part is Jurassic although the upper part may be Cretaceous. On the other hand, it is covered in places by the basal formation of the Eocene Wasatch group.

The Wasatch Range (exclusive of the Bear River Range, which is sometimes considered a part of the Wasatch) has long been known as essentially an eastward-dipping monocline cut off along its western side by a great normal fault whose scarp fronts the Great Basin from the east, as the similar scarp of the Sierra Nevada overlooks it from the west. In its structural features the Wasatch is transitional between the region which has just been considered and the Great Basin province. As is well known from the writings of Clarence King, S. F. Emmons, and later geologists, the range exhibits an older structure of broad folds, complicated by much accessory deformation, which was imposed upon the rocks before the range was given its present monoclinical form. In the middle section of the range, according to Boutwell,² there was only slight uplift at the close of the Jurassic, the main deformation, with intrusion of dioritic magma, taking place at the close of the Cretaceous. Boutwell³

¹ Geol. Atlas U. S., U. S. Geol. Surv., Randolph folio (in press).

² Boutwell, J. M., *Geology and ore deposits of the Park City district, Utah*: Prof. Paper, U. S. Geol. Surv., No. 77, pp. 104-105, 1912.

³ Boutwell, J. M., *Stratigraphy and structure of the Park City mining district, Utah*: Jour. Geology, vol. 15, p. 457, 1907.

was the first to recognize that overthrusting is an important element in the Wasatch structure. He mapped and described in the Park City district, southeast of Salt Lake City, a compound overthrust from the west with a displacement of at least 2000 feet. More recently Blackwelder¹ has described important thrusts in the vicinity of Ogden. The principal fault, the Willard thrust, which has been traced for fifteen or twenty miles along the front of the range, has a maximum horizontal displacement of about four miles, according to Blackwelder, and dips *east*. It has resulted in Algonkian strata being shoved from the east over beds up to and including the Carboniferous. Other overthrusts under the Willard thrust give the structure in general a shingled character, the component slabs all dipping east. The Willard thrust varies in dip up to 50°, the average being about 15°. Inasmuch as the Eocene beds in the region are slightly flexed, the thrust surface has probably undergone deformation to the same extent, but Blackwelder suggests that the surface may have been originally undulating. It is to be noted that the thrusts described by Professor Blackwelder differ from all of the important displacements of that type which have been studied in the Rocky Mountains, in that the overthrust blocks have apparently been pushed up from the east.

East of Ogden the overthrust faults are displaced by the transverse Huntsville fault of normal type. Blackwelder concludes that the overthrusts are of "Cretaceo-Eocene age, while the normal faults are probably post-early Eocene."²

In the southern part of the Wasatch Range, Loughlin³ has described two periods of thrust faulting, one earlier than the granitic intrusions and one associated with those intrusions. In Little Cottonwood Canyon the older overthrust dips east while younger thrusts dip west. If the relations of these thrusts

¹ Blackwelder, E., New light on the geology of the Wasatch Mountains, Utah: Bull. Geol. Soc. America, vol. 21, pp. 517-542, 1910.

² *Op. cit.*, p. 542.

³ Loughlin, G. F., Reconnaissance in the southern Wasatch Mountains, Utah: Jour. Geology, vol. 21, pp. 436-452, 1913.

to the granitic intrusions have been correctly interpreted, the deformation which they represent must be considerably older than the faults described by Blackwelder and probably belongs to the great post-Jurassic revolution that profoundly affected the country west of the Laramide System, although its effects in that chain appear to have been very feebly recorded. The structure of the southern Wasatch has been complicated, according to Loughlin, by block faulting in post-Eocene time, so that the structural features of this part of the range are of Great Basin rather than Rocky Mountain type. This and the exceptional character of the thrusts described by Blackwelder indicate that the Wasatch Range still offers many structural problems of great interest. Crossing as it does the great Uinta arch and occupying transition ground between the Laramide System on the east and the Great Basin on the west, as well as between the Rocky Mountains on the north and the Colorado Plateaus on the south, it is a critical tectonic point of the first rank and is likely to be one of the battlegrounds of geologic science for many years to come.

East of the Wasatch Range the remarkable transverse arch of the Uinta Mountains has attracted the attention of geographers and geologists since the days of the Powell and King surveys, although its structure still lacks detailed study. King¹ states that the range "consists of a broad central plateau 150 miles long by 30 miles wide, in which there are slight sags and local undulations, but the average dip of the strata is from the horizontal only up to 4 or 5 degrees. This broad flat-topped arch suddenly gives way along the north and south edges to two distinct axes of flexure where the horizontal rocks bend over, accompanied by distinct faulting at angles varying from 10 to 70 degrees. In the Green River canyon the southern line of flexure becomes immensely complicated and develops three local anticlinals." As regards the structural features of the range, the excellent early descriptions of S. F. Emmons² have

¹ King, Clarence, U. S. Geol. Explor. 40th Parallel, vol. 1, p. 753, 1878.

² Geol. Explor. 40th Parallel, vol. 2, pp. 191-325, 1877.

been supplemented by his own later work¹ and by that of Berkey² and Weeks.³ Suess⁴ regards the Uinta Range as structurally continuous with the Elk, Sawatch, and Sangre de Cristo ranges in Colorado, the whole line constituting the first mountain wave which sweeps around the northeastern side of the Colorado Plateau, and affording the most conspicuous example of the tendency of the Rocky Mountain ranges to bend or branch westward as they are followed north.

In the vicinity of the Wyoming lineament the lofty ranges to the north and south break down to what Veatch has described as "a number of dome and lozenge-shaped uplifts of greater or less extent and of considerable variation in axial trend."⁵

A point has now been reached whence the essential tectonic character of the portion of the Rocky Mountains lying north of the Wyoming lineament may be reviewed. As a whole, and after allowance has been made for imperfect knowledge of some of its parts, this long section of the Laramide System shows the action of vigorous compression exerted in directions generally normal to the local trend of the chain. The evidence of this compression is boldly written in folds, many of them overturned to the east or northeast, and in great thrust faults along which blocks of the earth's crust have been shoved for miles, as a rule from the west towards the Great Plains, and possibly, along the Endicott Range, from the south towards the Arctic Ocean. In British America and northern Montana the zone of maximum disturbance lies along the east base of the chain, but in southwestern Montana, Idaho, Wyoming, and Utah it is shifted to the middle and western portions.

¹ Emmons, S. F., Uinta Mountains: Bull. Geol. Soc. America, vol. 18, pp. 287-302, 1907.

² Berkey, C. P., Stratigraphy of the Uinta Mountains: *Ibid.*, vol. 16, pp. 517-530, 1905.

³ Weeks, F. B., Stratigraphy and structure of the Uinta Range: *Ibid.*, vol. 18, pp. 427-448, 1907.

⁴ Suess, E., *Face of the Earth*, English translation, vol. 1, p. 567; vol. 4, pp. 380-386, 1909.

⁵ Veatch, A. C., Coal fields of east-central Carbon County, Wyoming: Bull. U. S. Geol. Surv., No. 316, p. 245, 1907.

Although Willis has suggested a Miocene age of the Lewis overthrust, the preponderant testimony of geologists all along this section of the Laramide System is that the principal folding and overthrusting took place in post-Cretaceous or early Eocene time. In the United States important deformation appears to have begun at the close of the recognized Laramie, or possibly even earlier, and to have attained its maximum between the Fort Union, which chiefly on the basis of its plant remains is generally classed as basal Eocene, and the mammal-bearing lower Eocene Wasatch. Normal faulting followed the thrusting and in general finds its greatest development in those parts of the chain which lie to the west of the belt of overthrust.

Over most of the province no important or widespread deformation has been recognized between the beginning of the Paleozoic and the closing stages of the Cretaceous. At its southern end, however, in southwestern Wyoming, Veatch¹ has shown that although the principal deformation was effected at the close of the Cretaceous, moderate folding and important faulting are recorded in the Evanston, Almy, and Fowkes formations, which possibly belong in the Fort Union, whereas the undoubted Wasatch, represented by the unconformably overlying Knight formation, shows scarcely any deformation.

The only antecedent feature which is recognizable as having had a probable direct influence on the Laramide deformation is the fact that throughout Paleozoic and Mesozoic times the northern Rocky Mountain belt was an area of subsidence and of exceptionally heavy sedimentation, lying between the interior sea and Arctic Ocean on the one side and a land mass on the other. There is no clear evidence that any part of the belt was a land area at any time during this long interval. Apparently the whole region now occupied by the northern Rocky Mountains was covered by Cretaceous sediments.

From the evidence available, it is even clearer now than it

¹ Veatch, A. C., Geography and geology of southwestern Wyoming: Prof. Paper, U. S. Geol. Surv., No. 56, 1907.

was when Dawson¹ made the statement some years ago with special reference to the Canadian Rocky Mountains, that the major folding and thrusting, at least so far as concerns its visible effects, was away from, not towards, the Pacific Ocean. His explanation was a tangential thrust transmitted from the Pacific Basin.

In general the Cretaceous and older beds of the Great Plains, across a belt of varying width in front of the mountains, are folded and faulted in such a manner as to indicate that their deformation was contemporaneous with the Rocky Mountain uplift and to some extent was a direct result of the overthrusting. This strong local deformation does not appear to be in harmony with the view, advanced by Mr. Willis, that the Lewis overthrust surface is coincident with an Eocene peneplain.

In comparison with some other parts of the Cordillera, the northern Rocky Mountain section is not a region of great and general volcanic or plutonic activity. Yet in the Idaho and Boulder batholiths, intrusion has taken place on a mighty scale and the Yellowstone Plateau is an impressive record of volcanicity which is now in its final stage.

Southern Division or Park Range Province. The general structural features of the Park Range Province, which are very different from those of the northern Rocky Mountains, have been sketched by the pioneers in western geology. In a very rough and broad way the region as a whole is anticlinal, with large areas of crystalline pre-Cambrian rocks exposed between the upturned flanking beds. On the east, along the Laramie and Front ranges, the sedimentary strata of the Great Plains are bent abruptly upward against a mountain wall whose sheer continuous front is strongly suggestive of a weathered fault scarp. On the west the Paleozoic beds of the Colorado Plateau sweep at lower angles up the arch and have been eroded back into lines of outcrop which, as a whole, have little regularity, although exception must be noted with reference to the remarkably persistent ridge of Cretaceous beds known as the Grand

¹ Dawson, G. M., Geological record of the Rocky Mountain region in Canada: Bull. Geol. Soc. America, vol. 12, p. 87, 1901.

Hogback. On the west the geologic sequence is fairly well represented from the Cambrian to the Cretaceous, but along much of the eastern flank the oldest of the visible upturned beds are Mesozoic or late Paleozoic. Closer examination shows that the province, instead of consisting of a huge simple arch, comprises a number of more or less broadly anticlinal structures which correspond in a general way to the principal mountain masses. Dutton¹ characterized these ranges as being structurally broad platforms with monoclinal flexures or faults on their margins. His view of them appears to have been at one time fully accepted by Suess,² although in his final volume the latter remarks that we are left in doubt whether the units of the Park Range Province are true horsts or are simple anticlines. S. F. Emmons rejected the idea that these mountains are due to the action of forces operating in a vertical direction. He maintained that the orographic features of this province are "the result of compressive folding, producing a fracturing or faulting along the steeper side of a one-sided or S-fold, which is the prevailing type in this region."³

The Front, Park, Sawatch, Wet, and to a less extent the Sangre de Cristo mountains all show broad central areas of crystalline pre-Cambrian rock and according to Emmons⁴ were islands throughout Paleozoic and Mesozoic time; while Powell,⁵ on the other hand, regarded them as deeply eroded anticlinal arches of the same general type as the Uinta Range.

Although considerable detailed geologic work has been accomplished in Colorado of late years, it has for the most part been confined to areas which are too small or are not properly situated to throw much light on the orogenic development of the ranges most typical of the province. A very careful and

¹ Dutton, C. E., *Geology of the High Plateaus*, p. 47, 1880.

² *Face of the Earth*, English translation, vol. 1, pp. 567-568, 1904.

³ Emmons, S. F., *Orographic movements in the Rocky Mountains*: Bull. Geol. Soc. America, vol. 1, p. 271, 1890.

⁴ *Op. cit.*, pp. 272-274.

⁵ Powell, J. W., *Geology of the eastern portion of the Uintah Mountains*, p. 27, 1876.

fruitful study of the San Juan Mountains by Dr. Whitman Cross and his associates has been in progress for nearly twenty years; but he has to do here with an outlying mountain mass, containing, between the Archean and the base of the Paleozoic, a considerable thickness of folded Algonkian sediments, and separated from the main Rocky Mountain ranges by a great area of subsidence and volcanic accumulation comparable with that of the Yellowstone region. Where detailed investigations have been made of small areas in the heart of the Park Range province, as at Leadville,¹ Aspen,² Tenmile,³ and Breckenridge,⁴ the characteristic tectonic features are open folds, with numerous faults, generally of the normal type and frequently of great displacement. Spurr's sections in the Aspen district show a few overturned folds and some overthrust faults, indicating clearly that compressive stresses were active.

In far western Colorado, studies by H. S. Gale⁵ and others carried out in connection with the investigation of coal resources have thrown light on the structural and stratigraphic relations between the Park Range and Plateau provinces. Along the Grand Hogback monocline, which sweeps around from the south side of the Uinta Mountains to the vicinity of the Elk Mountains, both the Wasatch and Green River formations are involved in the uplift, apparently to the same extent as the Cretaceous (Mesaverde).⁶ Although plant remains belonging to the Fort Union flora have been found in the western Colorado coal field, Mr. Gale was unable to distinguish any formation

¹ Emmons, S. F., *Geology and mining industry of Leadville, Colo.*: Monograph U. S. Geol. Surv., vol. 12, 1886.

² Spurr, J. E., *Geology of the Aspen mining district, Colo.*: *Ibid.*, vol. 31, 1898.

³ *Geol. Atlas U. S., U. S. Geol. Surv., Tenmile district: Special folio, No. 48*, by S. F. Emmons, 1898.

⁴ Ransome, F. L., *Geology and ore deposits of the Breckenridge district, Colo.*: Prof. Paper, U. S. Geol. Surv., No. 75, 1911.

⁵ *Coal fields of northwestern Colorado and northeastern Utah*: Bull. U. S. Geol. Surv., No. 415, 1910.

⁶ Gale, H. S., *Op. cit.*, p. 84, and plates 13 and 17.

corresponding to that name from the Wasatch formation. An important unconformity at the top of the Mesaverde is indicated by the absence of the Lewis and Laramie formations, both represented in the Yampa coal field to the north, and the presence of a persistent conglomerate. Clearly there was uplift and vigorous erosion at the close of the Cretaceous, although the angular discordance between the Cretaceous and Tertiary beds is apparently small.

On the eastern side of the mountains, it will be remembered that in the Denver Basin the main orogenic disturbance is supposed to have taken place between the deposition of the Laramie and Arapahoe formations, the Arapahoe and Denver being regarded by Cross as Eocene, but older than Fort Union. In accordance with this view the main Laramide uplift was at the end of the Cretaceous. Cross states that "there is at present no available evidence to show a movement of any unusual importance between the Denver and Fort Union epochs."¹ If, however, as other geologists and paleontologists maintain, the Denver and Arapahoe formations are Cretaceous, then the main uplift took place before the close of the Cretaceous, or else undue importance has been attached to the unconformity at the base of the Arapahoe.

South of the Denver Basin, in the Raton coal field, W. T. Lee² has described an unconformity which he correlates with that at the base of the Arapahoe. According to him, the Laramie is here wanting, the formation immediately below the unconformity being of Montana age, and those above it Tertiary. He considers it not improbable that the Cretaceous formations once extended over most if not all of the area occupied by the Rocky Mountains, and that uplift, followed by erosion sufficient to cut down to the Archean rocks, took place at the close of the Cretaceous.

¹ Cross, W., The Laramie formation and the Shoshone Group: *Proc. Washington Acad. Sci.*, vol. 11, p. 43, 1909.

² Lee, W. T., Stratigraphy of the coal fields of New Mexico: *Bull. Geol. Soc. America*, vol. 23, pp. 612-613, 1912.

In the San Juan Mountains, according to Cross and Spencer,¹ the principal deformation of the Laramide revolution was effected at the close of the "Laramie" before the deposition of the supposedly Eocene Telluride conglomerate, but another important movement followed the deposition of the Eocene Torrejon formation in northwestern New Mexico, south of the San Juan Mountains.²

The idea that present areas of Archean rocks correspond in general to ancient islands or land masses in the Paleozoic and later seas was more widely held by the geologists of thirty or forty years ago than it is now. A number of these supposed islands against which the Paleozoic strata were thought to have been deposited have been shown, as in the Wasatch Range, to be intrusive granitic masses with associated contact-metamorphic rocks, and relations formerly interpreted as depositional overlaps have been explained as the result of faulting.

In the light of present knowledge, it appears that the Paleozoic islands postulated by Emmons in central and northern Colorado will probably be diminished in number, contracted in size, and modified in outline. Even from the Hayden map of Colorado it may reasonably be inferred that the Sawatch and Sangre de Cristo ranges were completely submerged in early Paleozoic time, and it is highly probable, especially from relations studied at Breckenridge, that the Dakota sandstone and several thousand feet of later Cretaceous sediments originally covered the entire Park Range Province. Nevertheless, it is to be remembered that the pre-Dakota formations in this province are comparatively thin, showing that the region subsided less rapidly than did the northern section of the Rocky Mountains. As Willis³ has pointed out, it has been a positive element in the continental structure. Moreover, the strati-

¹ Cross, W., and Spencer, A. C., *Geology of the Rico Mountains*: 21st Ann. Rept., U. S. Geol. Surv., part 2, pp. 99-100, 1900.

² Gardner, J. H., *The Puero and Torrejon formation of the Nacimiento group*: Jour. Geology, vol. 18, pp. 722-723, 1910.

³ Willis, B., *A theory of continental structure applied to North America*: Bull. Geol. Soc. America, vol. 18, p. 395, 1907.

graphic relations observable in the Park Range between Leadville and Breckenridge indicate that the pre-Dakota sediments successively overlapped against a land mass of Archean rocks which was not wholly submerged until Dakota time. This land mass would correspond to a part of the Colorado island of Emmons.

The contact between the Archean rocks of the Laramie and Front ranges and the steeply upturned beds of the Great Plains presents many as yet unsolved problems. In Wyoming, where the Casper formation, chiefly of Pennsylvanian age, lies at the base of the sedimentary series, the Laramie Range is explained¹ as an eroded broad anticline and the absence of the older Paleozoic formations is accounted for by a gradual overlap southward. If this view is correct, there was no Archean ridge, corresponding to the Laramie Range, standing above sea level in Pennsylvanian time. In Colorado, on the other hand, S. F. Emmons² maintained that the beds never formed an anticline over the Front Range, but were deposited against a land mass whose shore was generally parallel to and not far west of the present mountain front. Fenneman³ has modified the latter hypothesis by suggesting that the monocline is only in part due to "mountain-making forces," the greater part of it apparently having been accomplished during the deposition of the beds against a land mass to the west. Apparently he means that the land to the west was slowly rising as it was being worn down, while the adjoining sea bottom was slowly sinking under the accumulating sediments. Subsequently, compression may have intensified the fold where it is steepest.

The presence of Cambrian and Ordovician strata in the Manitou and Cañon City embayments and of isolated masses of older Paleozoic rocks at other points along the east base of

¹ Darton, N. H., Blackwelder, E., and Siebenthal, C. E., *Geol. Atlas U. S., U. S. Geol. Surv., Laramie-Sherman folio, No. 173, p. 11, 1910.*

² Emmons, S. F., Cross, W., and Eldridge, G. H., *Geology of the Denver Basin: Monograph U. S. Geol. Surv., vol. 27, p. 45, 1896.*

³ Fenneman, N. M., *Geology of the Boulder district, Colo.: Bull. U. S. Geol. Surv., No. 265, pp. 41-42, 1905.*

the Front Range, associated in some places with the local disappearance of some of the younger formations, has not yet been satisfactorily explained in connection with the general absence of these ancient sediments along the more regular portions of the mountain front. Eldridge¹ explained the relations as due to low folds or arches, formed in the sedimentary beds before the general uplift of the Rocky Mountains and during the period of general deposition. Lee² has offered a similar explanation for the Castle Rock region, south of Denver. On the other hand, Richardson³ accounts for the observed relations by faulting, probably thrust faulting from west to east. Thrust faulting at various places along the mountain front was recognized by the authors of the Denver monograph (p. 48) but appears to have been regarded by them as a minor structural feature.

Along the east base of the Wet Mountains, in the Cañon City region,⁴ Washburne reports that the Archean granite has been thrust to the east over the coal-bearing Cretaceous, the beds being overturned for over a mile away from the mountain front.

The foregoing very hasty sketch of relations, which have been observed along the zone where the Great Plains and Park Range Province meet, indicates that structural problems of great interest and importance are here awaiting investigation.

The structure of the Park Range Province, in brief, shows compression along east-west to northeast-southwest lines, whereby strata including the Cretaceous were gently folded over the region as a whole but sharply upturned along the greater part of its eastern edge. As the stratified formations in this province are comparatively thin, their massive Archean

¹ Emmons, S. F., Cross, W., and Eldridge, G. H., *Geology of the Denver Basin: Monograph U. S. Geol. Surv.*, vol. 27, pp. 82-111, 1896.

² Lee, W. T., *The areal geology of the Castle Rock region, Colo.: Am. Geologist*, vol. 29, pp. 96-110, 1902. (Mr. Lee no longer holds this view.—F. L. R.)

³ Richardson, G. B., *Structure of the foothills of the Front Range, central Colorado: Proc. Washington Acad. Sci.*, vol. 2, pp. 429-430, 1912.

⁴ Washburne, C. W., *The Cañon City coal field, Colorado: Bull. U. S. Geol. Surv.*, No. 381, p. 342, 1910.

base probably stood high enough to be well within the zone of thrust, and to its resistance, rather than to actual feebleness of the stresses concerned, may be due the fact that the beds are not more closely folded. Profound faulting, generally of the normal type and prevailing in nearly north-south directions, followed the folding. Wherever detailed work has been done, the great normal faults have proved to be a very important element of the structure, and, it may be noted, one which has no recognition whatever on the Hayden geologic map of Colorado. The conspicuous part which they play in the geology of the Leadville and Tenmile districts is well known through the work of Emmons. Their major effects are pronounced also in the Breckenridge region, and, according to Washburne,¹ three great faults pass through South Park and are largely responsible for the existence of that depression. As a rule the downthrow of the important faults is to the west.

It is generally agreed by geologists that the major deformation in the Park Range Province took place at the close of the Cretaceous, although an important unconformity has been observed in widely separated localities between Jurassic beds and older formations down to the Archean.² How far this earlier movement determined the character of later deformation, it is impossible at present to say. The general elevation and most of the folding in the province probably dates from the close of the Cretaceous or from the early Eocene. The normal faulting was initiated a little later, and movement along the original fissures has probably continued up to very recent times. It may be still in progress. The monzonite-porphry intrusions characteristic of this province are probably all of Tertiary age, although Emmons's final conclusion was that the intrusion of the porphyries, the ore deposition, and the principal faulting at Leadville were all effected in Jurassic time.³

¹ Washburne, C. W., The South Park coal field, Colorado: Bull. U. S. Geol. Surv., No. 381, pp. 307-308, 1910.

² Emmons, S. F., Orographic movements in the Rocky Mountains: Bull. Geol. Soc. America, vol. 1, p. 270, 1890.

³ Emmons, S. F., Orographic movements in the Rocky Mountains: Bull.

In this part of the Rocky Mountains the geologists of the 40th parallel survey¹ recognized at least eight epochs of deformation subsequent to the post-Cretaceous or Laramide revolution. These are (1) post-Wasatch, (2) post-Green River, (3) post-Bridger, (4) post-Eocene, (5) post-Miocene, (6) inter-Pliocene, (7) post-Pliocene, and (8) Recent. The determination of most of these rests upon deformation and unconformities observed in connection with the Tertiary deposits of the Green River, Uinta, and Huerfano basins, and it is questionable whether the geology of the province as a whole is well enough known to permit of the wide recognition and safe correlation of these later movements. Hills,² however, who assigns great importance to the post-Bridger deformation, essayed the task some years ago. He states that the post-Bridger movement was nearly as widespread and fully as intense as the post-Cretaceous movement, involving steep upturning of Eocene sediments and greatly increased elevation of the various ranges, the uplift in the Elk Mountains being at least 8000 feet. While Mr. Hills has perhaps exaggerated the general importance of this later movement, my knowledge of the province is neither wide nor intimate enough to constitute an adequate basis from which to criticise his conclusion.

COLORADO PLATEAUS

Of the Colorado Plateau Province I shall not have a great deal to say. Orogenically it is a relatively inert, rigid mass, whose structure and position are here interpreted as indicative rather of unequal subsidence of its parts from a general condition of high elevation at the close of the Cretaceous than

Geol. Soc. America, vol. 1, p. 271, 1890. See also Emmons and Irving, The Downtown district of Leadville, Colo.: Bull. U. S. Geol. Surv., No. 321, p. 67, 1907; and Ransome, F. L., Geology and ore deposits of the Breckenridge district, Colo.: Prof. Paper, U. S. Geol. Surv., No. 75, p. 64, 1911.

¹ King, C., Explor. 40th Parallel, vol. 1, p. 578, 1878.

² Hills, R. C., Orographic and structural features of Rocky Mountain geology: Proc. Colorado Sci. Soc., vol. 3, pp. 363-458, 1890.

of successive local uplifts as has been commonly held. For its western and northern portions no general descriptions have yet supplanted the glowing pages of Dutton. In that province, according to him:

“Great blocks have been lifted with a singular uniformity with comparatively little flexing and with little disarrangement, except at the fault planes which bound the several blocks. These divisional lines are sometimes sharp, trenchant faults, sometimes that peculiar form of displacement to which Messrs. Powell and Gilbert have given the name of monoclinical flexures, but most frequently the dislocation is a combined monoclinical flexure and a fault or series of faults with all shades of relative emphasis. . . . Sometimes the blocks are slightly tilted, causing a slight dip, and in the immediate neighborhood of a great dislocation a single flexure of the beds is usually seen; but on the whole, the amount of bending and undulation is very small. This small amount of departure from horizontality of the beds as they now lie has played its part in the determination of the topographical features as they appear in the landscape, and justifies the name which has been applied to it with one accord by all observers—The Plateau Country.”¹

According to Dutton, the physical break at the close of the Cretaceous is well marked in the Plateau Province, the strata having been flexed, tilted, and planated before the deposition of the fresh-water Eocene beds. The principal faulting is placed by him in the late Tertiary or Quaternary.

For the southeastern part of the Plateau Province, including what he has called the Corona Plateau of New Mexico, R. T. Hill has supplied the latest and most graphic general descriptions. I quote by permission from his manuscript:

“One could travel a line from Galveston, Texas, via Albuquerque, New Mexico, to Ash Fork, Arizona, over the Coast Prairies and Great Plains of Texas, the Corona Plateau of New Mexico and the Colorado Plateau of Arizona, without crossing a single mountain range or treading upon strata which have

¹ Dutton, C. E., *Geology of the High Plateaus of Utah*: U. S. Geog. and Geol. Surv., Rocky Mountain Region, Washington, pp. 5-6, 1880.

been seriously disturbed, except by faulting in the vicinity of the Rio Grande. In general along this line the uplift of this vast area has been practically accomplished without serious deformation or fracture, with the exception possibly of slight swells at Gallup, and one great fault west of the Sandias.

"In New Mexico between the Pecos and the Rio Grande and the Sangre de Cristo and the Gallinas mountains this line would cross an elevated plateau of Paleozoic limestones and red beds, which reaches an altitude of 7000 feet, and constitutes an extensive area of plain. From just west of the Pecos to Ash Fork, Arizona, a distance of 600 miles, the profile of this line, except immediately along the Rio Grande valley, would maintain an average elevation of 6500 feet, underlain by a mile in thickness of Carboniferous strata. An area of strata so extended, lifted so high without serious deformation and covering a region which has had no serious deformation since Algonkian time, is most remarkable.

"Yet but a short distance both to the north and to the south of this line, in the Rocky Mountains and in the Mexican Plateau, we have examples of intense mountain folding and deformation. One must perceive the fact that the long east-west belt of the Colorado Plateau along the 34th and 35th parallels, extending from the Pecos to the Colorado of the West, constitutes a most important division between the true Rocky Mountain and the Mexican provinces of the Cordilleran region, and represents a zone where processes of mountainous deformation have been least manifest in the great Cordilleran uplifts."¹

Hill's descriptions show clearly that the portion of the Colorado Plateau Province lying in central and southern New Mexico and in the northern part of the Trans-Pecos is transitional in character. From the east the ascent from the Great Plains to the summit of the Corona Plateau is made by a succession of broad-backed monoclinal blocks, with gentle slope

¹ Hill, R. T., Reconnaissance notes on the geology of the Trans-Pecos (Texas) province and related adjacent areas of the Cordilleran region: Bull. U. S. Geol. Surv. (in course of publication), 1913.

to the east and fault scarp to the west. To the south and west, no sharp line can be drawn between the faulted plateau and the more vigorous orogenic deformation of the Mexican Plateau and Nevada-Sonoran provinces.

MEXICAN PLATEAU

The central platform, or *Meseta Central*, of the Mexican Plateau slopes gently to the north and its structure is summed up by Suess¹ in the statement that it "is a broken-in, folded land of much the same type as the Basin Ranges." In fact, as has previously been stated, there is probably no real orographic boundary between the two provinces, although the beds entering into the structure of the ranges of the Nevada-Sonoran Province are Jurassic or older, whereas the beds of the Mexican Plateau are mainly Cretaceous and the Paleozoic is unrepresented.

The Sierra Madre Occidental as described by Weed² and Hovey³ consists of a folded basement of Cretaceous limestone cut by quartz monzonite or granite, upon which rests a great thickness of Tertiary lavas.

Concerning the Sierra Madre Oriental, Hill⁴ states: "The eastern margin of the Mexican Cordilleran plateau is a rim of mountain-crests, cumulative in altitude southward from the southern boundary of the United States and constituting a series of sierras or blocks, known as the Eastern Sierra Madre." Suess,⁵ however, basing his opinion largely on the work of the Geological Survey of Mexico, maintains that "there is no Sierra Madre Oriental but that the sierras of the interior

¹ *Face of the Earth*, English translation, vol. 4, p. 440, 1909.

² Weed, W. H., Notes on a section across the Sierra Madre Occidental of Chihuahua and Sinaloa, Mex.: Trans. Am. Inst. Min. Engrs., vol. 32, pp. 444-458, 1902.

³ Hovey, E. O., A geological reconnaissance in the western Sierra Madre of the State of Chihuahua, Mexico: Bull. Am. Mus. Nat. Hist., vol. 23, pp. 401-442, 1907.

⁴ Hill, R. T., Geographic and geologic features of Mexico: Trans. Am. Inst. Min. Eng., vol. 32, p. 167, 1902.

⁵ *Face of the Earth*, English translation, vol. 4, p. 433, 1909.

decrease in height towards the Atlantic coast and run out in free ends." While there is probably no continuous range along the eastern edge of the plateau, trips from Vera Cruz to the interior and from the interior to Tampico, made in 1906, have left with me a strong impression that the ascent from the *tierra caliente* to the plateau is across a great zone of faulting.

In that portion of the Mexican Plateau in Trans-Pecos, Texas, in the vicinity of Marathon, Hill¹ recognizes remnants of an old system of northeast-southwest folds which he correlates with Appalachian structure. These are crossed by the north-south and the northwest-southeast Tertiary structures. He believes that the earliest Tertiary uplift in this region was epeirogenic, followed by orogenic movements that were in the main due to collapse and normal faulting with little indication of lateral compression. According to Udden² and to Hill,³ a great longitudinal segment of Trans-Pecos Texas, lying between the Guadalupe, Davis, Ord, and Santiago mountains on the east, and the Diablo Plateau, Sierra Vieja, and Chinati mountains on the west, has been dropped from 5000 to 8000 feet by two faults which converge toward the north.

THE INTERMONTANE BELT

NORTHERN INTERIOR PLATEAUS

It is impossible in the present stage of knowledge to make any satisfactory generalization of the geologic structure of the northern Interior Plateaus of Canada and Alaska. Concerning Alaska, Brooks writes:

"No detailed structural features have been worked out in the great intermontane region where the bedrock succession includes Archean gneisses, probably terranes of every division

¹ Hill, R. T., Reconnaissance notes on the geology of the Trans-Pecos (Texas) province, etc.: Bull. U. S. Geol. Surv. (in preparation), 1913.

² Udden, J. A., A sketch of the geology of Chisos country, Brewster County, Texas: Bull. University Texas, No. 93, 1897.

³ *Loc. cit.*

of the Paleozoic, Lower and Upper Cretaceous, Eocene beds, and probably some Pliocene. Several unconformities have been noted in this succession, and the pre-Upper Cretaceous rocks are closely folded and faulted while the Eocene beds are locally often considerably deformed."¹

Kindle² has described the occurrence of important faults of normal type in the Porcupine Valley. One of these, with downthrow to the west, he believes to have a displacement of at least 4000 feet. The probable age of the faults is not given.

In general the structure of the Intermontane Belt in Canada and Alaska is complex, and much work remains to be done before the number, age, and relative importance of deformational epochs can be known. The most marked effects of deformation as a rule are those referable to late Mesozoic time. Although, unlike the Nevada-Sonoran region, part of the intermontane region in Canada was covered by Cretaceous deposits, geologic descriptions of that region as a rule fail to present clear evidence of deformation referable to the Laramide revolution. Camsell,³ however, in describing the Tulameen district near the western border of the Belt of Interior Plateaus gives the following sequence of events as recorded in the rocks:

1. Deposition of Triassic sediments and volcanics.
2. Mountain building and folding of the Triassic rocks.
3. Batholithic intrusion of granite, peridotite and pyroxenite, and granodiorite, in Jurassic period.
4. Laramide revolution.
5. Eocene erosion period.
6. Extrusion of lavas followed by deposition of coal-bearing sediments in the Oligocene period.
7. Batholithic intrusion of granite in Miocene period.
8. Erosion interval.

¹ Brooks, A. H., *Geography and geology of Alaska*: Prof. Paper, U. S. Geol. Surv., No. 45, p. 258, 1906.

² Kindle, E. M., *Geologic reconnaissance of the Porcupine Valley, Alaska*: Bull. Geol. Soc. America, vol. 19, p. 319, 1908.

³ Camsell, C., *Guide Book No. 9*, 12th Inter. Geol. Congress, p. 122, 1913.

9. Extrusion of olivine basalt.
10. Uplift of Cascade Mountains and Interior Plateau in Pliocene time, followed by deepening of valleys.
11. Glacial period.
12. Post-Glacial uplift.

He does not, however, present any details of the effects of the Laramide revolution.

In the Yukon Valley, fresh-water beds belonging to the Kenai formation and regarded as Eocene in age have been folded and faulted. The erosion surface of the Yukon Plateau was developed after this deformation, consequently, according to Brooks,¹ in late Eocene or early Miocene time. This surface has been correlated by Dawson,² Hayes,³ Spurr,⁴ Spencer,⁵ and by most geologists who have referred to it, with the interior plateau of British Columbia and has generally been considered Eocene. Spurr, however, thought it to be Miocene, and Brooks, as just noted, makes it late Eocene or early Miocene. Daly maintains that "the plateaus of the interior . . . in part . . . represent dissected lava tables; in part, dissected local peneplains of pre-Miocene date; in part, dissected mountain torsos, reduced during the early Tertiary and the Mesozoic. There is no evidence that a *general* peneplain was developed over this part of the Cordillera at any time; nor is it proved that the upland facets of the Interior Plateaus were due to general peneplanation of that broad belt in late Miocene and early Pliocene time. A superficial study of the Interior Plateaus might lead to that conclusion; in reality, the upland

¹ *Op. cit.*, pp. 278-279.

² Dawson, G. M., The later physiographical geology of the Rocky Mountain region in Canada: Trans. Roy. Soc. Canada, vol. 8, sec. 4, p. 12, 1890.

³ Hayes, C. W., An expedition through the Yukon district: Nat. Geog. Mag., vol. 4, pp. 128-162, 1892.

⁴ Spurr, J. E., Geology of the Yukon gold district: 18th Ann. Rept., U. S. Geol. Surv., part 3, p. 260, 1898.

⁵ Spencer, A. C., Pacific Mountain System in British Columbia and Alaska: Bull. Geol. Soc. America, vol. 14, p. 128, 1903.

relief has been conditioned by several pre-Miocene erosion cycles.’’¹

Drysdale,² however, states that “the present late mature upland (locally a peneplain) truncates or bevels” the gently folded Miocene or Oligocene lavas.

In any case, the general plateau character of this surface which most agree dates, in part at least, from early Tertiary time, and the fact that much of the area from the International Boundary north to the 55th parallel is covered by nearly horizontal lavas of mid-Tertiary age, indicate that the Belt of Interior Plateaus has been a fairly rigid mass throughout the Tertiary and in that respect differs markedly from the Nevada-Sonoran region.

East of the Intermontane Belt, in the mountains of northern Idaho and Montana, evidence of an old erosion surface, in places over 10,000 feet above sea-level, has been noted by various geologists. Umpleby³ has recently interpreted this evidence as indicative of a single peneplain of Eocene age continuous with that of the interior of British Columbia. Blackwelder⁴ has suggested that the peneplain in Idaho and Montana may be post-Middle Miocene, while the paleobotanical evidence from the Payette formation⁵ (lake beds) and certain general physiographic considerations suggest the possibility that it may be pre-Eocene. Evidently a comprehensive and critical study of the evidence for peneplanation in the northern Rocky Mountains and in the Belt of Interior Plateaus with a view to correlation of the peneplain remnants with each other and with the orogeny of the region is a problem for the future.

¹ Daly, R. A., Guide Book No. 8, 12th Inter. Geol. Congress, p. 164, 1913.

² Drysdale, C. W., *ibid.*, p. 236.

³ Umpleby, J. B., An old erosion surface in Idaho: its age and value as a datum plane: Jour. Geology, vol. 20, pp. 139-147, 1912; The old erosion surface in Idaho: a reply: *ibid.*, vol. 21, pp. 224-231, 1913; Geology and ore deposits of Lemhi County, Idaho: Bull. U. S. Geol. Surv., No. 528, pp. 23-29, 1913.

⁴ Blackwelder, E., The old erosion surface in Idaho: a criticism: Jour. Geology, vol. 20, pp. 410-414, 1912.

⁵ Knowlton, F. H., Bull. U. S. Geol. Surv., No. 204, p. 110, 1902.

COLUMBIA PLATEAU

The Columbia Plateau I shall pass over with the mere comment that its underlying structure is of course little known. The lavas buried a rugged topography,¹ as is shown in some of the deeper canyons and by the fact that the Blue Mountains of eastern Oregon rise like a great island above the general lava level. In the John Day Basin, as shown by Merriam,² folded Chico Cretaceous and older beds are overlain unconformably by the fresh-water Eocene Clarno formation. This is overlain, probably, unconformably, by the Oligocene John Day formation of continental deposition, covered in turn by a series of basaltic flows, supposedly of Lower Miocene age. On this lava rests the Mascall formation of Middle Miocene age. The Upper Miocene appears to be represented in this section by an unconformity, above which comes the Pliocene Rattlesnake formation.

NEVADA-SONORAN REGION

The characteristic orographic features of the Great Basin Ranges are too well known to require more than brief mention here. The whole province is diversified by mountain ranges which, while displaying considerable variety of trend, show a marked adherence to meridional lines in the Great Basin proper, and to northwest-southeast lines in Arizona. As Dutton has said, their appearance on a map suggests an army of caterpillars crawling toward Mexico. These ranges are generally narrow and short, although some fairly continuous crests attain lengths up to 300 miles. They are separated by flat-floored valleys which, despite some statements to the contrary, based on the occurrence of planated rock surfaces in certain localities, are, as a rule, deeply filled with detrital deposits, derived from the neighboring ranges.

¹ Russell, I. C., A reconnaissance in southeastern Washington: Water-Supply Paper, U. S. Geol. Surv., No. 4, pp. 30-37, 1897.

² Merriam, J. C., A contribution to the geology of the John Day Basin: Bull. Dept. Geol., University California, vol. 2, pp. 269-314, 1901.

Various views have been advanced to explain the origin of these mountains, but until about twelve years ago few geologists questioned the conclusion that they are essentially simple or compound fault blocks, modified by erosion. In 1901, Spurr¹ offered the explanation that the ranges are complex in origin and structure, but that they are essentially the result of long erosion on a series of parallel folds produced at the close of the Jurassic. He disagreed fundamentally from Dutton, who, after stating that the Basin Ranges contain folded strata, went on to say with keen discernment:

“But a very significant distinction is necessary here. These flexures are not, so far as can be discerned, associated with the building of the existing mountains in such a manner as to justify the inference that the flexing and the rearing of the ranges are correlatively associated. On the contrary, the flexures are in the main older than the mountains and the mountains were blocked out by faults from a platform which had been plicated long before, and after the inequalities due to such pre-existing flexures had been nearly obliterated by erosion. It may well be that this anterior curvation of the strata has been augmented and complicated by the later orographic movements. But it is not impossible to disentangle the distortions which antedate the uplifting from the bending and warping of the strata which accompanied it, and it is only the latter that we can properly associate and correlate with the structures of the present ranges. These present no analogy to what is usually understood by plication. The amount of bending caused by the uplifting of the ranges is just enough to give the range its general profile, and seldom anything more.”²

In view of the convincing refutation of Spurr's hypothesis

¹ Spurr, J. E., Origin and structure of the Basin Ranges: *Bull. Geol. Soc. America*, vol. 12, pp. 217-270, 1901.

² Dutton, C. E., *Geology of the High Plateaus of Utah*: U. S. Geog. Geol. Surv., Rocky Mountain region, p. 47, 1880.

by the independent papers of Davis¹ and Louderback,² no further consideration need be given it here.

More recently, eolists have attempted to account for the Great Basin Ranges as the result mainly of wind action or deflation. One of this school maintains that after the region was folded, faulted, and peneplained, the present topography was etched out by the wind. In other words, it is Spurr's hypothesis modified by the substitution of wind for water. That winds can erode in arid regions is undoubtedly true, as Cross,³ for example, has shown in the plateau country of Colorado and Utah; but to suppose that the ranges of Nevada and Arizona with their deep-cut ravines, fronted by aprons of coarse alluvial material, are the work of wind, indicates such complete obsession of the mind by a single idea as to blind the eyes to what is actually going on. That the wind does transport large quantities of dust and sand in the desert regions of the West, no one familiar with that country is likely to deny. But this agent, capricious as it is, does not strew boulders in front of the mountains, neither does it carve canyons, barrancas, or arroyos, with dendritic headwater branches. In comparing the efficiencies of wind and water in the erosion of an arid region, with reference obviously to such relative aridity as obtains in the Great Basin region, Keyes states: "Their relative efficiencies may be roughly measured by the fact that the total volume of rock waste brought down by the storm waters from a desert range in a year may be removed by the wind in a single day."⁴ These surely are wild words.

In the present address the Basin Ranges are considered as fault blocks, which, it is realized, may be of various degrees of

¹ Davis, W. M., The mountain ranges of the Great Basin: *Bull. Mus. Comp. Zoöl.*, vol. 42, pp. 129-177, 1903.

² Louderback, G. D., Basin Range structure of the Humboldt region: *Bull. Geol. Soc. America*, vol. 15, pp. 289-346, 1904.

³ Cross, W., Wind erosion in the Plateau Country: *Bull. Geol. Soc. America*, vol. 19, pp. 53-62, 1908.

⁴ Keyes, C. R., Deflation and the relative efficiencies of erosional processes under conditions of aridity: *Bull. Geol. Soc. America*, vol. 21, p. 587, 1910.

complexity, both as regards faulting and antecedent structures, and which in their topography display various aspects of erosion. The chief processes in the modification of their initial forms are disintegration, creep, and the eroding and transporting action of running water. In the erosion of the rocky ranges of the Nevada-Sonoran region, wind is believed to be of slight importance. Its action in that region is confined almost exclusively to the movement of fine material over the bolsons or lowland surfaces.

Some of the simplest of these ranges are those of southern Oregon described by Russell,¹ whose account of them has since been confirmed by Waring.² Here there has been little antecedent deformation in the visible portion of the blocks, which have moved as units and have been but slightly modified by erosion. Similar but more strongly eroded monoclinical blocks of unfolded strata may be seen along the southwestern border of the Colorado Plateau in the mountain belt of Arizona. The Pinal and Mescal ranges together constitute such a block. Throughout the greater part of the Nevada-Sonoran region, however, ancient folding, subsequent faulting, and still later erosion have coöperated in more complicated fashion in the formation of the ranges. Some of the Arizona ranges, such, for example, as the minor Dripping Spring Range in the Ray quadrangle, which has recently been mapped in detail, consist of innumerable small fault blocks in which as a whole the net movement has been relative uplift as compared with the rock floors of the adjacent valleys. In many other ranges it is highly probable that the initial difference in elevation between mountain and valley was brought about as an aggregate or net effect of numerous faults and not by one simple profound dislocation.

In most descriptions of the Basin Ranges they are referred to as mountain *uplifts*. The great impressive feature of this

¹ Russell, I. C., Geological reconnaissance in southern Oregon: Fourth Ann. Rept., U. S. Geol. Surv., pp. 431-464, 1884.

² Waring, G. A., Geology and water resources of a portion of south-central Oregon: Water-Supply Paper, U. S. Geol. Surv., No. 220, p. 25, 1908.

whole country, however, particularly to one, who, knowing something of its structure, looks over it from the crest of the Sierra Nevada or from the edge of the Colorado Plateau in Arizona, is that it is a collapsed region. Such uplift as may have taken place in any individual range was merely incidental to the structural failure and sinking of the whole province.

Le Conte,¹ many years ago, recognized this broad fact of subsidence as a necessary corollary of the structure, explaining it as the breaking down of an arch which had been lifted by intumescent lava at the close of the Tertiary. Recently Butler² has suggested a nearly identical explanation to account for the fault-block structure in the San Francisco district, Utah. It does not appear necessary, however, to postulate an up-arching of the region immediately before its foundering. For that supposition there is no direct evidence. The essential point is, that if the Nevada-Sonoran region, as seems evident from its structural features and its relation to the Wasatch, the Colorado Plateau and the Sierra Nevada, is a shattered and down-sunken area, its mean elevation with reference to adjacent provinces must at one time have been greater than at present.

PACIFIC SYSTEM

Existing knowledge of the ranges representing the Pacific System in Alaska has been so well summarized by Brooks³ and Suess⁴ that I need refer to these mountains here only in the briefest manner. On the west is the long arc of the volcanic Aleutian Range, continued northeastward, beyond a slight offset, by the Chigmit Mountains, northwest of Cook Inlet. The Aleutian Range, according to Brooks, is composed of volcanic

¹ Le Conte, J., On the origin of normal faults and of the structure of the Basin region: *Am. Jour. Sci.*, (3), vol. 38, pp. 257-263, 1889.

² Butler, B. S., Geology and ore deposits of the San Francisco and adjacent districts, Utah: Prof. Paper, U. S. Geol. Surv., No. 80, p. 27, 1913.

³ Brooks, Alfred H., Geography and geology of Alaska: Prof. Paper, U. S. Geol. Surv., No. 45, pp. 28-36, 1906.

⁴ Suess, E., *Face of the Earth*, English translation, vol. 4, pp. 346-350, and 371-378, 1909.

rocks piled upon a basement of folded Tertiary and Mesozoic strata. The range is overlapped to the northwest by the southwest end of the Alaska Range,¹ which in a magnificent arc of over 90° sweeps from a northeast to a southeast trend and is continued toward Mt. St. Elias by the Nutzotin and Scolai mountains. The Alaska Range is described as a closely folded and faulted synclinorium of Mesozoic and Paleozoic rocks cut by large masses of granodiorite. South of the Alaska Range and skirting the Gulf of Alaska is another curved chain formed from west to east by the Kenai and Chugach mountains, which, like the Alaska Range, are composed of closely folded Mesozoic(?) sediments. This chain also ends at the St. Elias Range and in the angle which it forms with the Alaska Range are the Wrangell Mountains, a pile of Tertiary and recent lavas resting on folded Mesozoic rocks in an upfaulted syncline. All of the ranges described except the Wrangell Mountains, together with the Endicott Range and its eastward continuation in the Romanof and Franklin Mountains, are included by Suess in his Alaskides and are regarded as part of his Asiatic system.

According to Brooks,² there were widespread crustal disturbances in the Mount McKinley region, accompanied by extensive intrusions of granitic and dioritic material, in post-Middle Jurassic time, followed by erosion. Late Jurassic and early Cretaceous time were periods of deposition. Intense folding, accompanied by some igneous intrusion, recurred in post-early Cretaceous time. Deposition was resumed in late Cretaceous time. The Eocene was marked by uplift, erosion, and deposition of the fluviatile Kenai formation. In post-Eocene time "the entire province was elevated several thousand feet and intense local deformation took place along the zones marked by the high ranges. This was followed by erosion and then by renewed uplift."³

The St. Elias Range extends southeast along the coast to

¹ Brooks, A. H., The Mount McKinley region, Alaska: Prof. Paper, U. S. Geol. Surv., No. 70, 1911.

² *Op. cit.*, p. 114.

³ Brooks, *loc. cit.*

Cross Sound. Brooks states that it appears to consist of complexly folded sedimentary rocks, probably in the main Paleozoic, with many intrusives. Its structure is as yet little known but apparently is due in part to important late Tertiary or Quaternary movements.¹

Southward, the trend of the St. Elias Range is continued by the partly submerged mountains of the Alexander Archipelago. These, Brooks states, are not sharply separable from the main Coast Range of British Columbia which borders the mainland to the east, from the 60th parallel to the Fraser River east of Vancouver. This latter range, as has been shown by G. M. Dawson and by many later observers, is composed mainly of a great batholith having the general composition of granodiorite.

The geologic structure of the Coast Range from Prince Rupert to Skagway has recently been well summarized by F. E. Wright,² who states that the main batholithic core of the range is generally bordered on the west by a belt several miles wide, of closely folded Carboniferous and Mesozoic strata which have been altered to crystalline schists. West of these rocks is a great zone of greenstone. Along the outer coast the structure is less uniform, owing to the irregular intrusion of the granodiorite in the islands of the Alexander Archipelago. According to Wright, the batholithic intrusions probably began in early Jurassic time and continued to Upper Jurassic or Lower Cretaceous time. Eocene (Kenai) coal-bearing beds were deposited in local basins and occur only near sea-level and there are some areas of nearly horizontal basalt flows of late Tertiary age. As Spencer³ has pointed out, the rocks and structure of the Coast Range in southeastern Alaska are very similar to those of the Sierra Nevada.

From Prince Rupert south to Vancouver, the exposed portion of the granodiorite batholith forms virtually the whole of the

¹ Martin, L., Guide Book No. 10, 12th Inter. Geol. Congress, pp. 135-136, 1913.

² *Ibid.*, pp. 41-48.

³ Spencer, A. C., The Juneau gold belt, Alaska: Bull. U. S. Geol. Surv., No. 287, pp. 10-11, 1906.

Coast Range, the western border of metamorphic rocks being represented by the ranges of Vancouver and Queen Charlotte islands. The older rocks of these islands, largely Mesozoic but perhaps in part Paleozoic, have been folded and metamorphosed, as farther north, and are unconformably overlain by the thick coal-bearing Nanaimo formation of Upper Cretaceous age, which in turn was overlain in the southern part of Vancouver Island by late Eocene lavas, chiefly basalts. In post-Eocene time, according to Clapp,¹ from whose excellent summary most of the statements here presented have been taken, the Nanaimo formation was thrown into broad open folds striking northwest-southeast. In places the folds are compressed, overturned to the southwest and broken by overthrusts in the same direction. This deformation was followed by long erosion and the peneplain then developed was uplifted and dissected, probably in Pliocene time.

In southern British Columbia the batholith, as indicated by various irregular areas of granodiorite, extends far to the eastward across the Belt of Interior Plateaus into the Columbia Ranges. In this region Daly² would link genetically with the granodiorite other intrusive masses of wide range in composition and has described the whole plutonic assemblage as the Okanagan composite batholith. In accordance with this view, the batholithic intrusions began, on a small scale, probably in late Carboniferous time, became of great importance in the Jurassic, and continued to late Tertiary time. The granodiorite masses are stated by Daly to have been intruded in Jurassic time. The effects of the Laramide revolution, which Daly places "at the close of the Laramie period," are believed to be recorded in the shearing, crushing, and foliation of the Jurassic and older intrusions, accompanied by strong folding of the Cretaceous strata in the Coast Range.

With reference to the Pacific Mountain System in British

¹ Clapp, C. H., Vancouver Island: Guide Book No. 8, 12th Inter. Geol. Congress, part 3, pp. 281-342, 1913.

² Daly, R. A., The Okanagan composite batholith: Bull. Geol. Soc. America, vol. 17, pp. 329-376, 1906.

Columbia and Alaska, A. C. Spencer¹ has ably presented the view that the ranges are remnants of an uplifted and much dissected peneplain which once was continuous with the Belt of Interior Plateaus. He assigns their elevation to post-Eocene time by "warping, flexure or displacement" and denies that mountain-building by tangential pressure had any part in their uplift. The principal rivers now flowing from the interior across the Coast Ranges are regarded by Spencer as antecedent to the uplift of the range, and their position is explained by the hypothesis that they have maintained the courses which they originally established on a peneplained surface that sloped gently westward to the ocean.

In the state of Washington, the portion of the Cascade Range north of Mount Rainier, which Smith² terms the Northern Cascades, displays structural features similar to those of the Coast Range of British Columbia. In central Washington the work of Smith and Calkins³ shows that pre-Tertiary rocks, generally much deformed, metamorphosed, and cut by granodiorite, are overlain in part by gently folded Eocene beds which in turn were covered by Miocene lavas. The Cretaceous deposits of the British Columbia Coast Range apparently never extended far south of the International Boundary, Mesozoic rocks being unknown in the central Washington section of the Cascades, although Smith and Calkins⁴ have shown that the Cretaceous Pasayten formation is extensively developed for ten or fifteen miles south of the boundary.

The Eocene is represented by two sedimentary formations, the upper being the coal-bearing Roslyn, separated by a thick series of lava flows, mainly basalt. In this region, according to Smith and Calkins, an important intrusion of granodiorite took

¹ The Pacific Mountain System in British Columbia and Alaska: Bull. Geol. Soc. America, vol. 14, pp. 117-132, 1903.

² Smith, G. O., Geol. Atlas U. S., U. S. Geol. Surv., folio No. 86, 1903.

³ Smith, G. O., *ibid.*, folio No. 106.

Smith, G. O., and Calkins, F. C., *ibid.*, folio No. 139, 1906.

⁴ Smith, G. O., and Calkins, F. C., A geological reconnaissance across the Cascade Range near the Forty-ninth Parallel: Bull. U. S. Geol. Surv., No. 235, 1904.

place in Miocene time. The Miocene formations, both lavas and sediments, were gently flexed and in Pliocene time were reduced to a peneplain.

A range corresponding in position to the Cascades was probably formed by folding at the close of the Cretaceous and may have had an even earlier origin; but the broad configuration of the present Northern Cascades is ascribed to an uplift which probably took place in late Tertiary or early Quaternary time, and was effected by broad, transverse "upwarps" which died out eastward on the Columbia Plateau and whose combined result was the separation of the Cascades from that plateau, as a generally north-south range.¹

In southern Washington and in Oregon the pre-Tertiary foundation of the Cascade is relatively depressed so that the older rocks composing it are visible in very few places under the Tertiary, principally Miocene, which make up this part of the range. According to Diller,² Cretaceous beds of Chico age probably once extended across the area now occupied by the Cascade Range.

Comparatively little is known of the structural features of the generally rather low Coast Range of Washington and Oregon. Crystalline rocks have been reported from the high Olympic Mountains at the north end of the range, but according to Arnold,³ it appears probable that the greater part of this geologically unexplored group is composed of a hard Cretaceous sandstone. Most of the Coast Range as far south as Coos Bay, Oregon, is apparently made up principally of folded Tertiary beds, the Eocene, Oligocene, and Miocene being particularly well represented.⁴

In southwestern Oregon, where the Coast Range and Klamath

¹ Smith and Calkins, *Op. cit.*, p. 12.

² Diller, J. S., The geology of Crater Lake, National Park: Prof. Paper, U. S. Geol. Surv., No. 3, p. 19, 1902.

³ Arnold, R., Geological reconnaissance of the coast of the Olympic Peninsula, Washington: Bull. Geol. Soc. America, vol. 17, pp. 458-459, 1906.

⁴ Weaver, C. E., A preliminary report on the Tertiary paleontology of western Washington: Bull. Washington Geol. Surv., No. 15, 80 pp., 1912.

Mountains join, the work of J. S. Diller¹ shows that gently folded Eocene beds rest with conspicuous unconformity on more closely folded Mesozoic rocks, with some schists that are probably pre-Mesozoic. Both systems of folds have the same general trend as the range. The Mesozoic rocks, according to Mr. Diller,² are divisible into the Galice formation, probably equivalent to the Jurassic Mariposa slate of the Sierra Nevada; the Dothan formation, which is probably the same as the Franciscan of the California Coast Ranges, and which is thought to be Jurassic; and the Myrtle formation of Knoxville Cretaceous age. The Myrtle lies unconformably on the Dothan.

From Cape Blanco, Oregon, to a point about half way between that headland and Cape Mendocino, California, the Klamath Mountains occupy the coast line. While topographically a part of the Coast Range, the Klamath Mountains through their extensive exposures of Paleozoic rocks serve as a partial link between that range and the Sierra Nevada, as Mr. Diller has shown in a number of publications. According to him, the complex of sedimentary and igneous rocks forming these mountains was folded and uplifted at the close of the Jurassic. They were probably at one time covered by Cretaceous deposits. There was deformation and uplift at the close of the Cretaceous and the Klamath Mountains have since been undergoing erosion. The erosion of Eocene, Oligocene, and Miocene time is believed by Mr. Diller to have produced the Klamath peneplain, whose uplift and dissection began near the close of the Miocene and continued with many oscillations through the Pliocene and Quaternary.³

The structure of the Klamath Mountains as a whole is complex, and little known. The major lines of deformation

¹ Diller, J. S., *Geol. Atlas U. S.*, U. S. Geol. Surv., folio No. 73, 1901; and folio No. 89, 1903.

² Diller, J. S., *The Mesozoic sediments of southwestern Oregon*: *Am. Jour. Sci.*, (4), vol. 23, pp. 401-421, 1907; *Strata containing the Jurassic flora of Oregon*: *Bull. Geol. Soc. America*, vol. 19, pp. 367-402, 1908.

³ Diller, J. S., *Geol. Atlas U. S.*, U. S. Geol. Surv., folio No. 138, 1906; also *Topographic development of the Klamath Mountains*: *Bull. U. S. Geol. Surv.*, No. 196, 1902.

appear to trend from north-northwest in the southern part of the mountains to north-northeast in the northern part. According to Hershey,¹ the folds of the southern Klamath Mountains are largely replaced northward by at least four great thrust faults with throws of a mile or more, the blocks being overthrust from the east. These dislocations have not been mapped² or worked out in detail and their ages are uncertain, and they may be older than the Horsetown formation of the Cretaceous, according to Hershey. The thick shaly Bragdon formation, whose age and position is still in dispute, being regarded by Diller as Carboniferous, by F. M. Anderson as Triassic, and by Hershey as Jurassic,³ occupies large areas in the Klamath Mountains and is a terrane in which the interpretation of structure is particularly difficult.

Although the rocks of the Klamath Mountains are similar to those of the Sierra Nevada, and the geologic history of the two ranges has much in common, the great line of batholithic intrusions which, as Lawson⁴ has pointed out, links the Sierra Nevada geologically with the northern Cascades and with the Coast Range of British Columbia, probably passes east of the Klamath Mountains, under the lavas of the southern Cascade Range.

The Sierra Nevada, broadly considered, is an inclined crustal block 350 miles long and 80 miles wide, with a gentle slope to the west and an abrupt descent, by a zone of fault-scarps, to the Great Basin on the east. Tectonically, as Diller⁵ long ago pointed out, the range is of the Great Basin type and, as in

¹ Hershey, O. H., Some western Klamath stratigraphy: *Am. Jour. Sci.*, (4), vol. 21, pp. 58-59, 1906.

² They are delineated approximately, however, on the geomorphic map of California in the atlas accompanying the report of the California Earthquake Commission, Carnegie Institution, Washington, 1908.

³ Diller, J. S., Klamath Mountain section of California: *Am. Jour. Sci.*, (4), vol. 15, p. 353, 1903.

⁴ Lawson, A. C., The Cordilleran Mesozoic revolution: *Jour. Geology*, vol. 1, pp. 579-586, 1893.

⁵ Diller, J. S., Notes on the geology of northern California: *Bull. U. S. Geol. Surv.*, No. 33, p. 15, 1886.

many ranges of that province, the present simple orographic form is contrasted with an older complex structure which was developed during the post-Jurassic orogenic revolution. In the Sierra Nevada, the trend of this older structure, characterized by closely compressed truncated folds with extensive batholithic intrusion of granodiorite, is approximately that of the present range and, according to Lindgren,¹ the former crest line of a Mesozoic range can, in the middle portion of the present range, still be traced with fair probability some thirty miles west of the zone of scarps which now marks the eastern boundary of the Sierra. The older range probably had more bilateral symmetry than the present one, with a long slope on the eastern as well as on the western side. In combating the notion that near the close of the Cretaceous the range was reduced nearly to a plain, Lindgren² has perhaps a little over-emphasized the supposed ruggedness of the topography at that time. It is certain that large areas of the western slope were eroded to a surface of gentle relief and while it is undoubtedly true that certain masses of resistant material stood boldly above the general surface and that much of the present striking evenness of ridge crests is due to their capping of Tertiary lava, nevertheless I believe that could one have looked over the range in late Cretaceous time, he would have been impressed, as is the casual traveller now, by the general approximation to, rather than by rugged departure from, a gently sloping plain. The detailed relief of the surface was, however, as Lindgren has shown, greater than accords with the usual conception of a peneplain.

The Sierra Nevada is divided from the Great Basin, not by a single fault, but by a series of great fault zones, of which the dominant members, as clearly outlined by Lindgren,³ are arranged *en echelon* as far north as Lake Tahoe, each fault having a more northerly trend than the range as a whole and

¹ Lindgren, W., The Tertiary gravels of the Sierra Nevada of California: Prof. Paper, U. S. Geol. Surv., No. 73, p. 44, 1911.

² *Op. cit.*, p. 37.

³ *Op. cit.*, p. 41, and fig. 3.

being replaced in turn toward the north by another fault to the west. From Lake Tahoe north, the main fault zones diverge and bend to the west, an outer zone passing along the southwest side of Honey Lake and an inner zone swinging into the range past Quincy in Plumas County, California. Between these two branches, as Lindgren points out, lies a depressed block occupied by Lake Tahoe and Sierra Valley. At its south end the fault zone appears to bend to the west, along the southeast base of the Tehachapi Mountains, to its point of termination at the San Andreas rift, south of Tejon Pass.¹

The faulting which separated the Sierra Nevada from the Great Basin has by some writers been regarded as dating only from late Miocene or post-Miocene time. Lindgren² is probably correct, however, in maintaining that the break began near the close of the Cretaceous. According to Knowlton,³ the flora of the auriferous gravels is Miocene, but as this flora comes from the bench gravels and as Eocene plants have been found by J. S. Diller in strata supposed to be contemporaneous with the oldest or "deep" gravels, and on other less definite evidence, Lindgren⁴ has concluded that these earliest Tertiary gravels are probably Eocene. The same geologist has shown that a sudden increase in grade, probably connected with renewed faulting along the east side of the range, took place shortly after the great andesitic eruptions began, presumably in late Miocene time. These movements have continued intermittently to the present. Lawson,⁵ in contrast with the foregoing views,

¹ Johnson, H. A., Water resources of Antelope Valley, California: Water-Supply Paper, U. S. Geol. Surv., No. 278, p. 201, 1911. Also Lawson, A. C., et al., Geomorphic map of California and Nevada: Report of the California Earthquake Commission, Atlas, map No. 1, Carnegie Institution of Washington, 1908.

² Lindgren, W., Tertiary gravels of the Sierra Nevada of California: Prof. Paper, U. S. Geol. Surv., No. 73, p. 41, 1911.

³ Knowlton, F. H., Flora of the auriferous gravels of California: *Ibid.*, p. 64, 1911.

⁴ *Op. cit.*, p. 57.

⁵ Lawson, A. C., The geomorphogeny of the upper Kern Basin: Bull. Dept. Geol., University California, vol. 3, p. 364, 1904.

maintains that the faulting which separated the Sierra Nevada and Great Basin did not begin until the end of the Pliocene.

The structural features of the Coast Ranges of California and the depositional record connected with the development of those structures have been summarized admirably by A. C. Lawson¹ and Ralph Arnold.² Their recapitulations have been freely used in the preparation of the brief statement that follows.

Geologists are generally agreed that the Coast Ranges begin on the north between the 41st and 42d parallels, where they overlap the Klamath Mountains, and that they continue southeast to the Santa Maria River, in the vicinity of the 35th parallel, where they end in the San Emidio Range. They here impinge upon the more nearly east-west ranges, including the San Rafael, which is transitional in character, the Santa Ynez, San Gabriel, and San Bernardino ranges, all of which make up what has inappropriately been termed the Sierra Madre, but which for clearer distinction I shall hereafter refer to as the Sierra de Los Angeles. South of them the trend of the Coast Ranges is resumed in the Peninsular Chain, which extends through Lower California.

On their seaward side, the Coast Ranges are fringed by a narrow continental shelf which falls off along its outer edge, in general very abruptly, to a depth of 2000 fathoms. South of Point Conception the shelf widens, as is indicated by the islands off the coast, but retains its steep outer slope. This great submarine declivity, viewed in connection with the character of the Coast Ranges between Point Conception and Cape Mendocino, has been interpreted by Professor Lawson as a somewhat degraded fault-scarp.

The prevalent basal formation throughout the Coast Ranges is the complex Franciscan formation, which is older than the Knoxville formation of the Cretaceous, and by most geologists

¹ Report of the California Earthquake Commission, vol. 1, part 1, pp. 5-24, Carnegie Institution of Washington, 1908.

² Environment of the Tertiary faunas of the Pacific Coast of the United States: Jour. Geology, vol. 17, pp. 509-533, 1909.

working in California is believed to be Jurassic. It was vigorously deformed and was planated by erosion before the deposition of the earliest recognizable Cretaceous in the region. Whether this deformation was, as I am inclined to believe with Fairbanks,¹ contemporaneous with the post-Jurassic deformation of the Sierra Nevada, or as Lawson maintains, of later date, lacks definite proof. The Franciscan is exposed over large areas in the northern part of the Coast Ranges, where it is overlapped on the east by the thick Cretaceous formations of the upper Sacramento Valley. South of San Francisco Bay it is more generally covered by later deposits. A few masses of pre-Franciscan rocks are known in the Coast Ranges, associated with granitic rocks which have invaded and metamorphosed them. These granitic rocks, which are exposed at intervals from the south end of the chain to Bodega Head, are believed by Professor Lawson to be pre-Franciscan and probably of the same age as the granodiorite batholith of the Sierra Nevada. Dr. Fairbanks,² however, to whom is chiefly due the credit for the recognition of the great unconformity between the Knoxville and the Franciscan, considers them to be much older than the granodiorite.

On the eroded and submerged surface of the Franciscan, the Knoxville, Horsetown, and Chico beds of the Cretaceous accumulated to a maximum thickness of at least 29,000 feet.

The deformation which accompanied the emergence of the Cretaceous sediments and preceded the deposition of the Eocene was apparently not acute, although a widespread unconformity has been rather generally recognized at the base of the Tertiary. According to Arnold,³ the Oligocene was a period of elevation and moderate erosion. The Oligocene beds as a rule rest on those of the Eocene, without noticeable unconformity.

At the close of the Oligocene, according to Arnold,⁴ diastrophic

¹ Fairbanks, H. W., *Geol. Atlas U. S.*, U. S. Geol. Surv., folio No. 101, p. 9, 1904.

² *Loc. cit.*

³ *Op. cit.*, p. 520.

⁴ *Loc. cit.*

movements outlined some of the major fault blocks now known in the Coast Ranges and the line of displacement since associated with the earthquake of 1906 came into existence at that time. The Miocene was a period of great general subsidence, although certain fault blocks were elevated as islands. Such folding as took place was local. After the deposition of over 8000 feet of strata in the Middle Miocene, there followed a period of vigorous deformation by folding and faulting, but more particularly by faulting, accompanied by considerable volcanic activity. At this time, according to Arnold,¹ the block southwest of the great rift fissure was uplifted and the granite and older rocks within it exposed to active erosion.

There was renewed submergence in the Upper Miocene, during which the San Pablo, Santa Margarita, and a part of the Fernando formations were deposited, the sediments of this age attaining a thickness of 8000 feet on the southwestern side of what is now the San Joaquin Valley.

There appears to have been uplift at the close of the Miocene (San Pablo) with the formation of some synclinal basins in which Pliocene deposits, both marine and fresh-water, accumulated to great thicknesses. These beds were folded and faulted by widespread mountain-making movements at the close of the Pliocene.

Lawson remarks of the movements of the Coast Ranges in Tertiary time:

"This record of oscillation is in marked contrast to the comparative stability of the Sierra Nevada. Except for a marginal strip of its foothill slopes, the region of the present Sierra Nevada has not been submerged beneath the sea. During the geologic ages in which the Coast Range region has been repeatedly depressed to receive marine sediments, the sum of the maximal sections of which amounts to 65,000 feet of strata, the western edge of the Sierra Nevada region has probably never been depressed over 1000 feet."²

He further points out that the axial line of the Great Valley

¹ *Op. cit.*, p. 525.

² Lawson, A. C., *Op. cit.*, pp. 11-12.

of California corresponds to a great tectonic hinge, along which "the mobile coastal region has swung in a vertical sense upon the edge of the interior plateau, here represented by the Sierra Nevada." The great mobility of the Coast Ranges has continued, as is well known, through Quaternary time to the present.

Of the complicated and generally rather obscure structure of the Coast Ranges much remains to be learned. Lawson, with particular reference to the middle section of the ranges, says:

"The conspicuous folds of the Coast Ranges are those which have been impressed upon the Tertiary and older strata together. These are usually rather sharp and more or less symmetrical synclines and anticlines, involving usually many thousands of feet of strata. In some cases these are asymmetric and even overturned, as in the Mount Diablo region, but they are never so closely appressed as to induce general and important deformation of the internal structure of the rocks affected. The folding has been effected without flowage, except perhaps locally where soft clays or shales were involved, and there has been no development of slaty cleavage or schistosity. In general the axes of the folds have a northwest-southeast trend, but there are numerous deviations from this rule and the axes of the minor folds are usually more or less divergent, as is of course generally true. There is, however, a pronounced parallelism in the dominant synclines and anticlines, the axes of which extend for many miles. Several of these are more or less oblique to the mean trend of the Coast Range belt, and thus appear to be truncated on the coast-line, or on the eastern margin of the ranges. The coincidence of many of the larger valleys with a synclinal axis is very marked."¹

Faulting has produced very important effects in the structure of the Coast Ranges. The major faults are parallel with the general trends of the ranges and most of those which have been recognized appear to be of the normal type. The most interesting of these faults is the great San Andreas rift, which has been traced for over 600 miles and along which displacement appears

¹ Lawson, A. C., *Op. cit.*, pp. 16-17.

to have been taking place from Miocene time. Much detailed geologic work remains to be done before it will be possible to make comprehensive statements regarding the character and displacement of the Coast Range faults as a whole. While there is some suggestion that they are folded in general toward the Pacific, the evidence is not sufficient to establish this as a definite conclusion.

The mountain ranges of the Sierra de Los Angeles and of the northern part of the Peninsular Chain are, according to Mendenhall,¹ uplifted and tilted fault blocks of late geologic age, the master fault of the region being the San Andreas rift which passes northeast of the San Gabriel Range and southwest of the San Bernardino Range. An important fault, having the general trend of the Sierra de Los Angeles, determines the south front of the San Gabriel Range,² and other faults of similar trend, according to Eldridge and Arnold,³ play an important part in the structure of the Santa Ynez Range, north of the Santa Barbara channel. In this part of the Sierra de Los Angeles, however, where Tertiary sediments prevail in great thickness, folding and overthrusting, generally toward the coast, appear to have produced fully as conspicuous orographic results as block-faulting.⁴ According to Arnold and Anderson,⁵ the nearly east-west structures of the Sierra de Los Angeles were probably developed somewhat later than the northwest-southeast structures of the Coast Ranges.

It may be noted that from west to east these transverse ranges

¹ Mendenhall, W. C., Groundwater and irrigation enterprises in the foothill belt, southern California: Water-Supply Paper, U. S. Geol. Surv., No. 219, pp. 16-18, 1908.

² Mendenhall, *Op. cit.*, p. 16.

Lawson, A. C., Report California Earthquake Commission, p. 23.

³ Eldridge, G. H., and Arnold, R., The Santa Clara Valley, Puente Hills and Los Angeles oil districts, southern California: Bull. U. S. Geol. Surv., No. 309, 1907.

⁴ Eldridge and Arnold, *Op. cit.*, plates 3 and 4.

Arnold, R., and Anderson, R., Geology and oil resources of the Santa Maria oil district, California: Bull. U. S. Geol. Surv., No. 322, p. 75, 1907.

⁵ *Loc. cit.*

appear to show an interesting transition in structure, and perhaps to some extent in trend, from a combination of folding and faulting such as is characteristic of the Coast Ranges, to tilted block mountains, exemplified by the San Bernardino Range, such as are characteristic of the Great Basin. Moreover, the general coincidence in trend of the faults and folds of the Sierra de Los Angeles with the Texas lineament tends to confirm the suggestion of Mr. R. T. Hill that these tectonic features stand in some significant relation to those which he has studied in New Mexico and Texas. Mr. Hill is at present engaged in a broad investigation of the geology of this critical region in the Pacific System, and there is every reason to expect that he will obtain some exceedingly interesting results.

The structure of Lower California is still very imperfectly known. Gabb¹ divided it into a southern part, south of Magdalena Bay, consisting of granitic mountains, and which in accordance with modern views probably belongs geologically with the Sierra Maestra del Sur; a middle part of flat-topped ridges, mesas, and desert valleys; and, north of latitude 28°, a high mountainous part, continuous with the mountains of upper California. According to the descriptions of Lindgren² and of Emmons and Merrill,³ the northern portion consists of an eastern range of granitic and metamorphic rocks partly buried under flat-lying Cretaceous and Tertiary beds. This range they believe represents geologically a southern continuation of the Sierra Nevada rather than of the Coast Ranges. West of this is a younger range composed chiefly of eruptive rocks.

We are now in a position to see that from a point at least as far north as the 60th parallel nearly to the tip of Lower

¹ Browne, J. Ross, *Mineral Resources U. S. for 1867*, Washington, 1868, pp. 630-639.

² Lindgren, W., Notes on the geology of Baja California, Mexico: *Proc., California Acad. Sci.*, (2), vol. 1, p. 173, 1888; vol. 2, p. 1, 1889; and vol. 3, p. 26, 1890.

³ Emmons, S. F., and Merrill, G. P., Geological sketch of Lower California: *Bull. Geol. Soc. America*, vol. 5, pp. 489-514, 1894.

California, the Pacific System is characterized by one very persistent member in which folding came to an end in Mesozoic time and which has since been comparatively rigid. The units composing this member are the Coast Range of British Columbia, the Cascade Range, the Klamath Mountains, the Sierra Nevada, and the Peninsular Chain. There has been some post-Mesozoic folding in the northern Cascades but the folds are generally open or may be ascribed to local deformation related to Tertiary granitic intrusions. As a rule the units of this chain, in so far as they have moved at all, have moved *en masse* or in large fault blocks. Binding these units into one great structure, and probably responsible in part for their rigidity, is a chain of batholithic intrusions, so uniform in petrographic character and so nearly continuous in exposure as to justify us in referring to them as parts of one great batholith. Opinions vary, within certain limits, as to the time of intrusion of this batholith. In the Sierra Nevada it followed the Mariposa late Jurassic, but preceded the deposition of the Chico Cretaceous. In British Columbia the intrusion is generally placed in the Jurassic. In Alaska it appears to have been followed by the deposition of beds which have been assigned to the Upper Jurassic, the intrusion according to Brooks being post-Middle Jurassic.

Lying between these rigid blocks and the sea, but not everywhere present, is an outer chain of ranges whose history is in marked contrast to that of the inner chain. They include the Coast Ranges of California, Oregon, and Washington, with possibly Vancouver and Queen Charlotte islands. The belt corresponding to these outer ranges, particularly the Coast Ranges of California, has undergone, in Tertiary time, astonishing vertical oscillations, often varying greatly in amount between regions not far apart, and its strata have been deformed by folding and faulting with a vigor and frequency unrecorded in beds of like age elsewhere on the North American continent.

The inner rigid chain is a remnant, or series of remnants, of the Mesozoic interior plateau; the outer Coast Ranges are of newer growth and have been built from the sediments washed from that plateau.

OROGENIC DEVELOPMENT

Having accomplished this necessarily hasty and incomplete review of the geographic and structural features of the Cordillera, we may now transport ourselves in imagination to late Cretaceous time. A curiously elongated land mass must then have stretched at least from the region corresponding to Central America to that now known as Alaska. As far north as the 46th parallel this land corresponded rather closely to the present Intermontane Belt; but north of that, it apparently was wider than the Northern Interior Plateau and included much or all of the area now occupied by the Pacific System. There is a possibility, however, that some part of the Northern Interior Plateau was beneath the sea at this time.

South of the 49th parallel, the Cretaceous land mass, which at the close of the post-Jurassic revolution was probably a lofty mountain region, presumably had been much worn down. The products of its erosion had been strewn along both coasts, partly in the Pacific and partly in the mid-continental sea, which in the Cordilleran region had been receiving heavy loads of sediments throughout the greater part of Paleozoic and Mesozoic time. Throughout most of this time also, the sea bottom off the eastern coast of the Cordilleran continent had been sinking and probably the continental mass had been slowly rising, in a relative sense, as it was eroded. There is no evidence that as a whole the land surface was ever reduced to a peneplain.

Even before Cretaceous time, when comparison is made between the thick deposits of Paleozoic and older sediments of the northern Rocky Mountains and the comparatively thin layer of the older stratified rocks over the southern section of the same chain, the feature which I have called the Wyoming lineament appears to have had recognizable existence.

Toward the close of Cretaceous time, the oscillations recorded in the character of the Laramie sediments indicate the approach of diastrophic conditions. In the northern section of the Rocky Mountain region, the principal deformation appears to have taken place at the close of the Fort Union; along the eastern side of the Front Range in Colorado the decisive movement has

been interpreted as having taken place at the close of the Laramie and before the deposition of the Arapahoe beds. At the south end of the Rocky Mountains, strong unconformities have been described both above and below the Nacimientto group, which means that notable deformation and erosion occurred at the close of the Cretaceous and again just before the deposition of the Wasatch Eocene. In the northwestern part of the Park Range Province, there was uplift and vigorous erosion at the close of the Cretaceous and renewed uplift after the deposition of the Wasatch and Green River beds.

Apparently the movements of the Laramide revolution were not of the same intensity in all parts of the Laramide System at the same time, and the accurate correlation of these movements is still a work for the future requiring much more detailed and comprehensive study than has yet been given to this problem. It is clearly not safe to assume that an unconformity observed in any one locality in this vast province is indicative of movement provincial in its extent.

In connection with any attempt to determine the time at which the Rocky Mountains were formed, the so-called Laramie problem assumes more than paleontologic and stratigraphic importance. At the risk of entering into dangerous territory, this problem may be very briefly stated as follows:

Between the uppermost recognized marine Cretaceous and the mammal-bearing Wasatch (Knight formation), of undoubted early Eocene age, there intervenes a series of coal-bearing estuarine, lacustrine, and fluviatile deposits whose characteristics are such as to indicate oscillatory transition from brackish-water to fresh-water conditions. Between this series and the Wasatch, pronounced angular unconformity has been recognized in a number of widely separated localities; between it and the marine Cretaceous there is, according to some, a widespread and significant unconformity; according to others, general transition, with only local breaks in the sedimentary record. This series is broadly divisible into two parts. The upper division is generally acknowledged by paleontologists to be early Eocene. It is the upper Fort Union of some workers,

the true and only Fort Union of others. With it are probably to be correlated the Puerco and Torrejon formations¹ of north-western New Mexico, with their fauna of small archaic mammals. The lower division includes the strata variously known as the "Ceratops beds," Lance formation, "Hell Creek beds," and by other local names. This division is considered by some, largely on account of its flora, to be part of the Fort Union, and by others, largely on account of its fauna, to be Cretaceous.

Up to a few years ago all of the beds here considered were included in the Laramie and were supposed to be Cretaceous. The paleobotanists, however, succeeded in wresting the *upper* or *true* Fort Union, as the point of view may be, from the Laramie and placing it in the Eocene. Subsequently King's definition of the Laramie was interpreted by the United States Geological Survey as including the conformable beds succeeding the uppermost marine Cretaceous and, by inference, also of Cretaceous age. By this definition the beds maintained by the adherents of one view to be lower Fort Union, are, if their opponents are right, Laramie.

There is another aspect to be had of the problem, that of the general geologist rather than the paleontologist. If, as seems to be the case, a large part, perhaps the greater part, of the Laramide revolution followed the deposition of the Fort Union beds, the question may be pertinently asked whether that great diastrophic event should not outweigh the floral and faunal evidence upon which the Fort Union is placed in the Eocene. Somewhat unexpected and perhaps unintentional support for this suggestion is furnished by Dr. Knowlton, who, in urging that the line of separation between the Cretaceous and Tertiary should be drawn at the top of the "true Laramie," writes:

"In favor of placing it at the point indicated we have the evidence of diastrophism as signalized by the upbuilding of the Rocky Mountains, the general elevation of the country, and the permanent banishment of the sea, as well as the change in the

¹ Gardner, J. H., The Puerco and Torrejon formations of the Nacimiento group: Jour. Geology, vol. 18, pp. 702-741, 1910.

character of the sediments. . . . If, as has been suggested, the line between the Cretaceous and Tertiary be drawn at the point where the dinosaurs happened to disappear, we are left without the support of contributory data."¹

In this connection it is to be remembered, however, that the "post-Laramie" revolution of the older geologists meant the "post-Fort Union" revolution, the Fort Union being, until recently, included in the Laramie. There is little to show that with the taxonomic restriction of the Laramie to certain lower beds, the long accepted view of the geologic date of the major Rocky Mountain uplift must also be shifted to agree with the "true Laramie," whatever that may be.

Ulrich states also:

"To postulate a period of major diastrophic activity, we need but to establish that strong folding actually occurred at such time in certain regions, and this proof should be sufficient warrant for the beginning of a new geologic period."²

The difficulties of the Laramie problem are of course enormously increased by the peculiar conditions under which the beds were deposited. Evidently, during the critical period in dispute, large areas of freshly deposited sediments became low-lying land, on which coal-producing and other forms of plants flourished and over which roamed the remarkable animals of that time. Such land must have been eroded, so that the deposits as we now see them may have been several times worked over by streams, waves, and currents, and may have travelled long distances by various modes of transport from their original source. It is to be expected that in a sedimentary series accumulated under such circumstances, local unconformities would be fairly common; but as the angular divergence in the bedding would in general be slight and as the low-lying,

¹ Knowlton, F. H., The stratigraphic relations and paleontology of the "Hell Creek beds," "Ceratops beds," and equivalents, and their reference to the Fort Union formation: *Proc. Washington Acad. Sci.*, vol. 11, pp. 236-237, 1909.

² Ulrich, E. O., Revision of the Paleozoic systems: *Bull. Geol. Soc. America*, vol. 22, p. 401, 1911.

scarcely consolidated land, which from time to time scarce rose above the level of deposition, would hardly furnish material for conglomerates, these unconformities might be very difficult to detect.

The Laramie problem is undoubtedly one of the great questions of North American geology, as upon it depends our interpretation of the history of the Cordillera in terms of the geologic time scale. If it can be solved without acrimony, in the spirit which places the ideal of truth above mere personal victory, the result will honor all who have worked earnestly toward that end.

The character of the Laramie deformation varied greatly in the different subdivisions of the Laramide System. In the northern Rocky Mountains it took the form of folds, in part overturned and overthrust to the east or northeast. In certain regions, the thrust surfaces themselves are described as folded. In the Park Range Province there was much less stratigraphic crumpling, while folding in the Plateau Province was relatively unimportant. Consequently it would appear that during the folding the Wyoming lineament must have corresponded to a zone of differential movement. In general the intensity of the deformation appears to have been roughly proportional to the depth of the sediments, being much greater to the north, where, according to the Canadian geologists, the beds attained a total thickness of eighteen miles, than in Colorado, where they were comparatively thin.

It has been a rather widely held tenet among geologists that most of the great mountain ranges of the globe have been formed by thrust from the nearest ocean basin, the classic example being the Appalachians. It has also been believed by many that the Laramide System is essentially Pacific in origin and that the deformation which gave it birth was the consequence of interaction between the Pacific Basin and the continental margin. Daly, as previously noted, maintains this view, which was also that of G. M. Dawson. According to Willis:

“The folding which occurred during the late Cretaceous and

Eocene throughout the Rocky Mountain province, even as far east as the Front range of Colorado, is to be attributed either to Pacific thrust or to pressure exerted from the region of the Great plains. The latter involves the spreading of the negative element that lies beneath the plains, at least according to the hypothesis entertained, that tangential movements in the earth's crust are due to displacement of the lighter elements by lateral spread of the denser masses. It would seem, however, that the relatively light and small negative element beneath the Great plains is a very inadequate source of tangential thrust as compared with the comparatively dense and enormous mass beneath the Pacific. As already stated, I regard the latter as the source of the orogenic activity which has produced the Cordillera from Alaska to Cape Horn, and this conclusion necessarily includes the section in Colorado."¹

Suess's views² on the origin of the Laramide System are nowhere very clearly summarized, but it is evident that he regards them as Pacific structures. He contrasts the ranges bordering that ocean with the Appalachians and other so-called Atlantic structures. He makes the generalization that the regions bordering on the Pacific are folded toward that ocean whereas the mountains on the Atlantic seaboard are folded inland. He explains the eastward overturns and overthrusts of the Rocky Mountains, so far as they were known when he wrote, as back-folding, due to excess of material in the upper zones of the earth. In accordance with his well-known theory, he considers that the Cordilleran folding is due not to a thrust from the Pacific but to an outward creep of the continental mass over a submarine depression or fore-deep. He sums up his general view of mountain-making very concisely in the following paragraph:

"The Oceanic subsidence resolves itself, more or less after the plan of the stresses in an asphalt pavement, into isolated, elongated arcuate fragments. Contraction has left the outer

¹ Willis, B., A theory of continental structure applied to North America: Bull. Geol. Soc. America, vol. 18, p. 406, 1907.

² Suess, E., *Op. cit.*, vol. 4, pp. 496, 510, 623, 633, etc., 1909.

and in part sedimentary covering of the earth in excess. The tangential force carries this excess, in arcuate folds, into and over the subsided fore-deep. The arcs encounter one another in linking or syntaxis. The movement increases; under the stupendous pressure the folds are urged on; they overturn; possibly also listric planes are produced. Finally back-folding sets in.''¹

Professor Chamberlin² has expounded a similar idea, although, so far as I am aware, he has not applied it, unless perhaps inferentially, to mountain-folding. Taylor's conception that the great mountain folds are due to general continental creep from high to low latitudes, while presenting some similarity to the views of Suess and Chamberlin in so far as relates to the mechanics of the zone of folding, differs fundamentally from them with respect to the general character and origin of the creeping movement.

When we attempt to apply the idea of suboceanic thrust to the Laramide System, at least one difficulty appears which has not yet been satisfactorily met. That such basins in their centripetal movement may, as Chamberlin³ has suggested, squeeze the lighter continental segments and force them upward is entirely conceivable; but the thrusts thus exerted would be abyssal and primarily downward, whereas the plication of sedimentary rocks is a relatively superficial process.⁴ The tendency of such squeezing would be to underthrust the deep-seated portions of the continental segments, not to overthrust their superficial or crustal portions. In short, it is very difficult to conceive of pressure from an ocean basin being directly transformed into tangential landward thrust in a higher zone

¹ *Op. cit.*, p. 582.

² Chamberlin, T. C., The fault problem: *Economic Geology*, vol. 2, pp. 704-721, 1907. Also, Diastrophism and deformative processes: *Jour. Geology*, vol. 21, pp. 517-533 and 577-587, 1913.

³ Chamberlin and Salisbury, *Geology*, vol. 1, p. 521, 1904.

⁴ Chamberlin, T. C., Diastrophism and deformative processes: *Jour. Geology*, vol. 21, p. 582, 1913.

Chamberlin, R. T., Appalachian folds of central Pennsylvania: *Ibid.*, vol. 28, pp. 228-251, 1910.

of the lithosphere. Particularly is this so where the movement would have to be transmitted through a high rigid continental mass such as in Cretaceous time intervened between the Pacific and the Laramide geosynclinal prism of deposition.

There are difficulties also in applying Suess's general theory to the Laramide System on the supposition that this is Pacific in origin. For in Cretaceous time there was no elevated continent on the eastern border of the tract of maximum deformation; there was land, instead of a fore-deep, to the west of it; and the general thrust, so far as its effects are visible to us, was to the east, not to the west. The work of recent years has so extended the region formerly known to be affected by this strong eastward overthrusting as to make the explanation of "back folding" or "back thrusting" appear at present more like an attempt at fitting facts to hypothesis than at unbiased interpretation.

The trend of the foregoing considerations has doubtless already suggested to most of you a third hypothesis for the origin of the Laramide System, and one which has perhaps not been accorded sufficient attention. This conjecture, for it can scarcely be called by any more dignified name, is that the system was developed by interaction between the region now occupied by the Great Plains and Gulf of Mexico on the east and the Cretaceous land mass to the west. It would be a natural extension of this view to conclude, as Mr. Alfred H. Brooks has suggested in conversation, that the Endicott Range of northern Alaska is genetically an Arctic, not a Pacific, feature. While it would be rash to say that movements of the Pacific Basin were not in some deep and inscrutable way connected with the Laramide revolution, the proposed hypothesis would deny to that great depression an immediate part in the formation of the Rocky Mountains.

Keeping fully in mind the speculative and tentative nature of the suggestion, we may suppose that in Cretaceous time the Cordilleran land mass was rising and was being eroded. In accordance with the general principles enunciated by Suess and Chamberlin, the rising mass probably had a tendency to

spread laterally, particularly to the east where sediments had previously accumulated to enormous thickness in the Laramide trough, derived doubtless from older land masses which occupied in part the position of the Cretaceous land. For a time, as Chamberlin¹ has pointed out, the effect of this creep of the protuberant mass would be to favor sedimentation by pushing the sea shelf outward and slightly downward. As uplift of the land mass and sedimentation of the adjoining area continued, resistance to lateral spread would diminish. Erosion, by cutting down the land, would tend to delay the final diastrophic event: but deposition, the complement of erosion, would tend to hasten it. Finally, if the forces causing the uplift of the land area were relaxed, by just so much as the underlying support of the protuberant arch was lessened would thrusting stresses accumulate along the borders of the land mass. Relief of these presumably would be accomplished by a thrusting forward of the land mass against the sediments to the east, the crumpling of these into folds, and their further deformation by thrust faulting. This diastrophic revolution it is to be expected would be followed by collapse and down-sinking of the imperfectly supported Cretaceous continent and by normal faulting behind the overthrusts.

So far as concerns the northern division of the Rocky Mountains in the United States and their relation to the Great Basin structure, which presumably extends under much of the Columbia Plateau Province, the facts on cursory examination appear to fit the hypothesis fairly well. As regards British Columbia, however, some doubt may well be entertained as to the adequacy of the proposed explanation. The Cretaceous land mass may possibly have been too narrow to have had an active part in the origin of the great Rocky Mountain ranges. A similar state of uncertainty exists with reference to the Mexican region.

It should be pointed out that in some respects the Appalachian and Laramide systems, which have been contrasted by Suess, although both are included in his Asiatic System, resemble each

¹ *Op. cit.*, p. 585.

other. Both are separated from the ocean by old-land belts which once were more extensive and relatively higher. Both had their positions determined by the accumulation of great sedimentary prisms, composed mainly of materials derived from these old-lands. Both were folded away from the ocean toward the interior. A somewhat similar position is occupied by the Himalayas, and Colonel Burrard,¹ finding a deficiency of gravity along their south base, has argued that, contrary to the view of Suess, these mountains could not have been crowded from the north against the Indian old-land, but must have been folded away from the old-land to the north.

Whatever may be the value of the hypothesis suggested as a possible explanation of the growth of the Laramide System, the fact remains that no explanation that has been offered is a fully satisfactory one. The origin of the Laramide System is still an unsolved problem.

Among the many other problems or features that specially invite further study may be mentioned (1) the great stratigraphic down-step at the Texas lineament from the Paleozoic of the Colorado Plateaus to the Cretaceous of the Mexican Plateau; (2) the contact between the Archean of the Park Range Province and the sedimentary beds of the Great Plains; (3) the relation of the Park Range deformation to Paleozoic or Mesozoic land masses; (4) the structure and physical history of the Wasatch Range; (5) the significance of the Wyoming lineament; (6) detailed and comprehensive study of the great fault systems of the northern Rocky Mountains; and (7) the origin and history of the remarkable "trenches" of these mountains in the northern United States and in British Columbia.

In the Intermontane Belt, the best known and most interesting province is the Nevada-Sonoran region, and to that I shall virtually confine my attention. Its Tertiary structural history and problems are those associated with subsidence, faulting, volcanism, erosion, and local fresh-water sedimentation or

¹ Burrard, Col. S. S., On the origin of the Himalaya Mountains: Prof. Paper No. 12, Surv. of India, 1912.

deposition. Here the great need is a reliable geologic chronometer by which to time and correlate the diastrophic events which have been in progress throughout the Tertiary. Some of the difficulties and problems involved in the interpretation of Tertiary geologic history in the Great Basin have been discussed rather fully in another place.¹ It must suffice to say here that King's conclusion that in Miocene time western Nevada was for the most part covered by Pahute Lake, in which the sediments of the "Truckee group" were laid down, was based upon very slender evidence as to the age and correlation of the sediments supposed to have been deposited in that body of water. Later work has indicated that fresh-water beds of various Tertiary ages have probably been included in the "Truckee group." Russell's study of Lake Lahontan has shown also that some of the sediments on which King founded his supposedly Pliocene Shoshone lake were laid down in the Quaternary lake. The history of diastrophism in the Nevada-Sonoran region thus waits upon the labors of the stratigrapher and paleontologist. A comprehensive study of the stratigraphy, fauna, and flora of the Tertiary fresh-water deposits of the Great Basin by competent investigators ought to yield results of unusual interest and importance. Prof. J. C. Merriam² has made notable advances in this field by his studies, still in progress, of the John Day Basin in Oregon, of the Virgin Valley, and other localities in northwestern Nevada, and of the Mohave Desert in California. He has brought out the interesting fact that whereas the Upper Miocene appears to be represented by an unconformity in northern Nevada and in Oregon, the Mohave region contains a full series of beds referable to that epoch. It is to be hoped that these studies, carried out by

¹ Ransome, F. L., The geology and ore deposits of Goldfield, Nevada: Prof. Paper, U. S. Geol. Surv., No. 66, pp. 86-107, 1909.

² Merriam, J. C., A contribution to the geology of the John Day Basin: Bull. Dept. Geol., University of California, vol. 2, pp. 269-314, 1901; Tertiary mammal beds of Virgin Valley and Thousand Creek in northwestern Nevada: *Idem*, vol. 6, pp. 21-53 and 199-304, 1910 and 1911; A collection of mammalian remains from Tertiary beds on the Mohave Desert: *Idem*, vol. 6, pp. 167-169, 1911.

private and university enterprise, will be continued to completion east of the Sierra Nevada. An investigation of such magnitude and scientific interest is one to which an enlightened government might well lend its substantial aid, or undertake itself.

As regards the more purely structural problems in the Great Basin region, it may be noted that notwithstanding the discussion which has centered about the desert ranges, no one of them has yet been topographically and geologically mapped in accurate detail. Until this is done and one or more typical ranges fully studied with reference to their structure and erosional history, not much new light is likely to be thrown on the Basin Range problem. Such study should embrace not only the range itself but the adjoining valleys, where borings might be undertaken in the joint interests of geology and water or other possible resources.

Volcanism and diastrophism have undoubtedly been very closely related in the Nevada-Sonoran region. Very little has been learned, however, of the nature of the connection between these two associated groups of phenomena.

The Pacific System is on the whole the youngest of the three great longitudinal divisions of the Cordillera, although the separation of its rigid eastern member from the now depressed Intermontane Belt probably dates from about the time of the Laramide revolution. This line of separation is most striking and has been most carefully studied on the east side of the Sierra Nevada which, as we have seen, was probably a distinct range in Cretaceous time.

Writers on the origin of the Sierra Nevada have held somewhat divergent views as to the character and effect of the faulting which was associated with the rejuvenation of the Cretaceous range. The latest carefully worked out conclusion, that of Lindgren,¹ considers that, even from the beginning, "the orogenic disturbance was probably of a twofold character, consisting of the lifting up of a large area, including at least a part of the present Great Basin, and a simultaneous breaking

¹ *Op. cit.*, p. 44.

and settling of the higher portions of the arch.' In other words, if I interpret him correctly, Professor Lindgren rejects the idea that the Sierra Nevada block has individually been tilted or uplifted along its eastern side. He holds that such increase in elevation or inclination as the block has received since Cretaceous time has been due to epeirogenic uplift or broad arching, involving much more than the Sierra block, and that the movement along the eastern faults is entirely of negative character, that is, a sinking of the adjacent part of the Great Basin. He believes that the total throw of faults is not enough to account for the increased grade given to the old Tertiary channels, and that block tilting could not have occurred without notable deformation of those channels. The sections across the range which are presented by Mr. Lindgren in his report as "indicating clearly the absolute insufficiency of the eastern faults to account for the increase in slope demonstrated by the grades of the channels,"¹ do not quite carry conviction. His conclusions rest upon two postulates: (1) that a large segment of the earth's crust (even when broken into parts by faults) is more susceptible of elevation and tilting without deformation of a particular part than would be that part if elevated and tilted by itself to the same degree; and (2) that the axis of rotation of the Sierra block was at its western edge, or in other words, the block moved as if hinged along its western margin. Neither postulate appears to be obviously true, nor is it necessary to suppose that a block in process of tilting is supported only at its edges. If it be granted, as is very probably true, that in Cretaceous time the region corresponding to the present Great Basin stood much higher than it does now, perhaps forming on the whole a great mountain province of which the Cretaceous Sierra Nevada was an outlying and comparatively low range, and if it also be accepted that the faulting which determined the eastern edge of the Sierra Nevada block began at the close of the Cretaceous and was accompanied by a breaking up and sinking of the Great Basin region, then it would appear more reasonable to suppose

¹ *Op. cit.*, p. 46.

that the Sierra block rose to some extent along its eastern side than to assume that the block stood still; for the fact that dislocation took place and that the country to the east parted from the Sierra block and sank shows that the latter block must itself have been withstanding powerful stresses tending to force it downward. On the relief of those stresses the block may be supposed to have undergone a compensatory upward movement on its eastern side. Lawson¹ has reached practically the same conclusion with reference to the section of the fault zone at Genoa, Nevada. As regards the western edge of the block, it may reasonably be postulated that this was not stationary but was free to subside and that, in fact, it did subside contemporaneously with the uplift to the east and with the deposition and deformation of the thick masses of Tertiary sediments which now form so large a part of the Coast Range of California. In short, it does not appear necessary to conclude that, if the Sierra block has moved as a unit, the total vertical displacement along the eastern fault zone, even if its maximum were determinable, is the full measure of Tertiary tilting; neither does the apparent rigidity or lack of local deformation of the Sierra block appear any more consistent with a supposed general uplift of that mass, together with a region that has already shown undubitable evidence, through faulting and subsidence, of being a geologically failing structure, than with the view that the Sierra block moved independently.

A thorough investigation of the whole fault zone which separates the Sierra Nevada from the Great Basin is a work that no one has yet undertaken, although the zone has been studied at certain localities and the effects of recent movement along it in Owens Valley have been carefully noted, particularly by W. D. Johnson.² As Professor Lawson³ has suggested, accurate level and triangulation lines should be run across this

¹ Lawson, A. C., The recent faultscarps at Genoa, Nevada: Bull. Seismological Soc. America, vol. 2, p. 199, 1912.

² Hobbs, W. H., The earthquake of 1872 in the Owens Valley, California: Beiträge zur Geophysik., Bd. X, pp. 352-384, 1910.

³ Lawson, A. C., *Op. cit.*, p. 200.

fault zone at various places so that its movements may in future be measured.

The diastrophic history of the outer or coastal ranges of the Pacific System has been written boldly and fully in the California Coast Ranges, although elsewhere the record is less complete or still lacks interpretation. In California there is evidence of but moderate or slight disturbance at the close of the Cretaceous, in marked contrast with what took place then or slightly later in the eastern part of the Cordilleran belt. There was more pronounced movement at the end of the Oligocene and strong orogenic deformation, both faulting and folding, at the end of the Middle Miocene (Monterey). Moderate folding terminated the Upper Miocene and pronounced folding and uplift, probably with faulting, closed the Pliocene. Faulting continues to be in progress. In southwest Oregon, the principal movements appear to have been post-Cretaceous and post-Eocene. In Alaska the Tertiary diastrophism was most effective in Eocene and post-Eocene time, although conspicuous disturbances of local character have continued to the present. In the California Coast Ranges, the Tertiary movements were exceedingly variable in their intensity from place to place. Faulting, apparently for the most part of normal type, began rather early in the Tertiary and later seems to have increased in relative importance as compared with folding.

Detailed working out of structure in the Coast Ranges has scarcely begun and the task presents peculiar difficulties. The sandstones and shales, which are the preponderant element of the sequence from the Jurassic to the Pliocene, are not everywhere readily distinguishable in the absence of fossils, and over broad areas they are heavily mantled by residual soils which effectually conceal the folded and faulted beds. In certain regions it is doubtful whether the structure can ever be deciphered as completely and certainly as is possible in other parts of the Cordilleran region.

The configuration of the coast for long distances and the abrupt descent from the coastal shelf into the depths of the Pacific are, as has been pointed out by Professor Lawson, the

consequences of faulting which undoubtedly is still in intermittent progress and has far outstripped marine sedimentation. Thrust from behind by the rigid block of the Sierra Nevada and rising precipitously from the deepening Pacific Basin, the Coast Ranges are manifestly in a state of trembling instability, and the geologist may look to them, not only as a record of the past, but as a region where great geotectonic features are in process of development and at so rapid a rate that there is fair prospect of our being able in a few generations to measure something more than the local changes which accompany a single earthquake. One of the problems now before geologists, geodists, and geophysicists is how best to contribute, by observational records and by the establishment of permanent benchmarks and triangulation points, to the work of those, yet unborn, who may study the structural geology of the Coast Ranges. From a scientific point of view, and perhaps I may safely say from a utilitarian point of view, the entire belt traversed by the San Andreas rift ought to be accurately mapped, both topographically and geologically, on a fairly large scale.

A region which will undoubtedly prove of exceptional interest with respect to the structural development of the Pacific System is that which centers about the Sierra de Los Angeles, the meeting ground of the Coast Ranges, the Sierra Nevada, and the Peninsular Chain. While it is not likely that this critical region, which, as it happens, is traversed by the San Andreas rift, will yield all of its tectonic secrets without long and detailed study, it is hoped that the reconnaissance work of Mr. R. T. Hill, now in progress there, will at least give definite shape to some of the problems which are suggested by what is already known of the geology.

In conclusion, I am fully conscious that the vast region whose Tertiary structural features have been so hastily and superficially sketched, contains many great regional problems connected with its development in Tertiary time which have not been mentioned or have barely been touched upon. Some, such as the origin, correlation, and diastrophic history of the great peneplain remnants of the Northern Interior Plateaus

and the Pacific System, would lead us into the field of the physiographer. Others, such as the tectonic effects of batholithic intrusion and of great lava outbursts, would trench upon the province of the petrologist in his wider excursions. Finally, there are smaller or local problems innumerable in this wonderful Cordilleran region, whose spell is on all who enter it but upon none more surely than the geologist, to whose ordered imagination even those stern aspects which some travellers find repellent, make an appeal more inspiring than does the soft beauty of a milder landscape.

PRINCIPAL AREAS COVERED BY TERTIARY FORMATIONS IN THE WESTERN UNITED STATES

FROM U. S. G. S. GEOLOGIC MAP OF NORTH AMERICA, 1911

CHAPTER VII

THE TERTIARY SEDIMENTARY RECORD AND ITS PROBLEMS

W. D. MATTHEW

*Nature and Source of the Tertiary Strata.—The Lacustrine Theory.—
Succession and Correlation of Tertiary Formations.—The Life Record
of the Cordilleran Tertiaries.*

SEC. I. NATURE AND SOURCE OF THE TERTIARY STRATA OF THE CORDILLERAN REGION

Introduction. As the latest of the geologic periods, the Tertiary record ought to be the easiest part of the world's history to interpret and understand. The conditions were less remote from present-day conditions; the records of geologic and biologic processes and events have suffered less change, destruction, or metamorphism than those of older periods. Here in New England, indeed, the Tertiary formations have mostly been plowed up and obliterated by the great glacial invasion. But in the Cordilleran region, as far north as the Canadian border, they present wonderfully complete series of marine formations upon the coast, of terrestrial formations in the interior.

The basic principle of modern geology, as enunciated by its founders, Lyell and Dana, is that the present is the key to the past, that geologic phenomena are to be interpreted through modern physiographic processes and results. To understand aright the nature and origin of the Tertiary sediments of the Cordilleras we must keep ever in mind what is going on at the present day, and especially in that region.

The conditions of erosion and sedimentation in the Cordilleran region are in large part the same as those with which we are familiar in the East, but there are some conspicuous differences. I have already referred to the Glacial episode which destroyed our Tertiary records in the East as far south as New York and Pennsylvania, and covered the country with heavy banks of formations accumulated under quite exceptional conditions, blocking channels, changing water courses, flooding the rivers southward of its limits with great volumes of water and loads of sediment. In the Cordilleran region, the glaciers played no such important part. South of the Canadian border they were restricted to the immediate vicinity of the greater mountain ranges, and their more overwhelming effects quite localized. Even the glacial alluvium, although spread more widely, has not the relative importance that it displays in the East.

Fig. 1. Upper part of White River terrane, Leptauchenia zone, Pine Ridge Indian Reservation, South Dakota. To illustrate the holding of the surface by the grass-sod cover, and the rapid erosion by wind and water where this has been cut through.—Am. Mus. Nat. Hist. Photo No. 36035.

Area and Extent of Western Tertiaries. These formations cover great areas in the western half of the United States. In Mexico to the south and in Canada to the north their extent is relatively small. For the most part, they cover the floors of the broad basins intervening between the complex systems of parallel and transverse ridges that lie between the Front Range in Colorado and the Coast Range in California. Eastward of the Front Range they stretch far across the plains from South Dakota to Texas.

Their strata are usually flat lying, forming the surfaces of the higher plains or dissected out to a greater or less extent by subsequent erosion. They are more or less consolidated into sandstones, shales, and conglomerates, and vary in thickness from a few hundred to several thousand feet. Along the Coast Ranges they are chiefly of marine or littoral origin, and have been involved in the faulting of that line of disturbance and uplift. Elsewhere they are clearly not marine formations, but their origin has been much disputed.

Peculiarities of Water Erosion. Water erosion in this arid region is irregular and comparatively slow. The rainfall is chiefly in the mountains; elsewhere the effects of occasional cloudbursts are severe but very localized. But the scarcity of water makes vegetation scanty, and especially upon sloping surfaces erosion may be relatively rapid in the softer rocks. The grass-covered topsoil holds back erosion, but where a stream has cut down through this protecting cover, the sloping sides cut rapidly, and are carved into bad lands or the characteristic escarpments.

Importance of Wind Erosion. Wind is a much more important agent in erosion than it is in the East. It plays a large part in carving out the gullies and fantastic buttes and pinnacles so characteristic of the scenery of all arid regions. How large a part it plays in the Cordilleras is a matter of dispute. Probably the prevalent opinion underestimates it; for geology as a science developed in western Europe and eastern North America, both countries of abundant rainfall and heavy vegeta-

tion, and this environment has inevitably influenced the views and traditions of geologic science, in this as in many other particulars.

Fig. 2. Castle Rock, Uinta Basin, Utah. A notable example of aeolian erosion.

Rocks Less Deeply Weathered. Active erosion is confined to mountains and the bad lands. On account of the dry climate, the exposed surfaces of rock are not wetted enough to stimulate

their decay. They break up from the violent contrasts of heat and cold, but they do not decay so rapidly as in a more humid climate.

Fig. 3. Uinta formation near White River, Utah. An example of æolian planation. The floors of these badland pockets, while they appear as though built up of wash from the sides, very commonly consist of undisturbed strata of the original formation, the surface being eroded and planed smooth by wind action.—Photo by Am. Mus. Nat. Hist.

Deposition of Material Eroded by Wind and Water. What becomes of the material removed by streams and wind? It is all eventually redeposited, some near by, much more in the lower reaches of the streams. As these emerge from the mountains, they spread out fanlike a broad stretch of the coarser gravels and sand, extending along their channels far out upon the plains. The finer sediments they carry farther and deposit in a thinner and more extended sheet over their lower flood plains. Part of the sediment is carried down to the deltas of the rivers, and there finally comes to rest. And some is carried out to sea and deposited along the littoral or in deeper waters.

The flood-plain formations and the torrent fans are but temporary stages, and sooner or later the stream will cut them out and carry them farther down. The delta and marine formations are relatively permanent.

Fig. 4. Canon of the North Platte River at Alcova, Wyoming. This canon is cut through a ridge which blocked the drainage of the Platte above it and extended Tertiary flood-plain deposits far up the valley of the Sweetwater. When the cut was completed these sediments commenced to be removed down river; only a few remnants are now left.—Am. Mus. Exped. 1899.

Tertiary Basins. If at any point the course of the stream is blocked, whether by an ice-dam or a rise of land across its valley, the sediment begins to pile up behind the barrier. If the barrier is raised more rapidly than the sediment can pile up behind it and the stream cut down through it, a lake will be formed, and the sediments will accumulate, partly on the bottom of the lake, chiefly as a delta at its head and a flood-plain sediment in the valley above the delta. This goes on until

the cutting through the obstruction and filling in above it have brought the grade to a slope where the stream can carry all the sediment it brings. Then the formation ceases to accumulate, and sooner or later the stream begins to cut into it again.

Whether or not an actual lake is formed under these conditions, the blocking of the stream valley reduces the grade of the stream for a long distance above, and causes it to deposit sediment over all that distance, so that the actual delta or lake-bottom deposits are in most cases a minor portion of the whole formation conditioned by such an obstruction, and as they are at the lower end of the formation, they are first subject to erosion and disappear early. Only when the lake is very extensive and lasts a long time, and the sediment accumulates very slowly, are the true lake-bottom deposits likely to make an important formation or one of any permanency.

Flood Plains. A flood-plain formation may be caused by a rise of land above instead of below its place of deposition. For the increased grade of the stream in its upper course makes it erode and carry more sediment, and this extra load is dropped when it reaches the undisturbed flood plain below. The formation piles up over the flood plain until it has increased the grade of the stream so that it can carry its load.

The sediment is distributed over the flood plain through continual shifting of the river course. It tends naturally to pile up chiefly in the immediate neighborhood of the stream; when this gets sufficiently above the level elsewhere, the stream shifts its course and seeks a lower portion of the area. The extreme irregularity and inconstancy of formations produced in this way are in contrast to the comparatively widespread uniformity of marine formations.

While as a whole the lower portions of such a formation are older than the upper portions, yet we cannot be sure that beds on the same level are of the same age. Undoubtedly they will be approximately so if they are near together. But if the general region of deposition is slowly shifting downstream or upstream, we may well have a formation apparently continuous, but of considerably different age in different areas.

Fig. 5. Lower and middle part of White River terrane (Chadron and Brule formations), Quinn Draw, Big Badlands of Cheyenne River, South Dakota. The lower beds are largely fluviatile, river channel and flood-plain deposits. Note the heavy sandstone lenses and layers and marked cross-bedding indicative of disturbed water deposition. The upper beds, finer grained and horizontally banded, were deposited probably in back-water conditions or are in part æolian. The extent to which volcanic material has contributed to this widespread terrane is indeterminate; if present in any large proportion its characters are obliterated by weathering and redeposit.—Am. Mus. Photo No. 36012.

Significance of Conglomerates. Conglomerate strata and unconformities also have quite a different significance in these stream-channel beds from that which they have in marine or lacustrine formations. A conglomerate overlying an eroded surface of older beds is the well-known mark, in marine stratigraphy, of an advancing sea overrunning a land area, and the first stage of a characteristic and well-defined succession of formations due to that overflow. A conglomerate in a flood-plain formation overlying an eroded surface means merely that the stream has shifted its channel from one area to another. The relations of such a conglomerate to the beds above and below will be much the same as with the marine formation. But instead of signifying the commencement of a cycle of deposition, it is merely a shift of deposition. Usually these conglomerates are not uniform over any wide area, but with a gradually shifting stream they may be continuous or comparatively so for a broad stretch of exposures. More generally they are found in limited strips or lenses.

Unconformities and Cross-bedding. Marked cross-bedding is characteristic of coarser portions of these flood-plain formations, but not at all peculiar to them. Unlike marine or lake-bottom deposits, however, they are laid down, not in a horizontal plane, but on a surface more or less sloping, and it might be said that they are always to some slight extent cross-bedded. A certain area may be filled by sediments coming from one side, and these will have a slight dip away from that side. Then the supply ceases from that side, and perhaps some local erosion follows. Afterwards the stream may break in from the other side, the dip will be reversed, the stream-channel conglomerate beds will be deposited on the eroded surface with an angular unconformity that is only partly attributable to the cross-bedding, and is partly continued in the finer sands and clays that follow.

These flood-plain formations are not only much more irregular than marine formations, but they are much more limited as to area. The flood-plain sediments of each river basin are largely independent of the rest. Of course a rising mountain ridge may cross and block several rivers, or a rise in a mountain

range will increase the slope and cutting action of all the rivers that head up into it and so cause all of them to accumulate simultaneously a flood-plain formation lower down upon their course. But two rivers heading up in different regions may have their flood plains quite near together or overlapping, and yet the succession of formations in each be wholly independent.¹

Fig. 6. Green River Eocene at Green River station, Wyoming. This is a true lacustrine formation of fissile cleavable calcareous shales. Fish, fresh-water shells are very abundant in some localities. mammals and other terrestrial animals are not found, although abundant in the overlying Bridger, a flood-plain formation.

Lacustrine Formations. Of true lacustrine formations we have examples in the desiccated lake basins of Nevada, Idaho, Utah, and eastern Oregon. Some of these expanded in Quaternary time to cover wide areas, and the basins are now exposed to view partly by drainage, chiefly by drying up. The deposits are mainly marginal, each inflowing river pushing out

¹ Such appears to be the case as between the formations of the Platte basin and the Niobrara-White-Cheyenne basin during the later Tertiary.

a delta into the lake, while all around the lake borders the cutting of terraces supplied materials for a marginal shelf. The bottom deposits are of minor proportions, and are in large part calcareous, chemical rather than mechanical sediments. This is largely true of the bottom deposits of all extensive lakes. The sediments are not carried far out from their margins. The accumulation of lake-bottom sediments must be comparatively slow, and its rate conditioned largely by the amount of lime in solution brought into the lake by inflowing streams.

Æolian Deposits. The importance of æolian deposits in the Cordilleran region has been little appreciated. Wind is an almost negligible factor in a humid region. In an arid region, it assumes great importance; both relative, on account of the slower action of the scanty rain and infrequent streams, and absolute, on account of the lack of a protective covering of vegetation and the exposure of bare surfaces of rock and soil to the action of the wind. All the material eroded by the wind must needs be deposited elsewhere, and with the prevalent west winds of this region it will be carried eastward until it meets with a protective covering of vegetation sufficient to hold or permanently arrest it.

Loess. While the coarser sediments may be carried forward as dune sands, the finer dust will be carried much farther and deposited on the sodded surface of the prairies, where the grass sifts out and holds it to add to the surface soil. In this way it contributes to the mantle of loess or prairie soil which covers the whole of the plains from the Mississippi Valley westward. The æolian loess is deposited not only in the river valleys, but upon the high-lying plains as well, wherever these are sufficiently grassed to hold the dust. The loess of the river valleys and of the eastern region nearest the Mississippi is no doubt chiefly fluvatile, but the loess of the high plains and grass-topped plateaus farther west is largely æolian in origin. It grades insensibly into the river loess, and has until recent years been usually considered as of river or even of lacustrine origin. The very uniform level surface of large areas of the plains has perhaps suggested the lacustrine hypothesis; but it is more in

accord with the æolian theory of origin, for every hollow or slightly sunken area in the grassy plains tends to accumulate water during the rains and as a result to have an unusually heavy growth of grass over its surface. This serves to sift out the dust more effectively during the ensuing dry season and the deposit is consequently heavier in every slight hollow, tending in time to fill the whole area to a level surface.

The great loess formations of China were accumulated under very similar conditions, and are generally regarded as of æolian origin, chiefly because of the high authority of Von Richthofen. This also has been disputed, however. Probably the loess of the more easterly and lower lying plains of the great Chinese basin is largely or mostly fluvatile, while that of the more westerly and higher lying districts is æolian.

Fig. 7. Upper part of White River terrane (Brule formation) at Sheep Mountain, Big Badlands, South Dakota. Flood-plain and æolian beds. Note the prominent horizontal color-banding, often cited as proof of lacustrine origin. But this color-banding is equally prominent in some modern æolian formations, notably volcanic ash deposits in the Philippines and Alaska. This color-banding is something quite distinct from the horizontal cleavage of fissile shales, such as the Green River, which does indicate deposition under quiet water.

Volcanic Ash an Important Source of Material. There is one element that is not today contributing to any appreciable extent to the formations of the Cordilleran regions, and probably was not important during the Pleistocene, but during the Tertiary was almost the principal source of the terrestrial sediments. This is volcanic ash.

Fig 8. Bridger formation, Henry's Fork, Wyoming. In the middle ground lie the fossiliferous Bridger beds, all redeposited volcanic material. Above them in the background are 500 feet of barren beds, with heavy ash beds of original deposit. These are capped by a conglomerate, probably of Pleistocene age.

A glance at the geologic map (Plate 1) will show what vast areas of the Cordilleras are covered by Tertiary volcanic rocks. What now remains of these huge outpourings of lavas and ashes are chiefly the lava beds and such ash beds as have been preserved by a capping of lava. The incoherent ash beds must have constituted originally a large proportion of the eruptions, except for the more basic lavas. By far the greater part of them

undoubtedly has been removed by the action of wind and streams, carried off to greater or less distances, re-sorted, and rearranged, mixed with normal sediments, and their volcanic origin more or less obscured by weathering and trituration of the particles. Volcanic ash is a principal source of a large part of the Tertiary formations of the plains. True ash beds are not uncommon, even at long distances from any of the volcanic areas.¹ But most of the material has been sorted and redistributed by streams and wind erosion.

¹ Barbour (Proc. Nebraska Acad. Sci., 1894-1895, p. 12) records their occurrence in all parts of Nebraska except the extreme eastern counties, at distances up to four or five hundred miles from the nearest possible source, derived evidently from the southwest, and interbedded with the Pleistocene loess in such a way as to indicate that the western loess is at least partially æolian. The writer has seen beds of ash interbedded with Upper Miocene fossiliferous beds in western Kansas and western Nebraska, two hundred miles east of the Front Range. The upper fifth of the Bridger formation in Wyoming is chiefly ash beds. They are recorded by Peale as interstratified with various Tertiary formations in the "lake-beds" of southwestern Montana. The reports of the Fortieth Parallel Survey show that a large part of the Tertiary formations in Idaho, Nevada, Utah, and other inter-mountain states is volcanic ash of direct deposition. Frequent references are found in the Hayden Survey Reports.

In the later work carried on over the Cordilleran region by the present United States Geological Survey, references to volcanic ash and "tuff" deposits occur even more frequently.

Turner, 1896, *Sierra Nevada*: 17th Ann. Rept. U. S. Geol. Surv., part 1, pp. 537, 599.

Darton, 1906, *Geology of the Big Horn Mountains*: Prof. Paper, U. S. Geol. Surv., No. 56, p. 67.

Darton, 1905, *Central Great Plains*: *ibid.*, No. 32, pp. 45, 173.

Darton, 1903, *Geol. and Water Resources of Nebraska West of the 100th Meridian*: *ibid.*, No. 17, pp. 35, 42-43.

Veatch, 1907, *Geography of a portion of Southern Wyoming*: *ibid.*, No. 56, p. 90.

Ransome, 1909, *Geol. and Ore Deposits of Goldfield*: *ibid.*, No. 66, p. 66.

Matthew, 1909, *Bull. Am. Mus. Nat. Hist.*, vol. 23, p. 170.

Matthew and Cook, 1909, *ibid.*, vol. 26, p. 362.

O'Harra, *Badland Formations of the Black Hills Region of South Dakota*: *Bull. South Dakota School of Mines, Dept. Geol.*, No. 9, 1910, pp. 61, 66.

Under this process the volcanic ash is progressively converted into normal sedimentary gravels, sands, muds, and clays. But it is a long time before the sorting is as complete as it is with sediments which are themselves derived from sedimentary or metamorphic rocks, in which the sorting process has already separated out these characteristic results of water-sorting action.

Fig. 9. The Washakie, an Eocene formation of redeposited ash. Detail from northwest face of Haystack Mountain.—Am. Mus. Exped. 1907.

How large a portion of the Tertiary of the western plains and deserts is of volcanic material redistributed by water can only be surmised from the very considerable amount which is still recognizably so. It is certain at least that the Bridger and Washakie formations and the Wasatch group in southwestern Wyoming, the John Day and Mascall of Oregon, a great part of the Tertiary of southwestern Montana, the Miocene and Pliocene of northwestern Nevada, the Miocene of several localities on the Plains, are wholly or chiefly redeposited volcanic ashes. On the other hand, the absence of any large proportion

of recognizable volcanic material has been shown in some of the Paleocene and Lower Eocene deposits in the Puerco basin in New Mexico, the Big Horn and Wind River basins in Wyoming, the Arapahoe beds near Denver, Colorado, and the sandstones and gravels in the White River formation, and in many other localities the descriptions of the Tertiary formations indicate that their source was the older sedimentary, not the igneous rocks.

It is perhaps not unreasonable to assume that the Tertiary igneous rocks which cover perhaps one-fourth of the Cordilleran region were accompanied by an almost equally extensive outpouring of ashes, cinders, and pumice, most of which has been removed by wind and water and scattered over all the Western States, and in part carried to the sea margin, the rest helping to build up the continental formations of the western interior. The contrast between the extent and thickness of these formations in the western United States and Mexico and their scantiness in western Canada and along the Atlantic seaboard is thus partly accounted for. Where Tertiary volcanics are abundant, the stratified terrestrial Tertiary formations are extensive and thick. Away from the chief Tertiary volcanic outbreaks, they thin out and disappear.

Pleistocene loess, which is not to any large extent composed of volcanic materials, also thins out in passing eastward over the plains from the Front Range to eastern Kansas and Nebraska, so that it is evidently not safe to assume that this was the chief factor in conditioning these relationships. But it seems safe to conclude that volcanic ash was a more important source of these Cordilleran Tertiaries than has been usually believed.

SEC. II. THE LACUSTRINE THEORY

History of the Theory. All the pioneer geologists who described the Cordilleran formations speak of the Tertiary strata as lake deposits. So far as I understand their views, this was at first rather an assumption than a definitely proposed theory of origin. It is well to remember that in the earlier days

Fig. 10. Wasatch formation in the Big Horn Valley, Wyoming. A Tertiary flood-plain formation with little or no indication of volcanic ash as the source of its material.—Am. Mus. Nat. Hist. Photo No. 35962.

of recent volcanic activity has been shown in some of the Paleocene and Lower Eocene deposits in the Puerto basin in New Mexico, the Big Horn and Wind River basins in Wyoming, the Arapahoe Lake near Denver, Colorado, and the sandstones and gravels in the White River formation, and in many other localities the development of the Tertiary formations indicate that their origin was the older Tertiary, not the Quaternary.

It is perhaps not unreasonable to assume that the Tertiary geosynclines which have produced the great Tertiary basins were formed by an extension of the great Tertiary orogenic movement which has been followed by great and continuous folding over all the Western States, and in part extends to the eastern base of the Western interior. The contrast between the extent of these formations in the western United States and Mexico and their confinement to western Canada and the Atlantic seaboard is thus partly accounted for. The Tertiary volcanics are abundant in the stratified Tertiary formations, and their Tertiary origin is evident. Away from the coast the Tertiary volcanics are abundant, but the Tertiary volcanics are abundant in the Tertiary formations.

It is evident that the Tertiary volcanics are abundant in the Tertiary formations, and their Tertiary origin is evident. Away from the coast the Tertiary volcanics are abundant, but the Tertiary volcanics are abundant in the Tertiary formations.

THE TERTIARY

During the past few years all the prominent geologists who have written on the Tertiary formations speak of the Tertiary as a single period. So far as I understand their views, they are all in agreement in the opinion that a definitely proposed theory of origin. It is not so common that in the earlier days

of geology all sedimentary formations were supposed to have been deposited under water. This was a relic of the old Neptunian theories which viewed the earth as gradually built up by successive upheavals from an all-encompassing sea—a view whose influence is still to be seen in many geologic textbooks. These western Tertiaries were obviously not deposited under salt water, therefore they must have been deposited under fresh water. In the same way we find non-marine formations in the East, such as the Newark, promptly dubbed estuarine. It was not that the idea of terrestrial deposition had been considered and rejected, but simply that it had not entered any one's head that considerable permanent geologic formations could be deposited except in a sea bottom or lake bottom. In just the same way we find the brackish water deposits, which would now be regarded as delta formations, considered at that time as deposited in enclosed seas or semi-fresh lakes. With the progress of exploration, this lacustrine theory came to be more definitely stated and outlined in its application to the Cordilleran Tertiaries. The areas which these lakes must have covered, the length of time through which each endured, their geologic succession and correlation, were estimated upon the data furnished by the Hayden, Wheeler, and King surveys. King, in the final report of the Fortieth Parallel Survey, gives names to each of the successive Tertiary lakes, defines their supposed extent as far as there was any evidence, and points out an important corollary of the lacustrine theory, namely, that since the long gentle slope from west to east on which the Miocene Tertiary of the Plains now lies must have been horizontal when the lake beds were deposited, the western part of the plains must then have been three or four thousand feet lower than its present level, relatively at least to the eastward border of the Plains Tertiary. This was one of the principal points of evidence used to determine the time of elevation of the Rocky Mountains. The Front Range was a sea border near the close of the Cretaceous; it now stands on a platform 5000 feet high; but in the Oligocene the platform was 3000 feet lower, or about 2000 feet.

The careful study by Gilbert and Russell of the two great Pleistocene lakes of the inter-mountain region, Lakes Bonneville and Lahontan, where shrunken remnants now remain in the Great Salt Lake and in various small salt lakes and sinks of Nevada, seemed to support the lacustrine theory of the Cordilleran Tertiaries by the detailed proof that they afforded of extensive lakes in more recent times in the same region. Thus the theory came to be quite universally accepted, and such conservative geologists as Dana, and such conservative palæontologists as Leidy, while they recognized and noted certain stratigraphic and faunal difficulties, did not see in them any reason to reject or modify the theory. For half a century, from 1850 to 1900, it remained in full possession of the field.

Difficulties in Its Application. But towards the end of the last century, several lines of evidence were being brought forward which tended to undermine the lacustrine theory and show that it must be greatly modified if not abandoned in its application to the Cordilleran Tertiaries. The most influential of these I believe was the progress of physiography and its closer relations with stratigraphic geology, as developed especially under the leadership of Davis of Harvard. Professor Davis's illuminating presentation of the methods of erosion and sedimentation now going on over all continental surfaces emphasized especially the importance of stream and river sedimentation as compared with lacustrine, and the true nature of lake deposits. Closely allied were the studies of Gilbert, Russell, and many other stratigraphers of the United States Geological Survey and of various state surveys and universities, and the work of the glacialists both in this country and abroad. All these tended to bring about a better understanding of the real nature and relative importance of sedimentary agencies, whose application to the western Tertiary could not long be delayed.

A second line of evidence was the revival of interest in vertebrate palæontology which began with the founding by Osborn in 1891 of the Department of Vertebrate Palæontology in the American Museum of Natural History, and was followed

in a few years by the founding of similar departments in the Field Museum of Natural History in Chicago, the Carnegie Museum at Pittsburgh, and by renewed vigor in several of the older institutions. This revival, still in progress, has brought about, through exploration of the more promising collecting grounds, a growing appreciation of the close connection between the biologic and geologic aspects of our science. The history of the Tertiary life, the evolution and succession of its faunas, cannot be successfully interpreted unless we understand aright the nature, origin, and succession of the strata from which our records are obtained, and are able to reconstruct with some degree of accuracy the environment in which these faunas lived, and the changes which it underwent. The difficulties already apparent to the judicial mind of Leidy in 1869, in interpreting the occurrence of the White River fossils and the nature and limits of the fauna upon the lacustrine theory, were confirmed and supplemented by the later collectors and students, and appeared inexplicable except by fantastic theories whose improbability was apparent and demonstrable.

A third source of light was the discussion as to the origin of the Pleistocene loess of the Mississippi Valley and the western plains, a formation whose composite nature, mainly fluvial and æolian, is now generally admitted, and which affords a marked analogy to the finer and more widespread Tertiary continental formations.

The gold-bearing gravels of the Sierras had been regarded by Whitney as river-gravels in 1864-1870, and certain coarser phases of the later Tertiaries of Kansas were considered by Gilbert¹ and Haworth² as flood-plain formation in 1896. W. D. Johnson³ in 1901 interpreted the Tertiary of the high plains of Kansas as fluvial in origin. Matthew in 1899⁴ advocated an æolian origin for the Colorado White River, the first attempt

¹ 17th Ann. Rept., U. S. Geol. Surv., part 2, 1896, p. 575.

² 2d Ann. Rept., Kansas University Geol. Surv., 1896, p. 13.

³ 21st Ann. Rept., U. S. Geol. Surv., part 4, 1906, p. 612.

⁴ Amer. Nat., vol. 32, p. 403; Bull. Amer. Mus. Nat. Hist., vol. 12, pp. 25, 26.

to explain the fine-grained phases of the Tertiary upon other than a lacustrine basis. He regarded this formation as analogous to the loess of the high plains. In 1901¹ these conclusions were elaborated and somewhat modified to admit the flood-plain source of a considerable part of the White River as a probable alternative. Davis in 1900² discussed the general origin of the Tertiary basin deposits of the Rockies, explaining them as chiefly due to river aggradation, and only in small part lacustrine. Merriam in 1901³ referred the John Day tertiaries to the aggradational work of rivers instead of lakes. Hatcher in 1902⁴ discussed the mode of formation of the Great Plains tertiaries at considerable length, comparing the conditions during Tertiary time to those now prevalent over the interior plains of Argentina and Bolivia. This veteran collector had long been skeptical of the lacustrine theory. The importance of these continental flood-plain formations has in more recent years been fully elaborated by many able writers, among whom Barrell, Huntington, Willis, and many others have added largely to our comprehension of the subject.

The most serious difficulty in the interpretation of the finer "clays" of the Tertiary lake basins as to any large extent æolian was felt to be the lack of adequate supply of dust to form such extensive loess deposits, if derived merely from the æolian erosion of exposed areas or arid regions adjoining. But the appreciation of the large extent to which these formations are composed of volcanic ash, as brought out by Merriam⁵ and Sinclair,⁶ and more recently emphasized by Osborn,⁷ and the weight laid by Keyes⁸ upon the importance of æolian erosion

¹ Mem. Amer. Mus. Nat. Hist., vol. 1, p. 359.

² Proc. Amer. Acad. Arts and Sci., vol. 35, pp. 345-373.

³ Bull. Dept. Geol., University California, vol. 2, p. 299.

⁴ Proc. Amer. Philos. Soc., vol. 41, p. 113.

⁵ Merriam, *loc. cit.*

⁶ Sinclair, Bull. Amer. Mus. Nat. Hist., vol. 22, 1906, p. 273; *ibid.*, vol. 26, 1909, p. 25.

⁷ Osborn, *The Age of Mammals*, 1910, p. 91.

⁸ Keyes, Bull. Geol. Soc. America, vol. 23, 1912, pp. 537-562.

in arid regions, have brought forward adequate sources of supply. Professor Osborn some years ago was inclined to regard the marked color banding of so many of these Tertiary formations as an argument against their æolian origin, but with his usual openmindedness, he called the writer's attention recently to a series of photographs of recent ash formations in the Philippines in which the color banding was a conspicuous feature.

The mode of origin of the Tertiaries of the Cordilleras is generally admitted today to be chiefly flood-plain sedimentation, true lake deposits playing but a minor part. To what extent æolian sedimentation is responsible is as yet far from clear. From the considerations already set forth, I am disposed to believe that it played a very considerable part in building up the finer and more uniform deposits analogous in character to the loess, and, like it, built up to no small extent by dust deposits upon sodded prairie surfaces.

True lacustrine formations of considerable extent, as distinguished from the temporary lakes or playas formed by the flooding of broad areas with imperfect drainage, are by no means absent. The Green River formation, with its great thickness of widespread, uniformly thin-bedded, calcareous fissile shales, carrying an abundant fish and fresh-water invertebrate fauna, is an example. The smaller Florissant Lake in Colorado, with abundant insect and plant fossils, but no terrestrial vertebrates, is composed of volcanic tuffs, again distinguished by the laminated fissile character of the shales, very different from the so-called clays of the terrestrial Tertiary formations. And among the numerous smaller or larger Tertiary formations in the Basin region which have been uncritically referred to lacustrine agency, there are a considerable number that appear, from the descriptions of their character and location and lists of their fauna, to have been really deposited in permanent lakes. But all these are decidedly the minority. The great bulk of the Cordilleran Tertiary, as also the Pleistocene formations, are fluvial or æolian in origin.

SEC. III. THE SUCCESSION AND CORRELATION OF THE CORDILLERAN TERTIARIES

In considering the source of the western Tertiary it has been convenient to treat it as a whole—as a mantle spread during

Fig. 11. Principal Eocene formations of the Cordilleras, showing their deposition in the intermontane basins.—After Osborn, 1909.

Tertiary time over a large portion of the western continent, and partially dissected and removed by subsequent erosion. In point of fact, it consists of a large number of independent

formations deposited at different times, due to different agencies, or to the same agencies operating independently in different areas.

We must first consider the limitations of these formations or stratigraphic units. Broadly speaking, terrestrial formations differ from marine and littoral in their extremely localized and inconstant character. The agent of deposition of a fluvial formation is a river or rivers coming down from the mountains and deploying upon the plains. Each stream or river is to some extent independent of all the others. Its sources of material are supplied by the uplifting and erosion of the mountains in which it rises or of the higher lying plains through which it flows. The accumulation is caused in many cases by the blocking of its lower course. Great volcanic outbursts may supply material for extensive formations to the rivers which head up into the region where they occur.

The æolian formations are deposited upon the sodded prairies, and the areas favorable for such deposition will be limited by quite another set of factors, by the proximity of grassy plains to wind-swept deserts, by the direction of prevalent winds, by the extent and distance of volcanic sources of supply. Obviously these varying factors do not make for uniformity. There is no one widespread agent like the sea, which can spread a single formation over half a continent, and may even enable us to trace some degree of correspondence in stratigraphic succession over several continents at once.

Extensive movements of continental uplift or depression, widespread changes in climate, may indeed induce a general resemblance of sedimentation over a wide area. But each of the river basins within that area will be partially independent, affected by local conditions, and the æolian phases will be independent of any of the fluvial sedimentary groups, although inextricably mixed with them, and affected likewise by the time and place and extent of volcanic outbursts.

Except upon the great plains, the formations occur today mostly in mountain basins more or less completely isolated. On the plains they are more continuous, but the infinite com-

plexity of make-up of each of these formations laid down by the shifting rivers of an imperfectly drained plain makes it impossible to trace out their stratigraphic relations one to another over broad areas, except in the most general way. The correlation of these formations is, therefore, built up chiefly upon their fossil faunas and floras.

Fig. 12. Correlation principal mammal-bearing formations of the Western United States, Oligocene to Pleistocene. Changes recently proposed in the classification of the European Cenozoic will involve, if generally accepted, material alterations in this correlation. The Upper Uinta will be included in the Lower Oligocene; the John Day and uppermost beds of the Brule will be Lower Miocene; the Upper Harrison, Upper Rosebud and equivalents Middle Miocene; the Deep River and equivalents an early phase of Upper Miocene. The Peace Creek, here reckoned as Pliocene, appears to be rather of Pleistocene age.—After Osborn, 1910.

Principles of Correlation. For purposes of correlation it is commonly assumed that identical or equivalent faunas show that the rocks containing them are of identical age. This assumption is at best only approximately true, and should be used only within certain restricted limits. For the modern faunas and floras of different regions of the earth's surface are

neither identical nor equivalent. The existing animals and plants of some regions differ widely from those of others and are much more nearly allied to Tertiary types. The same is true of different facies of the fauna of a single region. The animals of the swamps or of the wooded river valleys are very different from those of the arid plains. Marine animals are much more widespread than terrestrial, but their faunal provinces are quite as clearly marked and the greater progressiveness of some compared with others is no less manifest.

TWO PLEISTOCENE FAUNAS OF DIVERSE TYPE

CONARD FISSURE, ARKANSAS (forest fauna)

Shrews (*Sorex*, *Blarina*) abundant
 Mole (*Scalopus*)
 Bats (*Vespertilio*, *Myotis*) abundant
 Skunks (*Mephitis*, *Spilogale*, *Brachyprotoma*)
 Fisher Marten (*Martes pennanti*)
 Mink (*Lutreola vison*)
 Weasels (*Mustela*) common
 Gray Wolf (*Canis occidentalis*)
 Foxes (*Vulpes*, *Urocyon*)
 Raccoon (*Procyon*)
 Black Bear (*Ursus*) abundant
 Lynx and Puma (*Felis*)
 Sabre-Tooth Tiger (*Smilodontopsis*)
 Porcupine (*Erethizon*)
 Woodchuck (*Marmota*)
 Squirrel (*Sciurus*)
 Chipmunk (*Tamias*) common
 Gopher (*Spermophilus*) common
 Pocket Gopher (*Geomys*) common
 Beaver (*Castor*)
 White-Footed Mouse (*Peromyscus*) abundant
 Harvest Mouse (*Reithrodontomys*)

HAY SPRINGS, NEBRASKA (plains fauna)

Coyote (*Canis latrans*)

 Short-Faced Bear (*Arctotherium*)
 Lynx and Puma (*Felis*)

 Prairie Dog (*Cynomys*)

 Pocket Gopher (*Thomomys*)
 Giant Beaver (*Castoroides*)

Woodrat (<i>Neotoma</i>) abundant	
Muskrat (<i>Fiber</i>)	Muskrat (<i>Fiber</i>)
Meadow Mouse (<i>Microtus</i>) abundant	Meadow Mouse (<i>Microtus</i>)
Hares and Rabbits (<i>Lepus</i>) abundant	
	Ground Sloth (<i>Paramylodon</i>)
	Mammoth (<i>Elephas</i>)
Horse (<i>Equus</i>) very rare	Horse (<i>Equus</i>) abundant
Peccaries (<i>Mylohyus</i>) abundant	Peccary (<i>Platygonus</i>)
	Camels (<i>Camelops</i> , etc.)
Deer (<i>Cervus</i> , <i>Odocoileus</i>)	Pronghorn (<i>Antilocapra</i>)
Musk-Ox (<i>Symbos</i>)	

TWO SIMILAR FAUNAS OF DIVERSE AGE

PIKERMI (MIOCENE)	CENTRAL AFRICA (MODERN) ¹
Baboons (<i>Mesopithecus</i>)	Baboons (<i>Cercopithecus</i> , etc.)
Short-Faced Dog (<i>Simocyon</i>)	
Marten (<i>Martes</i>)	Moishond (<i>Zorilla</i>)
Badger-Martens (<i>Promephitis</i> , <i>Meles</i>)	Ratel (<i>Mellivora</i>)
Hyæna-Civet (<i>Ictitherium</i>)	Civets (<i>Viverra</i> , etc.)
Hyænas (<i>Hyænictis</i> , <i>Palyæna</i> , <i>Hyæna</i>)	Hyænas (<i>Hyæna</i>)
Sabre-Tooth Tigers (<i>Machærodus</i>)	
True Cats (<i>Felis</i> sp. div.)	True Cats (<i>Felis</i> , sp. div.)
Porcupine (<i>Hystrix</i>)	Porcupine (<i>Hystrix</i>)
Chalicotheres (<i>Chalicotherium</i>)	
Mastodons (<i>Mastodon</i> sp. div.)	Elephant (<i>Loxodonta</i>)
<i>Dinotherium</i>	
Rhinoceroses (<i>Opsiceros</i> , <i>Diceros</i> , <i>rhinus</i> , <i>Acerotherium</i>)	Rhinoceros (<i>Opsiceros</i> , <i>Cælodonta</i>)
Three-Toed Horses (<i>Hipparion</i>)	Zebras (<i>Equus</i>)
Pigs (<i>Sus erymanthius</i>)	Close to Red River-Hog
Giraffe (<i>Camelopardalis</i> , <i>Helladotherium</i>)	Giraffes (<i>Camelopardalis</i> , <i>Okapia</i>)
Antelopes (<i>Palæotragus</i> , <i>Palæoryx</i> , <i>Tragocerus</i> , <i>Palæoreas</i> , <i>Gazella</i> , etc.)	All more or less nearly allied to living African antelopes
Tragulines (<i>Dremotherium</i>)	Tragulines (<i>Hyæmoschus</i>)

¹ Partial list for comparison with Pikermi fauna.

The Tertiary faunas and floras may have been less diversified than those of today, but there is no reason to believe that they even approached uniformity in different regions, or that the differences of facies due to different environments within the same geographic region were any less manifest.

	NEOTROPICAL	HOLARCTIC	ORIENTAL	ETHIOPIAN	AUSTRALIAN
MODERN	<i>Holarctic fauna dominant. A few survivors of the autochthonous fauna.</i>	<i>Man cosmopolitan. Higher Ruminants. Myomorph Rodents. Dogs, Cats, Bears.</i>	<i>Antelopes, Elephants, Cattle, Deer, Rhinoceros. (Fauna of Pliocene and Pleistocene Holarctic.)</i>	<i>Antelopes, Horses, Elephants, Rhinoceros.</i>	<i>Herbivorous and Carnivorous Marsupials. A few Placentals.</i>
PLEISTOCENE	<i>Giant Edentates. Macrauchenia and Toxodon. Holarctic Carnivores & Ungulates.</i>	<i>Man. Modern genera of Placental Mammals. Mastodons, Elephants, Horses, Rhinoceroses.</i>	<i>Elephants, Cattle, Rhinoceroses, Horses, Camels.</i>	<i>Modern genera of African mammals.</i>	<i>Herbivorous and Carnivorous Marsupials.</i>
PLIOCENE	<i>Autochthonous fauna dominant. Earliest invasion of Holarctic fauna.</i>	<i>Mostly modern genera of Placental Mammals. Elephants & Mastodons. Rhinoceroses. Monkeys.</i>	<i>Mastodons, Elephants, Rhinoceroses, Giraffes, Ruminants. 3-toed Horses etc.</i>		
MIOCENE	<i>Peculiar types of Ungulates. Edentates. Marsupial Carnivores.</i>	<i>Modern families of Placental Mammals. Mastodons. Monkeys.</i>	<i>Primitive Ruminants. Mastodons etc.</i>	<i>Mastodons. Rhinoceroses.</i>	
OLIGOCENE	<i>Evolution of peculiar types of Ungulates etc.</i>	<i>Evolution of modern families of placental mammals.</i>		<i>Peculiar types of Ungulates. Invasion of Holarctic fauna.</i>	
EOCENE	<i>Primitive Placental Ungulates. Marsupial Carnivores.</i>	<i>Modern orders of Placental Mammals. Ungulates, Carnivores, Primates.</i>			
PALEOCENE		<i>Primitive Placental Carnivores and Ungulates.</i>			
CRETACIC		<i>Marsupials dominant. No Placentals positively known.</i>			

Fig. 13. Principal characteristics of the Mammalian Faunas of different regions.

Differences between two extinct faunas compared may be due to difference in geologic time, in geographic region, or in environmental facies, or to any admixture of these. Identity of two faunas is a much better test of contemporaneity than diversity of faunas is of difference in age. But even identity may be largely affected by geographic or environmental differences. If a whole fauna, or most of it, disappears from a given locality on account of change in climate, etc., but survives with little alteration in another region where the old environment remains, obviously we shall have in the geologic

record of the two regions nearly identical faunas which will not be of the same age. The degree of resemblance of any modern fauna or flora to extinct faunas of other regions is a test of the degree of weight we should attach to this difficulty. And the distinctions between a modern fauna and extinct ones of other regions which closely resemble it afford the means of distinguishing between synchronous and homotaxial faunas in correlation. Such a fauna surviving in another region does not remain exactly the same. Some of its members do not change appreciably. Others change a little, and a few change to a marked degree. There are usually added to it some survivals of the older faunas of the region, and often some more recent immigrants, while certain groups of the invading fauna are absent, not having left their original home.

It would seem from this that a partial similarity in faunas is not trustworthy evidence of their being of the same age. But on the other hand, such a partial similarity may be due to the presence of a number of wide-ranging cosmopolitan genera which distributed themselves all over the world within a space of time that is geologically negligible, and were hence less affected by environment, while the differences in the faunas compared may be due to local diversity of fauna or varying facies. In such a case the occurrence of these cosmopolitan genera, especially if their geologic range be restricted, may afford the best of evidence for synchronism. Examples of all these principles might be drawn from a comparison of the Tertiary faunas of Europe with that of West and Central Africa. They lead to the conclusion that exact correlation of strata cannot be attained through mere comparison of faunas as respects their degree of resemblance or difference. In the absence of better evidence we may admit such comparisons as giving an approximate and provisional correlation. But it is not exact, unless we are comparing faunas of the same geographic region and of the same environmental phase.

To attain a true correlation, we must study the evolution and dispersal of each race of animals represented in the faunas compared. We must know their place of origin, their methods

and means of migration, the approximate history of their evolution, the environment to which they were at first adapted, and the changed environment to which they later became adapted. The basis of such a study must needs be the approximate correlations of fossil faunas already secured. Its conclusions must be used to correct and modify those approximate correlations.

These considerations are somewhat idealistic at present. They are far from being generally appreciated. Many geologists and some palæontologists are not conscious of any appreciable defects in the current methods of correlation. But in the correlation of Tertiary continental formations, and in the study especially of fossil mammals, they assume a marked importance, and lie back of most of the controversies and unsettled problems in this subject.

Relative Value in Correlation of Vertebrates, Invertebrates and Plants. Fossils are the geologist's timepiece, whereby he is enabled to measure the progress of geologic time, and compare it in different regions. The qualities of a good timepiece vary in importance with the use to which it is put. For some purposes, it is most important that it should be always at hand; for others, that it should be thoroughly reliable; for others, again, great precision is necessary. No class of fossils excels in all these advantages, but the different groups combine them in various degrees.

Obviously it is an advantage to be able to get the evidence whenever it is required, and to get it in abundance. For most stratigraphic work the common fossils must needs be chiefly used; those which are rare or limited in their distribution can less often be found when their evidence is needed. *Abundance* is, therefore, the prime requisite.

The reliability of the evidence depends upon several factors: First, whether the fossil is *characteristic*—easily recognized—so that no mistake is possible even with badly preserved or fragmentary specimens; second, whether its geographic range is wide; third, whether its geologic range is clearly defined and certainly known; fourth, whether its phylogenetic position is

clearly shown in its structure, so that the older species of a group are obviously more primitive, the younger more specialized in their construction.

The precision of the evidence will depend upon the limited range of the fossil in geologic time, that is to say, upon the rapidity of evolutionary changes, of the appearance of new types and extinction of old in the group or phylum to which it belongs.

Invertebrates are the most generally useful of our geologic timekeepers, especially in marine formations. They are by far the most abundant of fossils, and are usually reliable. Their geographic range is wide, their geologic range is usually definite, and their phyletic position oftentimes clearly manifest. The structure of their hard parts, while varying widely in different groups, is simple in comparison with that of the Vertebrata, and their geologic range much wider, the rate of evolution being comparatively slow. They are less characteristic and less precise in their indications. Plants in the non-marine formations are by far the most abundant fossil, and on this account the most generally used in stratigraphic work. So far as the complexity of the parts preserved is concerned, they rank perhaps with the simpler groups of invertebrates, for it is only very rarely that we deal with anything more than leaves. Their geographic range is usually wide. But (with due deference to the claims of palæobotanists) their geologic and phylogenetic positions are, in my judgment, by no means so clearly defined as those of invertebrate or vertebrate fossils. In precision their evidence compares with that of invertebrates, exclusive of the higher groups such as crustaceans and cephalopods.

Vertebrates, especially terrestrial vertebrates, are comparatively rare as fossils, and this fact limits severely their usefulness in correlation. On the other hand, the structure of their hard parts attains a degree of complexity far beyond that of the lower animals and plants. There is as much character, Stehlin justly observes, in a single tooth of a mammal, as in the entire hard skeleton of a mollusc. Hence much reliance can be placed

even upon very fragmentary fossils among Mammalia. Their geographic range is often limited. Few genera, and no species, of mammals, are cosmopolitan. Nor can we always be as certain as we would wish of the true geologic range, especially of the rarer genera. On the other hand, the phylogenetic position of a fossil mammal is usually clear and unmistakable. The later species are clearly derivatives from the older, their position could not be reversed, even had we no stratigraphic evidence to check our conclusions.

Moreover, the mammals afford much more precise correlations than any other group. Their hard parts, highly complex in structure, respond more rapidly to the influence of changing environment and lapse of time. Their evolutionary progress is much more rapid. The geologic range of a genus of Tertiary mammals corresponds roughly with an epoch of this period; that of a species is much shorter. Most of the living genera of invertebrates and plants have endured since the Cretaceous or early Tertiary; many of them are much older.

Owing to the rarity of complete skeletons, the greater part of the records of vertebrate fossils are based upon fragmentary materials. Very commonly a tooth or fragment of the jaw, a vertebra or a limb bone, is the sole basis of such a record. Such inadequately based records must be used with reserve in correlation. The identification may be reasonably safe or it may be essentially provisional. The prevalent custom of identifying such fragmentary specimens by a method of exclusion, or in reliance upon their recorded stratigraphic position, has led often to unfortunate results, through the uncritical use in correlation of faunal lists based upon such provisional identifications. The evidence of a single skull or skeleton may well outweigh that of many such fragments.

All species, whether of animals or plants, are more or less limited to certain environmental facies, and this must always be considered in correlation. Moreover, in all classes of fossils there are some progressive groups and others persistent and slow to change, and the former will have more weight in precise correlation. We may conclude, however, that, as between these

three lines of evidence, the invertebrates will be most generally useful in correlations of marine, the plants in correlation of terrestrial formations, but that the evidence of terrestrial vertebrates, where adequate and properly interpreted, will afford more exact and probably more reliable correlations of epicontinental strata.

Fig. 14. Correlation of the principal sections of the Cordilleran Tertiary.—After Osborn, 1910.

Some slight changes in this correlation, resulting from later discoveries, are shown in Fig. 15.

The correlation of our western Tertiaries has been very thoroughly and authoritatively treated by Professor Osborn in the *Age of Mammals*. His conclusions, shown in this diagram (Fig. 20), are based chiefly upon comparisons of mammalian faunas; the lower vertebrates, invertebrates, and plants do not afford exact or complete data for any precise correlation, but serve in certain cases to confirm or modify the conclusions. The results of glacial geology are of very great value in correlating Pleistocene faunas.

Pleistocene Correlation. The complete correlation of the numerous scattered Pleistocene formations which cover a large portion of the interior basins, plains, and prairies is not yet possible in detail. Here and there where they contain adequate mammalian faunas it may be possible. Where they are related to the better understood glacial advances and recessions, a more certain correlation may be made. *Equus* is the most abundant and widely spread fossil mammalian genus in the earlier Pleistocene deposits, its appearance and extinction the best-known criterion of their age. Species of *Equus* occur in the Pliocene of the Old World, but in this country it is not found in any certain Pliocene beds, and is first represented by large and progressive species. The late Professor Calvin succeeded in 1909 in discovering a typical and fairly abundant *Equus* fauna in the Aftonian interglacial deposits, thus linking up the *Equus* zone with the earliest of the four recognized interglacial epochs. More recently Hay has brought forward evidence that *Equus* did not survive the Wisconsin glaciation, the latest of the glacial advances, and that its abundance in the Pleistocene faunas was limited to the Aftonian. Bisons, on the other hand, were rare or absent in the older interglacial epochs, but abundant in the later ones. The living species of bison, Dr. Hay holds, did not appear until after the Wisconsin glaciation; the American mastodon, the Siberian mammoth, and its close relative, the Columbian mammoth, the giant beaver *Castoroides*, three extinct genera of musk-oxen, and the extinct moose *Cervalces*, all belong to this post-glacial fauna.

According to Hay's division we should have :

Faunal Zones	Localities	Characteristic Mammals
Post-Glacial Wabash or Upper Pleistocene	Peat-bog and post-glacial swamps, typically near Fairmount, Indiana	No horses or tapirs Bisons, modern species Musk-oxen, <i>Castoroides</i> <i>Mylohyus</i> and ? <i>Platygonus</i> <i>Megalonyx</i> (rare) No other edentates. Mastodon and Mammoth
Late Interglacial Sangamon or Middle Pleistocene	?Conard Fissure, Arkansas (Wisconsin auct. Osborn, Illinoian auct. Hay) No typical fauna specified	Numerous bisons of ex- tinct species Few edentates, few horses, few sabre-tooth cats No camels
Early Interglacial Aftonian or Lower Pleistocene	Hay Springs, Nebraska Port Kennedy, Pennsyl- vania Silver Lake, Oregon Peace Cr'k, etc., Florida	Mastodon and Mammoth Numerous edentates, horses, tapirs, and sabre- tooth cats Few bisons <i>Platygonus</i> and <i>Mylohyus</i>

Dr. Hay does not refer to the status of the Rancho-la-Brea fauna, which is difficult to place by the above criteria. This is by far the most complete of our Pleistocene faunas, and if it can be satisfactorily correlated with the marine succession of the Pacific coast will probably serve as a standard for reference and revision of the above classification.

The correlation of the mammalian faunas with the glacial stages is the most important advance of recent years. Dr. Hay's investigations, now in progress, in American Pleistocene faunas will doubtless lead to further satisfactory results. But it must be admitted that the really sound and permanent results in correlation of the American Pleistocene are scanty by comparison with the exact and elaborate scale that has been worked

Faunal Correlation of Cordilleran Tertiary

Tertiary Epochs	Equivalence of Terranes, Formations and Assises				Faunal Zones	Equidae 1 st appearance	
Pliocene	Loup River of Hayden and Leidy	Ogalalla of Darlon	Blanco	Thousand Crk	Glyptotherium	? Equus	
			Snow Creek				
Miocene		Aricaree	Rattlesnake	Republican R.	Hipparion	Hipparion	
			Nebraska	Clarendon			
		Pawnee Crk	Deep River	Ticholepus	Merychippus		
		Mascall	Shreve Crk				
	Oligocene	White River	Brule	Up. Harrison	U. Rosebud	Merychoceros	Parahippus
				L. Harrison	L. Rosebud	Promerychoc.	
John Day					Diceraethm	Miohippus	
				Martin Cañon	Leptauchenia		
Eocene	Uinta	Washakie			Diplacodon	Epihippus	
					Dolichorhin.		
	Bridger				Uintath'm	Orohippus	
				Huerfano	Orohippus		
Eocene	Green River	Lost Cabin	Wind River	Knight	Lambdaeth'm	Eohippus	
	Wasatch of Big Horn Basin	Lysite			Systemodon	No Perissodactyla	
		Gray Bull					
Paleocene	Puerco of Cope	Sand Creek				No Perissodactyla	
		Clark Fork					
Paleocene	Puerco of Cope	Torrejon	Ft. Union		Pantolambda	No Perissodactyla	
		Puerco			Polyastodon		

out in Europe and very generally accepted. This is partly because less attention has been paid to the Pleistocene outside of its glacial formations, partly because the region covered is so much more extensive, and the workers are few in number.

It is well to keep in mind, however, that the classification of the European Pleistocene, precise and elaborate as it appears, and thoroughly correlated with glacial stages and with human cultural stages, is still in no small part a working hypothesis

Correlation of Cordilleran with European Tertiary

<i>Equidae</i> 1 st appearance	Typical Cordilleran mammal faunas	Typical European mammal faunas	European Stages	Tertiary Epochs	
		Val d'Arno	Sicilian		
		? Mont pellier	Astian		Pliocene
		? Casino	Plaisancian		
<i>Hipparion</i>	Blanco Thousand Creek Snake Creek Republican R. Nebraska	{ Pikermi Samos Eppelsheim			
			Pontian	Upper	
<i>Merychippus</i>	{ Pawnee Creek Deep River Mescal Shrop Creek	= Sansan	Vindobonian	Middle	Miocene
<i>Parahippus</i>	{ Upper Harrison Upper Rosebud Lower Harrison Lower Rosebud	? Orleanais	Burdigalian	Lower	
<i>Mionippus</i>	John Day Upper Brule	= St Gerand-le-Puy ? { La Milloque Saint-Henri	Aquitanian	Upper	
<i>Meshippus</i>	Lower Brule	? La Ferté etc.	Stampian	Middle	Oligocene
	Chadron	= Ronzon	Sannoisian	Lower	
<i>Exhippus</i>	Upper Uinta Lower Uinta	? Frohnstetten ? Gypse supérieure	Ludian	Upper	
<i>Orohippus</i>	Upper Bridger Lower Bridger	? Gypse inférieure ? Calcaire gross. sup.	Bartonian	Middle	Eocene
	Lost Cabin	? Calc. gross. infér.	Lutetian		
<i>Eohippus</i>	Lysite	? Sables à Terebines	Ypresian	Lower	
	{ Gray Bull Sand Coulee	{ Argile plastique ③ Lower London Clay	Spargnacian		
<i>No Perisso-</i> <i>dactyla</i>	Clark Fork		Thanetian		
	Torrejon	Cernaysian			Paleocene
	Puerco		? Montian		

subject to modification by future discovery, rather than a proven conclusion.

Tertiary Correlations. The western Tertiary formations appear in some respects much more satisfactorily correlated than the Pleistocene. They form much more definite and clearly limited stratigraphic units. It may be remembered, however, that no attempt is made to subdivide the Tertiary as closely

as we do the Pleistocene. The whole of the Pleistocene, according to Walcott's estimate, is about equivalent to one-thirtieth of the Tertiary.¹ We are well satisfied to divide the Tertiary into four or five main divisions, each with two or three subdivisions. Each of these subdivisions then covers probably more time than the whole of the Pleistocene. The scale of our correlation has evidently changed, and with good reason; for it would be utterly impossible to divide the Tertiary stages to a degree of minuteness corresponding in time ratio to that of the Pleistocene.

The equivalence or succession of the Cordilleran Tertiary formations *inter se* has been pretty accurately determined so far as the principal mammal-bearing formations are concerned. The evidence upon which it rests is set forth in various papers by Osborn and others.

Correlation with the European standard is more difficult. It is obtained chiefly by comparison of the European and American mammal faunas. But aside from the uncertainties attaching to such correlations of faunas in widely distant regions, there are several open questions among European writers as to the placing of their mammal faunas. Moreover, while certain American faunas agree very closely with faunas of the European Tertiaries, others are so different that comparison is difficult; they are perhaps equivalent but not identical.

The identical faunas we have good reason for regarding as synchronous; for the phylogenetic studies of European faunas indicate that they mostly came from Asia, and similar studies of American Tertiary mammals indicate that a large part was likewise derived through successive waves of migration from Asia. If, then, Asia was the great dispersal centre of the Tertiary mammals, the successive waves of migration spreading into Europe on one hand and North America on the other should bring about the simultaneous appearance from time to time in these two continents of a new fauna of common

¹ The disparity is considerably greater than this if the rate of evolutionary change in mammalian phyla be taken as a standard of measurement.

origin. While during the intervals between these migrations the faunas would develop independently in Europe and North America and tend to become divergent, each new invasion would renew the close affinity. These invaders from a common source supply us with fixed points of correlation to which we must adjust the intervening stages in our series.

Fixed Points in Tertiary Correlation. The best of these fixed points in the early Tertiary is the Sparnacian or Lower Eocene. The Argiles plastiques of the Paris basin and the London Clay of the Thames basin have supplied a small fauna which so far as it goes is identical with the Wasatch fauna of America. The genera, *Coryphodon*, *Hyracotherium* (= *Eohippus*), *Pachyæna*, *Palæonictis* are characteristic of our Wasatch, and the species are closely related. Two of them are of families not found in the Paleocene of Europe or America, while *Pachyæna* has a more primitive predecessor, *Dissacus*, also common to both continents. They all, therefore, appear to be Asiatic immigrants.

A second fixed point is at the beginning of the Oligocene. A large increment of new and progressive groups appears at this stage, some of them identical in Europe and America, others closely allied and tending to reunite the faunas which had become quite divergent at the close of the Eocene. The Ronzon horizon in Europe is compared by Osborn with the Titanotherium zone or Chadron formation of the White River group. The appearance of true rhinoceroses (*Subhyracodon*, etc.) of *Entelodon*, *Ancodus*, etc., with closely related species in the two continents, may be noted.

The third point is the base of the Pleistocene, and is dependent upon stratigraphic evidence of the earliest glacial advance in the two regions.

Paleocene Correlation. The correlation of the Paleocene is not quite so clear. The Cernaysien has been compared to the Torrejon on faunal grounds, the genera *Dissacus*, *Arctocyon* (= *Clænodon*) being common or closely related. But the remainder of the Cernaysien fauna does not afford any close comparisons with the large Torrejon fauna. The Fort Union flora is stated by Knowlton to be equivalent to the flora of

Sezanne in the Paris basin and to other European floras assigned to the Paleocene. The Puerco fauna has no European equivalent. It is provisionally correlated by Osborn with the Montien or lower Thanetien, but the single fossil mammal from the Montien is a tibia identified by Dollo as *Coryphodon*, a Wasatch genus unknown in the Torrejon or Puerco, but appearing first in the Clark-Fork fauna at the top of the Paleocene.

CORRELATION OF EOCENE FORMATIONS					FAUNAL ZONES	
OLIGOCENE	CENTRAL WYOMING	WHITE RIVER, S. DAK.			DICERATOTHERIUM PROTOCERAS OREODON	
	White River	Boole Chadron			TITANOTHERIUM	SANHOISIAN
UPPER EOCENE	Uinta		WINTA, UTAH		DIPLACODON	LUDIAN
		WASHAKIE, WYO.			EOBASILEUS	BARTONIAN
MIDDLE EOCENE		U ^{rs} WASATCH L ^o WARRAND	BRIDGER, WYO.	Upper Uinta Lower Uinta	UINTATHERIUM	LUTETIAN
			U ^{rs} BRIDGER L ^o BRIDGER		OROHIPPUS	
LOWER EOCENE	BIG HORN BASIN WYOMING	WIND RIVER WYOMING	EVANSTON, WYO.		LAMBOOTHERIUM	YPRESIAN
	Lost Cabin L ^{ts} ITE GRAY BULL	Lost Cabin L ^{ts} ITE	TYPICAL WASATCH KNIGHT	NEW MEXICO U ^{rs} WASATCH Lower Wasatch	SYSTEMODON	SPARNACIAN
PALEOCENE	CLARK FORK ALBERTA	CENT. MONTANA	S.E. WYOMING	Torrejon Puerco	PANTOLAMBOA	THANETIAN
	PASKAPOO	FT. UNION			POLYMASTOON	? MONTIAN
CRETACEOUS	EDMONTON PIEDRE (INADQ) BULLY RIVER	HELL CREEK PIEDRE (INADQ) JUDITH RIVER	LANCE FOR HILLS (INADQ) PIEDRE (INADQ)	OJO ALAMO	TRICERATOPS	DANIAN
					MONOCLONIUS	ATURIAN

Fig. 15. Correlation of early Tertiary Cordilleran formations, as based upon the vertebrate faunas. Recent data indicate that the Paskapoo is equivalent rather to the Lance than to the Fort Union.

Correlation of the Ceratops Beds. Knowlton, Peale, and others are disposed to include in the Paleocene the Lance, Arapahoe, Denver, Ojo Alamo, Judith River, and Edmonton beds, containing the Ceratopsia and other Dinosaurs and a few mammals. Stanton regards all these beds as uppermost Cretaceous, while Hay is inclined to place the Puerco and possibly the Fort Union and Torrejon in the Cretaceous, drawing the Cretaceous-Tertiary line above rather than below the Paleocene faunal zones.

Eldridge, Lee, Peale, Veatch, Knowlton, and others have reported stratigraphic unconformity between the Laramie

formation and the overlying Ceratops beds, which they regard as of great magnitude and constancy. The flora of the Ceratops beds is determined by Knowlton as closely allied to that of the Fort Union, overlying the Ceratops beds, which in turn is correlated with the Paleocene flora of Europe. He concludes that the flora and the unconformity afford the most competent evidence and that the dinosaurs could have survived into the Eocene in America even though they did not in Europe. Dr. Stanton and Dr. Hay have urged that too much weight should not be attached to unconformities in these delta and flood-plain deposits; that the larger time divisions of geology must needs rest on world-wide changes of fauna, not on stratigraphic unconformities; that the faunal evidence, especially of the higher vertebrates, is very much against the reference of the Ceratops beds to the Eocene, since it is not merely certain dinosaurs but the whole fauna that is of Cretaceous type, and that the fossil plants, while they do resemble Paleocene floras of Europe, cannot be shown to differ from late Cretaceous floras of Europe because there are none with which to compare. They further point out that the Tertiary and modern flora really appeared in the Middle Cretaceous, and that all changes since then have been of quite a minor character, rather in the nature of rearrangement and specific difference than of any radical alteration.

It is not advisable to discuss this question at present, but so far as my own study of the problem goes, I do not see that recent additions to our knowledge have changed materially the *relative* weight of the arguments *pro* and *con*. I anticipate that the final conclusions of the discussion now in progress¹ will leave the dividing line between Cretaceous and Tertiary pretty much where it is today, above the latest dinosaur fauna and below the earliest placental mammal fauna at present known.

Table of Tertiary Correlations. The accompanying tables (pp. 412-413) are substantially in accord with Osborn's full pres-

¹ The principal contributions to the discussion at the Princeton meeting of the Palæontological Society are published in the Bulletin of the Geological Society of America, vol. 25, pp. 321-402.

entation, modified slightly by recent discoveries. The evolution stages of the Equidæ afford a check on which I am disposed to place much reliance. Each new stage in this series appears at a quite definite horizon, abundant from the first appearance, and either disappears with the incoming of its successor, or survives in diminishing numbers, sometimes evolving parallel but less progressive subphyla. There is probably one stage, that of the Middle Pliocene (Blanco), that is not yet definable, from the exceedingly fragmentary nature of the known Equid remains of this stage. The occurrence of *Equus* in the top of the Pliocene is unsupported by positively authenticated records. All the other stages are very clear and definite.

There are several points at which there are differences of opinion as to the correlation of the Cordilleran Tertiaries. Scott is disposed to place the Upper Uinta as Lower Oligocene, considering the whole of the White River as Middle, and the John Day as Upper Oligocene. This view, although tenable twenty years ago when the faunas of the Chadron and Upper Brule were very little known, can hardly be supported in view of the faunal correlations now possible between the Chadron and Ronzon, and between the John Day and the uppermost levels of the Brule, above the Leptauchenia-Protoceras zone.

Peterson, in a correlation recently published,¹ refers the John Day to the Lower Miocene, and the Upper Harrison to the Middle or Upper Miocene, regarding it as equivalent to the Mascall. The reference of the John Day to Lower Miocene is dependent upon the reference of the European Aquitanian (St. Gérand-le-Puy fauna) to the Miocene, and will be considered later; the correlation of the Harrison with the Mascall appears to me wholly untenable, but Dr. Peterson will no doubt publish his reasons for it before long.

The line of demarkation between Miocene and Pliocene is a very unsatisfactory one, partly because our Pliocene is so imperfectly known, partly because of divergent views as to the placing of the European equivalents. Recent discoveries of

¹ Am. Jour. Sci., 1913, vol. 35, p. 352.

Miocene mammal faunas in southern Texas¹ and California² will lead, it may be hoped, to satisfactory correlations with the marine Tertiaries of the Gulf and Pacific coasts, and thus assist in solving the problem. But for reasons stated on pages 406-409, I am disposed to believe that final decisions on exact Tertiary correlations should be based rather upon adequate evidence and more thorough study of the mammalian faunal succession in Europe and in this country than upon better correlation with the marine Tertiaries.

The classification of the European stages is that of Stehlin³ and Depéret.⁴ Opinion is divided in Europe as to whether the Aquitanian should be regarded as Upper Oligocene or Lower Miocene; whether the Pikermi fauna belongs in the Miocene or Pliocene, whether the Sicilian is Pliocene or Pleistocene, whether the equivalents of the Frohnstetten fauna are Eocene or Oligocene, whether the Montian is Paleocene or Cretaceous. In the absence of an authoritative and conclusive verdict, it appears better to hold to the current usage in these as in other questions of classification. If indeed a change is made, it might be better to cut deeper, to treat the Tertiary as some of the older systems have been treated, and divide it into two distinct systems or periods. This solution, by no means new to American geologists, is adopted by Schuchert, 1909, in his *Palæogeography of North America*, and in Haug's recent *Traité de Géologie* (1911). It appears to the writer a more logical arrangement than the current one, but whether geological opinion is yet ripe for the change may be doubted.

¹ Dumble, E. T., in litt.

² Merriam, J. C., personal communication.

³ Stehlin, Bull. Soc. Géol. France, vol. 9, 1909, pp. 488-520.

⁴ Depéret, Comptes Rendus, Acad. Sci., Paris, vol. 141, 1905, pp. 702-705; *ibid.*, vol. 142, 1906, pp. 618-621; vol. 143, pp. 1120-1123.

*Principal Genera of Lower Oligocene (Ronzon and Chadron) in
Europe and North America*

NORTH AMERICAN (CHADRON)	EUROPE (RONZON AND EQUIVA- LENTS)
Marsupialia: <i>Peratherium</i>	<i>Peratherium</i> , <i>Amphiperatherium</i>
Insectivora: <i>Ictops</i> , etc.	<i>Tetracus</i>
Creodonta: <i>Hyænodon</i>	<i>Hyænodon</i>
Carnivora: <i>Cynodictis?</i> <i>Cynodon</i>	<i>Cynodictis</i> , <i>Cynodon</i>
<i>Daphænus</i>	<i>Amphicynodon</i>
<i>Dinictis</i> and <i>Hoplophoneus</i>	<i>Ælurictis</i>
<i>Bunælorus</i>	<i>Proplesictis</i>
Rodentia: <i>Ischyromys</i> and <i>Adji- daumo</i>	
<i>Cylindrodon</i>	<i>Cricetodon</i>
<i>Palæolagus</i>	<i>Theridomyidæ</i>
Perissodactyla: <i>Mesohippus</i>	<i>Palæotherium</i> , <i>Plagiolophus</i>
<i>Subhyracodon</i> , <i>Trigoniās</i>	<i>Ronzotherium</i> , <i>Prohyracodon</i> , <i>Men- inatherium</i>
<i>Titanotherium</i>	<i>Titanotherium</i> , <i>Brachydiastema- therium</i>
<i>Colodon</i>	
Artiodactyla: <i>Leptochærus</i>	
<i>Perchærus</i>	
<i>Entelodon</i>	<i>Entelodon</i>
<i>Bathygenys</i> , <i>Oreodon</i>	
<i>Agriochærus</i>	
<i>Eotylopus</i> , <i>Poëbrotherium</i>	
<i>Anthracotherium</i> , <i>Heptacodon</i>	<i>Anthracotherium</i>
<i>Ancodon</i>	<i>Ancodon</i>
<i>Leptomeryx</i>	<i>Cænotherium</i> , <i>Gelocus</i>

*Principal Genera of Lower Eocene (Sparnacian and Wasatch)
in Europe and North America*

NORTH AMERICA (WASATCH)	EUROPE (SPARNACIAN)
Primates: <i>Pelycodus</i>	
<i>Anaptomorphus</i>	
Insectivora: <i>Diacodon</i>	
<i>Esthonyx</i>	

<i>Palæosinopa</i>	
Condylarthra: <i>Phenacodus</i>	
<i>Hyopsodus</i> , <i>Meniscotherium</i>	
Creodonta: <i>Didymictis</i> , etc.	
<i>Oxyæna</i> , <i>Palæonictis</i> , etc.	<i>Palæonictis</i>
<i>Sinopa</i>	? <i>Argillotherium</i>
<i>Pachyæna</i>	<i>Pachyæna</i>
Rodentia: <i>Paramys</i>	
Amblypoda: <i>Coryphodon</i>	<i>Coryphodon</i>
Perissodactyla: <i>Eohippus</i> (= <i>Hyra-</i> <i>cotherium</i>)	<i>Hyracotherium</i>
<i>Systemodon</i>	
Artiodactyla: <i>Diacodexis</i>	

SEC. IV. THE LIFE RECORD OF THE CORDILLERAN TERTIARIES; ITS INTERPRETATION AND ITS PROBLEMS

Introductory. The record of the terrestrial life of the Tertiary is nowhere so fully preserved as in the Western States. The European record has been more thoroughly studied, but nevertheless it is less complete, and especially in its earlier portions. The only other record of Tertiary land life that is worth comparing with it is in Argentina, and that is in need of thorough and critical revision before its alleged completeness can be accepted. In other regions the record is very defective, chiefly, one may hope, because so small a part of the earth's surface has been thoroughly explored by geologists. In Asia, Africa, Australia, and South America are vast central arid regions where may yet be found series of Tertiary formations similar to those of the Cordilleras. But as yet their geology is very slightly known and their Tertiary land life not at all. We have indeed large faunas from the Oligocene of Egypt and from the later Tertiary of India and other outlying regions in Asia, but it is well to remember that Egypt is not Africa any more than Yucatan is North America.¹

¹ The modern fauna of Egypt is much more nearly related to that of southern Europe and western Asia than it is to that of Central and South Africa; just as the modern fauna of Yucatan is more nearly related to that of South America than to those of the United States and Canada.

The European Tertiary formations have in some respects an advantage over our Cordilleran series. They have been studied by a much larger corps of scientists for a considerably longer period. Further, during the Tertiary, Europe was an archipelago, much as the East Indies are today, and its land areas were continually shifting and changing in extent and position, so that the terrestrial and marine formations are intercalated one with another to such an extent that they can be very exactly correlated. Our western Tertiaries, on the other hand, are widely separated from the marine or littoral formations of the Atlantic and Gulf coasts, and on the Pacific coast the violent disturbances and heavy faulting of the continental margin have made it difficult to correlate the marine and littoral formations with those of the interior. While the fossiliferous terrestrial formations can be correlated exactly and certainly with each other, their correlation with the marine series and with the European standards of nomenclature is much more difficult. The margin of possible error is not large, where we have an adequate mammalian fauna. But such differences of opinion as do exist relate to this question, not to the true succession of the vertebrate faunas, which is settled beyond any reasonable doubt.

Degree of Imperfection of the Record. How near does our record come to being complete? We do not, of course, expect that the known fauna includes all or nearly all of the animals that were living in North America during the Tertiary. But does it include most of the species then living in that part of the continent; or is it even fairly representative of them? This question can only be answered by inference. We may assume that the fauna and flora of the western United States was about as large and varied in any Tertiary epoch as it is today. If so, there must have been about 300 genera and 1500 species of land vertebrates living at any one epoch. The White River Oreodon zone fauna, the largest of our Tertiary lists, gives

A full knowledge of the fauna of Yucatan would give us a very partial and misleading idea of the fauna of North America as a whole. Corresponding relations hold good for India in its faunal relation to the main mass of the Asiatic continent.

about 50 genera and 125 species or perhaps one-sixth as many genera and one-twelfth as many species as we may conclude were living in North America (north of Mexico) at that time. The Torrejon, another large and varied fauna, is only half as large.

Difference in Different Groups. The mammals indeed are much better known proportionately, and examination of the comparative numbers in different orders of mammals would indicate that we do have a fairly complete acquaintance with the larger genera of mammals—such as belong to the Ungulates and Carnivores. But as regards small mammals and reptiles, the list is evidently very incomplete, while the flying animals, bats, and birds are quite unrepresented in it, as are also the Batrachia, and the fishes are practically absent.

Allowance must doubtless be made for the finer distinctions made between genera and especially between species of modern vertebrates. But on the other hand, many of the fossil genera and species of our lists rest upon very inadequate evidence and are of doubtful validity, and these objections do not affect the disproportion of numbers in different groups of animals. We must conclude that our fossil faunas give at best a very incomplete and partial representation of the land vertebrates of the time, chiefly representing the terrestrial and fossorial vertebrates of large or medium size.

Invertebrate Record very Scanty. If we turn to the invertebrates and plants, the representation is pitifully small as compared with the enormous numbers of these classes. I have not at hand the figures for an exact comparison, but it is safe to say that the largest known fossil fauna¹ is not one per cent of the living fauna in any class. The representation is equally disproportionate in different groups, as, for instance, may be judged from the relative abundance of arborescent dicotyledons in any of the described Tertiary floras.

What Portions of Faunas are Preserved in Different Types of Formations. The reasons for the defectiveness of our record are not far to seek. Our Tertiary formations were deposited in

¹ Of the continental tertiaries. Marine faunas are far more complete.

a limited number of ways, lacustrine, fluvial, flood plain, and æolian, each environment favoring the preservation of certain groups of animals and plants, while many important groups would rarely or never be preserved. In the river flood plains and loess the bones of vertebrates and sometimes the trunks and leaves of trees, less often the remains of herbaceous plants, or the shells of land and fresh-water molluscs, were entombed and preserved, rarely anything else. In lake or pond deposits, the remains of fishes, of plants growing along their margins, of aquatic molluscs, and sometimes of a great variety of insects would be preserved, especially when the ashes from volcanic eruptions in the neighborhood were contributing to the formation. Birds, especially aquatic birds, might be preserved under such circumstances, but thus far have very rarely been found in the Cordilleran Tertiaries.

When Negative Evidence can be used. So far as the flood-plain and loess formations are concerned, we have a remarkably complete series of strata accumulated under similar or nearly similar conditions through all the Tertiary epochs. The same groups of animals or, at all events, groups of similar habitat and adaptation are preserved throughout. Of these groups, we can trace the evolution and phylogeny from beginning to end. Furthermore, we can reasonably infer that the absence of a certain group of animals in a fauna, while it is abundant in later or earlier faunas, all derived from formations of similar origin, does really mean that it was not present in the fauna of that epoch. Thus we are justified in concluding that the absence of ancestral Perissodactyls, Artiodactyls, Rodents or Primates in the Torrejon fauna, while they are abundant in the Wasatch faunas, means that they had not yet arrived in the Cordilleran region; that the absence of Titanotheres after the Lower Oligocene means that they became extinct—in that region at least—at that time. But we cannot make such inferences from the absence of bats, of birds, of batrachians.

Tertiary Evolution of Mammalia Contrasted with Other Groups. The Tertiary is peculiarly the period of mammalian evolution. The amount of change in structure, habits, and

Fig. 16. The recent origin of the principal existing genera, families and orders of mammals and birds is contrasted with the much greater antiquity of the lower vertebrates, invertebrates and plants.

variety which took place among mammals is in striking contrast to the slight changes which we find in the lower vertebrates, invertebrates, or plants. Many of the genera of reptiles have survived since the beginning of the Tertiary with no more than specific change; many genera of fishes are as old or older; and the same is true of invertebrates to a still greater degree. The modern genera of dicotyledonous plants date back in large part to the mid-Cretaceous; the inferior classes are of much greater age. In contrast to this, we find that the mammalian genera are seldom more ancient than the Miocene, that the mammalian families were first differentiated during the Eocene or later, and even the orders probably began their differentiation about the end of the Cretaceous or beginning of the Tertiary. The difference between the mammals of any two successive epochs is as great as, or greater than, the difference between the reptiles, invertebrates, and plants of the end of the Cretaceous and those now living.

It is this rapid divergent evolution and adaptation of the mammals, this deployment of the order, as Chamberlin aptly phrases it, that characterizes the Tertiary as the Age of Mammals. The order had originated long before, as far back as the Triassic at least. But it had remained an unimportant, or at least little known, part of the land fauna until the extinction of the Dinosaurs at the end of the Cretaceous. Then the mammals commenced the great expansive movement of divergence and adaptation to various specialized modes of life that culminated in the numerous and widely different races of the present day.

Causes of Tertiary Deployment of Mammals. The fact of this great Tertiary deployment of the Mammalia is patent; its causes are obscure and but imperfectly understood in the light of our present knowledge. The movement parallels the earlier deployment of the reptiles during the Mesozoic; but it is by no means clear that it was accompanied and caused by parallel changes in the physical environment. It has been very generally associated with the appearance and expansion of the higher modern types of vegetation. But so far as the records go, these

Fig. 17. Deployment of the Mammalia during the Tertiary Period.

appeared and became dominant considerably before the expansive evolution of the mammals began. Certainly the expansion and evolution did not go hand in hand, as one might expect if they were correlated changes. We may grant that the evolution of modern mammals was dependent upon the existence of the modernized flora. But other factors evidently deferred the initiation of their evolution until long after the modern flora in all its essentials had originated and become dominant. Among these other factors two are recognizable as probably important—the existence of land reptiles (dinosaurs) filling the place in the environment which the mammals were to occupy later; and the restricted area of dry land during the middle and later Cretaceous, and uniformly warm, humid climate, and presumable prevalence or even universal covering of swamp and forest.

The mammals, warm-blooded and protected by a coat of hair, would seem to be primarily a group of animals able to withstand the cold and the varying temperature of an open country in which the cold-blooded, scaly, or naked reptiles could not maintain a continuously active life.

The birds, too, if I interpret aright the significance of their fundamental characters, were primarily a group adapted to withstand cold and variable climate, and although we have little direct evidence as to the date of evolution and expansion of the modern groups, it is probable that it took place coördinately with the mammalian deployment; for all the widely varied orders of modern mammals display in their anatomy a fundamental resemblance that indicates a relatively close affinity as compared with the orders of reptiles, and this appears to be at least equally true of the modern orders of birds. In both cases, it is probably dependent upon the relatively recent origin of their ordinal differences, as compared with the much more fundamental distinctions between the orders of reptiles, fishes, or of invertebrates.

The ancestral mammals, the ancestral birds, were two among the numerous ordinal groups into which the reptiles diverged during the Mesozoic, but were adapted, as the other reptilian orders were not, to withstand and prosper in an environment of

cold or varying temperature. During the Tertiary each of these groups underwent a great expansive and progressive evolution, correlated, so far as we can understand its causes, with the great expansion of the dry-land areas and the progressively cold and arid climatic change which culminated in the Great Ice Age. Most of the other reptilian orders became extinct. The surviving groups continued on with but little change, except that they became more and more restricted to tropical environment or were compelled to become dormant or torpid during the cold season, which they were unfitted to withstand in activity.

Both in mammals and birds the protective coat made it possible to maintain a constant and uniform high body temperature, and hence to evolve a more active circulation of the blood. This in turn led to the evolution of the higher type of brain, which is the real basis of the dominance of these higher vertebrates. The progressive development of higher intelligence which we witness among the successive mammalian faunas of the Tertiary is the most important element of their evolution. But it is well to remember that it was dependent upon the more rapid and perfect circulation of the blood, and that this in turn was conditioned by a protective covering which would allow of a uniformly warm body temperature. For in this light we can appreciate why it was that the mammals, after playing a minor and subordinate rôle during the Mesozoic, evolved and expanded during the Tertiary into so great a variety of diverse and progressive groups, while the changes in the lower vertebrates, invertebrates, and plants were relatively small. The current explanations of this impressive feature in the history of life attribute the expansion of the mammals to the appearance of the flowering plants and to the extinction of the dinosaurs and other ancient reptilian orders. But these factors alone do not solve the problem. The fundamental causes, as I see them, lay in the physical environment and its changes; the changes in the biotic environment were conditioned by these.

Relative Antiquity of Different Groups of Animals. In the accompanying table (Fig. 16), the geological range of a few typical dominant land animals and plants of the northern world

is given. The contrast between the range of the Mammalia and that of the lower vertebrates and invertebrates or plants is obvious. The genera selected are widespread, dominant types of the modern flora and fauna of the northern world. There are of course in each class genera of much greater antiquity which still survive, especially in tropical and southern regions. But they would not alter materially the relative antiquity of the lower animals and plants as compared with mammals (and, so far as our imperfect data go, with birds).

We know enough of fossil mammals to be able to trace approximately the origin and differentiation of the chief modern orders, families, and genera. It may be said, with little margin of error, that the differentiation of the modern orders began about the end of the Cretaceous, that the differentiation of the families began in the Eocene, that the modern genera first appeared in the Miocene and Pliocene.

With the lower animals and plants we are by no means so certain. Their geologic record is much less complete—at least as regards land animals—in comparison with the numbers and variety of the living forms. And the parts preserved are much less characteristic, and hence are not so certainly referable to the genus or even to the family or order. For the history of their evolution we are very largely dependent upon the comparative anatomy of the living forms, and our theories are not sufficiently checked by palæontology.

Centres of Dispersal. The evolution of a race, to whatsoever cause or causes we ascribe it, does not take place simultaneously and uniformly over all parts of the earth. It will be more progressive in certain regions, where the new environment appears at an earlier date, or where animals existed better fitted to adapt themselves to the oncoming conditions. Some one region there will be where the new environment first appears and where the race is earliest adapted to it. The progressive stages will tend to spread out from this centre, displacing the older stages in the evolution of the race. But while the new stage is spreading out over other regions, it will also be progressing in its centre of dispersal to a more advanced stage,

which in turn will spread outwardly. We must conceive of the evolution and dispersal of a race as a series of waves of migration spreading outward from the region most favorable to its early development.

Fig. 18. Zoölogical Regions of the Earth, on a North Polar Projection, showing the true relations of the northern continents which are united in a single irregular land mass, from which the southern or peripheral continents project as peninsulas. The areas of shallow water, less than 100 fathoms in depth, are left unshaded; the shaded oceans are sharply differentiated by the continental shelf and have an average depth of two miles; but very little of the shaded area is less than 1000 fathoms in depth.

Other things being equal, a large region is likely to produce more and higher progressive types than a small one, simply because there are more individuals or more species to compete. Continents are more generally centres of dispersal than islands, large areas of uniform physical environment than small ones.

Moreover, we know that during the Tertiary period there has been a slow progressive change in climate from relatively uniform warm and humid all over the world to the present cold climates at the poles and arid conditions over large parts of the earth. This has been associated with extension of the land areas and elevation of the mountain regions, and its culmination was reached in the Glacial Epoch. The new conditions of cold climate and violent seasonal change appeared first at the poles and thence spread outwards; while the arid conditions were more advanced in the interior of the great continents, where the mountain ranges of their borders cut off the rain-bearing winds. The progressive fauna and flora, adapted to these new conditions of cold and aridity, would naturally appear first in the arctic and cold temperate regions and in the arid interior of the great continents, spreading thence over the rest of the world.

If we consider the arrangement of the land areas of the earth, including with the land shallow areas as far as the continental shelf (the 100-fathom line), it will be obvious that the northern continents, Europe, Asia, and North America, constitute a great central land mass connected by bridges of land or shallow water with the outlying continents of Africa, South America, and Australia. A large part of the northern land area lies within the temperate zone. The southern continents, on the other hand, are separated from each other by wide stretches of abyssal ocean, and only a small part of their area lies within the temperate zone.

Dispersal Chiefly from Holarctic Centres. The northern continents, therefore, afford more favorable areas for the progressive evolution and dispersal of Tertiary animals. When united by emergence of the shallow seas they constitute a great central northern land mass whose fauna and flora should be more progressive than those of the tropical and southern peripheral regions, and would tend to overrun those regions whenever a land connection permitted. When the continents were less fully emerged from the ocean, the northern land mass would be split in two, and the southern continents isolated. Under these conditions Asia and North America would tend to evolve parallel

but distinct faunas and floras, and each of the southern continents would evolve its biota independently, but more in adaptation to tropical than cold climates, and hence less progressive and less exactly parallel with the northern evolution during the Tertiary. The reunion of these independent centres of evolution and dispersal would result in the intermigration and admixture of the various races evolved in each region, but

Fig. 19. The Southern Continents, South Polar Projection, showing the continental shelf completely surrounding and isolating them, in contrast to the union of the northern continents. The progressive shading indicates depths up to 1000, 2000 and 3000 fathoms; less than 100 fathoms is left unshaded.

the more progressive faunas of the larger northern centre of development would tend to take the upper hand, and displace the faunas of the southern regions.

These general conclusions are fully illustrated in what we know of the origin and dispersal of man and of Tertiary animals and plants. The Holarctic region, comprising Asia north of the Himalayas, Europe and northern Africa, and North America, is today the home of the most progressive and dominant races, and is the centre from which most cosmopolitan races have spread. And in the Holarctic region, Asia, the largest of its sub-regions, appears to be the chief centre of dispersal, North America being the second, and Europe and northern Africa third in importance.

Effect upon the North American Tertiary Succession. Applying these generalities to the evolution of the Cordilleran Tertiary faunas, we expect to find it consisting in part and at times of races locally evolved, or at least evolved in North America, but in greater part of a succession of invasions of new and progressive types migrating from the north, either from the northern portion of our own continent or from northern Asia. Where the invasion is from a dispersal centre not far distant, we may expect to find that the new stages have been represented in the preceding fauna by nearly related types, more primitive but not directly ancestral. Where the invasion is from a more distant region, or where the course of migration has been hindered for a longer time by barriers of some kind, we may expect that the newly appearing types will be but distantly related to their predecessors and much more progressive. These relationships, considered in comparison with the evolution of the same or similar races in India to the south, and in Europe to the west of Asia, afford a clue to the centre of dispersal of each race, and to the union or separation of North America and Asia. The relations of the successive faunas of North and South America afford similar evidence as to the connection of these continents and the origin of their faunas.

Our Tertiary record gives us in some phyla the direct or nearly direct history of the local evolution of the race. In the

majority it is the record of a series of successive migrating stages from some more or less distant centre of dispersal.

The Paleocene Formations. The earliest of the western Tertiary formations is the Fort Union, covering a wide area in Montana, Wyoming, and the Dakotas, and with outlying equivalents in the Paskapoo of Alberta,¹ and the Puerco and Torrejon in New Mexico. These formations cover collectively a great area; they attain a thickness of 300 to 2000 feet and contain very considerable coal beds. The mass of the formation is sandstone and finer arkoses, prevalently dark and fine grained in its lower portions; so distinctively so, that the name of sombre beds is widely used. Its relations to the underlying Lance, which forms the latest member of the Cretaceous as here divided, are said by Knowlton to be very close, so that this author regards the two as a continuous formation. This has been disputed, and it is certain that the relations of the New Mexican and Canadian equivalents to the underlying Cretaceous are not remarkably close. Whether or not there is any considerable stratigraphic break, the origin of the formations is similar. Both are evidently river-deposited sediments accumulated on the lower flood plains and flooded deltas but little above sea-level. The frequent lignite or coal seams, the generally fine-grained widespread uniform character and prevalent dark color suggest conditions such as prevail today in the lower Mississippi or Amazon.

Such a deposit must have accumulated slowly. There is no evidence so far as I am aware of any considerable volcanic constituent or great physiographic changes during this epoch. Hence we may conclude that the Fort Union and its equivalents were slowly deposited and that their accumulation may cover a fairly long period of time. Their close association with the Lance and associated formations indicates that no widespread mountain-making movement separated the two. The substantial

¹ A small collection of fossil mammals from the Paskapoo, studied since these lines were written, indicates that it is older than the Torrejon and Puerco, probably equivalent to the Lance in age, but like the Fort Union in facies.

identity of the flora points to the same conclusion. Dinosaurs, however, are found universally abundant up to a certain level, above this no trace of them. With the dinosaurs is found a mammalian fauna of archaic type and containing no known placentals. In the Fort Union no trace of dinosaurs is found, but at various levels, and especially near the top, fossil mammals have been found. A considerable fauna is found at one locality, but it has not been fully described; it is certainly equivalent or nearly related to the Torrejon fauna. But our chief dependence for the fossil mammals is on the Puerco or Nacimiento formation of New Mexico, which has yielded two large and varied faunas, one in the upper, the other in the lower, part of the formation.¹ These faunas, the Torrejon and Puerco of later writers, are quite distinct and of very different type from the mammals of the Triceratops zone or Lance formation.² They are predominantly placental mammals not derived from nor nearly related to anything in the Lance. In the Puerco, there is a considerable element of the Multituberculates which may be regarded as derived from the corresponding group in the Lance; but if this be so, there is a very considerable time break between them. The Multituberculates survive into the Torrejon in smaller numbers, and a few specimens have been found in the lowest beds of the Wasatch group above the Paleocene.

The sharp break in the characters of the mammals is best explained as due to migration; a new fauna appearing of whose time and place of development we know nothing except inferentially. I think it most likely that the whole fauna excepting probably the Multituberculates was either immigrant from some other region or represents an environmental facies that has not been discovered in any Cretaceous formation.

¹ The latest work indicates that there are four fossiliferous horizons, but the differences in fauna cannot yet be stated.

² And also of a facies somewhat different from the Fort Union. The indicated conditions of deposition were less swampy, more of fluvial type.

Characters of the Paleocene Fauna. However this may be, the Paleocene fauna and flora are of very remarkable interest. The flora is quite modern in aspect. Nearly all its plants belong to living genera, a few to living species. But the modern species most nearly related now belong mostly to a warmer and more humid climate. They are found especially in the lowlands of the Gulf and Atlantic coasts of the United States. The fresh-water Mollusca are equally modern in type and closely allied to the living species of the Mississippi and Ohio basins. The Reptilia are very imperfectly known. The crocodiles belong to the modern genus, which appeared in the Cretaceous, and survives to the present day with little change except that it is now restricted to more tropical regions. A peculiar type of reptile, *Champsosaurus*, is present, apparently aquatic and fish-eating in its habits but very remotely allied to any living reptiles. These reptiles are found only in the late Cretaceous (Belly River, Judith River, Lance), and Paleocene (Puerco, Torrejon, Fort Union, Cernaysien, Paskapoo). Nothing is known of their earlier evolution. Presumably they are an aquatic offshoot of the Rhynchocephalia,¹ and thus distantly related to the rock-lizard of New Zealand.

The turtles belong to both Cretaceous and Tertiary groups. The primitive group of Amphichelydia, chiefly Mesozoic, survived into the Paleocene and Eocene, and is nearly related to the modern fresh-water turtles of the southern continents (Pleurodira). The Dermatemydidae are another group chiefly Cretaceous and continuing in diminished numbers in the early Tertiary, but still surviving in Central America. But we find

¹ I use this term in a very broad sense. It is doubtful in Broom's opinion whether the various Permian and Mesozoic genera which have been placed in this order are at all nearly related to *Sphenodon* or to each other. But they do indicate that during the Mesozoic there were several groups of land reptiles analogous to the modern lizards, and perhaps numerous and varied, but very little known as fossils because of their terrestrial habitat. I have elsewhere urged that we know very little of the upland life of pre-Tertiary time, because the formations in which this record would be chiefly preserved have been mostly removed by erosion and redeposited as swamp, delta, and littoral formations.

with them turtles nearly allied to the modern soft-shelled turtles (*Trionychidæ*), which first appeared in the Upper Cretaceous. The tortoises and marsh-turtles common in the Eocene and later formations had not yet appeared (no *Emydidæ*, no *Testudinidæ*).

The mammals are numerous and varied, some forty genera and some seventy to eighty species being known from the Puerco and Torrejon alone; and the undescribed Fort Union fauna and new collections from the New Mexican region will probably enlarge the list materially. They are dominantly placentals even in the Puerco, overwhelmingly so in the Torrejon. The *Multituberculates*, usually considered to be marsupials, are highly specialized survivals of a group characteristic of the Mesozoic, and unknown after the Paleocene.¹ The placentals, on the other hand, are very primitive and generalized. They are all rather nearly related to each other, and difficult to place in any of the specialized groups or orders into which the later Tertiary and modern placental mammals are divided. None of them are very large, the largest not exceeding a mastiff in size. They all have short-crowned teeth adapted to omnivorous or fruit-eating habits, short limbs, long heavy tails, five-toed feet. They are all small brained as compared with almost any modern placental mammal, or even with most modern marsupials. Broadly speaking, these Paleocene placentals represent the ancestral group from which the modern mammals are derived, but in detail they are not ancestral to any of the placental races of later Tertiary and modern times. We can trace the ancestry of various phyla more or less exactly down to the Lower Eocene, but we have failed to find Paleocene ancestors for any one of them. Some of the Paleocene races survive into the Eocene, but none of them later. The direct ancestry of the later Tertiary mammals we shall no doubt find in some region, perhaps Asia, as yet unexplored. The placental mammals of the Cordilleran Paleocene, as I interpret them, are the first of the successive

¹ Save for three specimens found at the base of the Wasatch by Mr. Granger in 1912-1913.

waves of migrating faunas derived from that unknown centre of dispersal.

Adaptation and Environment of Paleocene Mammals. These Paleocene placentals then do represent as a whole (although not in detail) the type from which the various specialized races have been derived. In attempting to understand the evolution of these races, it must be kept in mind that they are all modified from this type towards whatever changed organization may be adapted to their special needs. The modern Carnivora have perhaps departed less than any other of the descendant groups from this primitive type. In these and also in the Primates, the most important changes are in the much larger brain and higher intelligence, and the perfection of the mechanism of limbs and feet for the varied uses—walking, fighting, climbing, prehension—that they serve in these orders. Most of the Carnivora have become more strictly flesh-eating or predaceous; most of the Primates have become strictly fruit-eaters, and more completely arboreal. But on the whole these two orders are the nearest modern analogues. The insectivores, as an order, are less specialized than either, but the living insectivores are each quite highly specialized in diverse and unusual directions. I am more disposed to think of these, our distant ancestors, at the dawn of the Tertiary, as a sort of hybrid between a lemur and a mongoose, rather catholic in their tastes, living among and partly in the trees, with sharp nose, bright eyes and a shrewd little brain behind them, looking out, if you will, from a perch among the branches, upon a world that was to be singularly kind to them and their descendants. When in the Paleocene we first set eyes upon them, a kindly providence, working through we know not what natural means of extinction, had just removed from their path the huge and horrific dinosaurs which had terrorized the world for so many ages. The slow lumbering crocodiles and turtles were probably an object of contempt, spiced, however, with a certain watchfulness. Even the quick-moving but brainless lizards were no match for the intelligent activity of the little mammals. Only the birds, remote relatives, but equally endowed with intelligence, equally quick and active,

might dispute the mastery of the land world. But these, deeply absorbed in perfecting their flight, in solving the problems and mysteries of aërial navigation, aimed at the conquest of the dominions of the air, and left the mammals to rule over the land, only reserving to themselves a few coaling stations, as it were, among the trees and elsewhere on the land, and picking up any unappropriated islands of the ocean where the mammals had not made good their territorial claims by occupation and settlement.

General Direction of Tertiary Mammal Evolution. From this beginning in the Paleocene we trace the evolution of the mammals through the Tertiary in an ever increasing diversity of structure and adaptation, in an ever increasing dominance of the fauna of the open plains, of arid regions, and of cold climates over the fauna of the tropic forests, which more nearly retained the original environment and primitive structure and habits. Studied in detail, it is a history of immense complexity, of the interaction of numerous changing factors of environment—geographic, climatic, biologic—affecting and controlling the evolution of each race, for the full understanding of which our documents are far from sufficient. Race after race we see assuming adaptations of more or less similar types, each a little better equipped than its predecessor, each more specialized for its mode of life, culminating—if indeed it be a culmination—in the finished mechanism of the various kinds of modern quadrupeds. And through all the adaptive divergences we see a steady, continuous improvement in the size and quality of the brain, more marked in some races than in others, but rarely if ever lacking, raising the mammals continually higher above the semi-automatic and instinctive life of the lower animals toward the intelligent and reasoning activities attained by man.

Brain development, involving the coördination of the animal mechanism, is the slowest phase of evolutionary progress. But it is the one in which superiority is most advantageous to the race under all conditions of changing environment, and in the long run must lead to dominance. We see again and again in the history of life how readily the higher brained types can

assume the mechanical adaptations for some new or long-forsaken mode of life and become dominant over lower-brained types whose adaptation of body and limbs had been perfected by a much longer residence in the environment. The mammalian brain is the fundamental basis of the dominance of this class of animals. The latest stage of its evolution shown in man, leading to an actual control of the environment, progressively more complete, opens a wholly new chapter in the history of life—the Psychozoic Age, as Le Conte aptly called it.

Fig. 20. Geographical Distribution of the Primates, living and extinct, and their indicated dispersal from Holarctica.

Characteristic Features in the Evolution of the Principal Orders of Placental Mammals. In the foregoing pages I have attempted to outline various problems relating to the stratigraphy and correlation of our western Tertiary formations, the

general principles of evolution and dispersal of the Tertiary mammals, the character and environment of those which lived at the dawn of this period, and their relationship to the successive faunas which subsequently inhabited this country. I conclude with a brief review of the evolution, group by group, of the various races of mammals in Tertiary North America, pointing out the most obvious features in the record of each group, commencing with the Primates.

Primates. This order, including lemurs, monkeys, apes, and man, is naturally the one whose evolution is of greatest interest to us.

So far as man and his immediate ancestry are concerned, the New World has supplied no important evidence. No early Pleistocene man, no Tertiary anthropoids, have been found in this country. It is possible that they may be at some time in the future, but at present the record is negative.

On the other hand, the older stages of Primate evolution, during the Eocene, are richly represented in the western faunas, while very scanty and fragmentary in the Old World. The collections, especially of Yale University and the American Museum of Natural History, contain a large series of Eocene Primates, chiefly from the Bridger and Wasatch formations. These collections have been in part studied by Marsh, Cope, Wortman, and others, but are very imperfectly known to the scientific world.

Of the two divisions of living Primates, the Lemuroidea, lemurs and their allies, are much more primitive than the Anthropeidea, including monkeys, baboons, apes, and man, but they have certain specialized characters which prevent our regarding them as direct ancestors of the higher Primates. The lower incisor teeth project forward instead of upward, and the lower canines are like these incisors, while the first premolar has taken on the form and functions of a canine tooth. In this, as in some other characters, the living lemurs are off the direct line of descent.

The best-known Primates of our American Eocene are the Notharctidæ or Limnotheriidæ. Of these animals, we know the

Fig. 21. Affinities and Derivation of the Living and Extinct Groups of Primates.

entire skeleton, so that we can estimate their affinities quite exactly. They are very like the modern lemurs in skeleton, and even more primitive in skull construction, but they lack the special characters which prevent us from deriving the higher Primates from the modern lemurs. It is not probable that they were the ancestors of the Old World monkeys, but the New World monkeys may be descended from the Notharctidae, and the Old World monkeys are probably descended from animals very much like them and nearly related. Another group of Eocene Primates is the Anaplorhynchidae, tiny animals mostly known only from the jaws, although a single skull has been found. These appear also to be in the Lemuroid stage of evolution, but more progressive and perhaps nearer relatives of the unknown Eocene ancestors of the Old World monkeys. But until we know more about their skeleton, or study and compare more thoroughly the specimens that are at hand, the true affinities of these animals remain in dispute. They are apparently related to the living tarsier of Malaysia, which is considered by some authorities a primitive survival of the

monkeys, by others a very progressive lemur. The difference in opinion is not so wide as it seems, if we consider the lemurs as aberrant survivors of the ancestors of the monkey group. Either way, it is an intermediate form, a synthetic type, and so apparently are these little Anaptomorphidæ, only their geological age allows us to regard them as not far distant from the direct ancestry of the higher group.

These two groups, Notharctids and Anaptomorphids, are unmistakable Primates. They have the characteristic features of the order in brain, teeth, limbs, and feet, the opposable inner digit of hand and foot, nails instead of claws upon the toes, etc. There are, however, several other groups of small animals in our Eocene and Paleocene, which are apparently or truly intermediate between Primates and Insectivores. Their position in one or the other order is disputed, and what we know of them shows that they are more or less synthetic types, indicating the derivation of the Primate order from the more primitive and lowly order of Insectivora. Such are the Apatemyidæ and Mixodectidæ, rare and imperfectly known groups, and certain rare and minute types (*Entomolestes*, etc.) related to the modern tree shrews (*Tupaia*), which Gregory and Elliott-Smith regard as representing the remote insectivorous ancestors of the Primates.

From these early Primates and from the groups which connect them with the Insectivora, we may hope to reconstruct the steps through which the order to which man belongs was evolved from lower mammals. Of the evolution of man from the higher Primates, we are not likely to obtain evidence in the New World.

Carnivora. Next to the Primates in intelligence and activity stand the highly organized Carnivora, or beasts of prey. The evolution of the various modern races can be traced back through numerous and varied fossil species to the beginning of the Tertiary, either in the Old or the New World. There are likewise numerous extinct races of various degrees of relationship to those which have survived. The dominant races of modern

Fig. 22. Affinities of the families of Terrestrial Carnivora, Living and Extinct.

Carnivora, the dogs, cats, mustelines, bears, etc., are all derivable from one of the families of Eocene carnivores, the *Miacidæ*; the other Eocene families evolved into various specialized races, but became extinct before the close of the Oligocene. Comparison of the record of fossil Carnivora of the Cordilleran Tertiaries with those of Europe indicates that the raccoons evolved in North America, the viverrines and bears and hyænas in the Palearctic region, while the dog, cat, and mustelid families were Holarctic, appearing in Europe and North America at about the same time, some races a little earlier in the one, some in the other region.

The dominant races are progressive, some in one feature, some in another. The dogs, conservative in teeth, have evolved great speed and endurance in running. The cats have developed a more strictly predaceous type of teeth and evolved the limbs and feet into very efficient fighting weapons. The mustelines,

Fig. 23. *Trilacodon* affinis, a Creodont or Primitive Carnivore of the Middle Eocene. From the Bridger formation, Wyoming. Note the small brain-case, the long heavy tail, and peculiar broken arch of the back, all suggestive of carnivorous mammals, but indicating rather a similar evolutionary stage than any near relationship. —Am. Mus. Photo No. 33369.

Fig. 24. Restoration of *Oryzodon*, a Lower Eocene Creodont, by C. R. Knight. Note the short limbs, five-toed feet and long heavy tail. —After Osborn.

Fig. 25. *Stylacodon*, a Creodont. Restoration by C. R. Knight, based on bones, which is the best known of the group.

Among the most characteristic of the Creodonts of the earlier Tertiary are *Hesperocyon* and *Oryzodon* of the Eocene, and *Hesperocyon* is especially well known from the Bridger formation. It is a small, slender, four-legged animal, with a long, heavy tail, and a small head. It is a typical example of the Creodont type, and is well represented by the bones of the Bridger formation.

Fig. 23. *Tritemnodon agilis*, a Creodont or Primitive Carnivore of the Middle Eocene. From the Bridger formation, Wyoming. Note the small brain-case, the long heavy tail, and peculiar broken arch of the back, all suggestive of carnivorous marsupials, but indicating rather a similar evolutionary stage than any near relationship.—Am. Mus. Photo No. 35369.

Fig. 24. Restoration of *Oxyæna*, a Lower Eocene Creodont, by C. R. Knight. Note the short limbs, five-toed feet and long heavy tail.—After Osborn.

primarily almost as predaceous as the cats, have perfected a more generally flexible organization adapted to varied habits of life. The bears, forsaking the carnivorous habits, have come to depend mainly upon fruit and vegetable food, and developed great size and strength while losing some of their activity. But all the carnivore races, and especially the more progressive groups, have developed notably and continuously in brain capacity and intelligence. The extinct races, and those which survive in the marginal or peripheral continents, are notable for their lack of progressiveness in this respect. The primitive Carnivora or Creodonta are all small brained, not excelling the modern marsupials in this respect.

Fig. 25. Sabre-tooth Tiger *Smilodon*. Restoration by C. R. Knight, based on the skeleton in the American Museum.

Among the most characteristic of the Carnivora of the earlier Tertiary are *Mesonyx* and *Oxyana* of the Eocene, and *Hyænodon* of the Oligocene, representative of extinct families of Creodonta. In the later Tertiary the most remarkable extinct type is the sabre-tooth tiger, allied to the cats but distinguished by the

great dagger-tusks, adapted to pierce the thick hides of large and bulky quadrupeds. This race evolved into large and very powerful beasts, equalling a grizzly bear in size and with curved and flattened sabres seven inches long. Formidable creatures they must have been to the eye of primitive man, for they survived long enough to be his contemporaries.

Fig. 26. Distribution of Modern Perissodactyls and the hypothetical Centres of Dispersal of the Horses, Rhinoceroses and Tapirs.

Perissodactyls. The modern hoofed quadrupeds fall into two principal groups named,¹ from one of the most obvious distinctions, Perissodactyla and Artiodactyla, or odd-toed and even-toed, from the symmetry of the foot. In one the median line of the foot passes through the central digit, in the other between two middle digits.

¹ By Richard Owen in 1848.

The Perissodaetyls include the horse, rhinoceros, and tapir families, survivors of an order much more abundant in the Tertiary than now. The three families represent in a broad way three successively higher grades of specialization, although each family has acquired certain peculiarities of its own.

Tapirs. The tapirs, the most ancient of the three, have four toes in the front foot and three in the hind foot, short-crowned teeth, a rather short neck and legs. They inhabit two marginal regions of the earth, South America and the East Indies, but were formerly inhabitants of the great central land masses of Holarctica. A series of ancestral stages can be traced in the Tertiary of Europe and North America back to the Lower Eocene. They did not reach South America until the Pleistocene. When they arrived in the East Indies we do not know, for there is practically no fossil record in that region for Tertiary faunas. The European record is more complete for the Later Tertiary, but fossil tapirs have been found in North America in the Pleistocene, and ancestral stages in the Middle Miocene, Oligocene, Upper, Middle, and Lower Eocene. As they are traced backward, the ancestral stages are smaller, the teeth more and more like the primitive pattern common to all the earliest Perissodaetyls, and in every detail of skeleton construction they approach more closely to the common ancestral type. The first indications of a proboscis appear in *Helaletes* of the Middle Eocene; in *Protapirus* of the Oligocene it is more apparent; in the later Tertiary it is much as in modern tapirs. The feet have changed comparatively little except for size and robustness.

Rhinoceroses. The rhinoceroses are a more progressive family than the tapirs, and the modern survivors have a wider geographic range. They inhabit the whole of Africa, southern Asia, and the East Indies. Their remains have been found in the Pleistocene formations of Europe and Asia. Various kinds of rhinoceroses are abundant in the Tertiary of Europe and North America, some ancestral to the modern genera, some side branches. Apparently they never reached South America. In Africa, they are found in the later Tertiary, but had not arrived

ADAPTIVE RADIATION OF THE PERISSODACTYLA.
EVOLUTION OF THE DIFFERENT KINDS OF ODD-TOED HOOFED MAMMALS
AS SHOWN IN THE UPPER GRINDING TEETH.

Fig. 27. Divergent evolution of the Perissodactyl families during the Tertiary period, from a common ancestral type approximately represented by the Condylarthra, to the diverse specialized races, existing and extinct.—Am. Mus. Photo No. 35405.

in that continent in the Oligocene. They are abundant in the Asiatic Tertiaries as far back as the records take us, but for their Eocene history we are dependent on Europe and North America, neither of which has yielded a direct ancestral series, although *Lophiodon* of Europe and *Hyrachyus* of North America are collateral ancestors, and all are evidently traceable

back to the same common ancestry about the beginning of the Tertiary.

They have three toes in fore and hind foot, the teeth are longer crowned than in the tapirs, and adapted to a grinding rather than a chopping action. The front teeth have disappeared or become developed into tusks, and the horns are a formidable weapon of offense. The Asiatic rhinoceroses have a single horn; in the African species, there are two, one behind another.

In the Middle Tertiary, rhinoceroses were very abundant in North America, as well as in Europe and Asia. The earlier types were hornless, but in the late Oligocene and early Miocene we find genera which had a pair of horns at the front of the skull. These left no descendants, but later in the Miocene appear rhinoceroses with median horns, at the front of the skull or on the forehead, as in modern kinds. The direct ancestry of the modern genera is to be found in Europe and Asia; the North American Tertiary rhinoceroses were rather successive side branches invading this more marginal area from the Palæarctic region which was the centre of their evolution and dispersal.

The Eocene rhinoceroses have four complete digits on the foot. The outer digit in some of the Oligocene and Miocene genera is reduced to a short splint or nodule of bone; in others it persists, reduced to varying degrees of uselessness and rudimentary. The front teeth are all present in the Eocene stages, but in the later Tertiary the incisors and canines disappear one by one until only a single pair of large tusk-like incisors is left in the lower jaws and sometimes a similar pair in the upper jaws. The grinding teeth are similarly traceable back towards the common ancestral type of the Perissodactyls, the Eocene ancestors of rhinoceroses being but little removed from it as compared with their modern descendants.

Horses. The horses are the most specialized family of Perissodactyls, farthest removed from the ancestral type, and fortunately the series of intermediate links is more complete and direct than it is perhaps in any other phylum of Mammalia. This is due especially to the perfection of the American docu-

ments and to the diligent research of American palæontologists. The phylogeny of the horse has become the classic example of evolution, and the famous collections brought together by the late Professor Marsh and now in the Museum of Yale, have played no small part in convincing the world of the truth of Darwinism. The great collections brought together in more recent years by the American Museum of Natural History have served to confirm and extend the phylogeny as laid down by Marsh, but have not altered it to any great extent.

Fig. 28. *Hipparion whitneyi*, a three-toed horse from the Upper Miocene of South Dakota. *Hipparion* is found in the late Miocene or Pliocene of North America, Asia, Europe and northern Africa, and less certainly recorded from South America. The existing horses are probably derived from one or more species of this genus, but cannot be certainly traced to any known species.—Am. Mus. Nat. Hist. Photo No. 35294. After Osborn.

In Europe there is also a series of stages of ancestral equines in the Tertiary formations, but it is distinctly less direct, forming a series of successive side branches from the main line of descent. These were regarded, before the American Tertiaries

were explored, as an ancestral series, and the work of Hensel, Rüttimeyer, Gaudry, Huxley, and especially of the brilliant Waldemar Kowalewsky from 1863 to 1873, were among the earliest examples of application to palæontology of the evolutionary concept and methods.

The modern horses, asses, and zebras, all closely allied species, have a single toe on each foot, the second and fourth metapodials represented by long splints at the back of the heavy cylindrical cannon bone, or third metapodial, the side toes having disappeared. Their teeth are long prismatic columns growing up from below as they are worn off on the grinding surface, which displays a complex pattern of enamel crests supported by dentine and "cement."

The present distribution of the Equidæ is in central and southwestern Asia, northern, eastern, and southern Africa. They are animals of the arid plains and deserts, peculiarly fitted to inhabit broad open plains and to endure the harsh conditions of such regions. Their range is somewhat scattered and discontinuous, and is a mere fraction of their former distribution. In the Pleistocene, they inhabited all parts of Europe, Asia, Africa (except perhaps west Africa), and North and South America from Alaska to Patagonia. There were numerous species and two or more extinct genera besides the modern *Equus*. All of them were one-toed, and, whether in teeth or feet, were very closely allied to the modern species. The horse was cosmopolitan in the Pleistocene, except that he never reached Australia or any of the oceanic islands that lie outside the continental shelf. The cause or causes of his extinction over so large a portion of his range remain doubtful; various reasons have been suggested—none of them proven. It is certain that when reintroduced in the New World by white men, he flourished and prospered greatly in the unsettled portions of the plains.

In the Tertiary formations of the western United States, we can trace back the ancestry of the horse step by step, through a dozen or more successive stages, to little ancestors of the primitive *Perissodactyl* type, four-toed, with short-crowned

Fig. 29. *Eohippus* and *Equus scotti*. First and last stages in the evolution of the horse in North America.—Originals in Am. Mus. Nat. Hist. Photo No. 35282. After Osborn.

teeth, simple premolars, no cement, and closely allied to the contemporary ancestors of rhinoceroses, tapirs, and other Perissodactyls. The Miocene and Pliocene Equidæ are three-toed, the side toes slender but complete, and not reaching to the ground. Their grinding teeth are progressively longer crowned and more heavily cemented, from *Parahippus* of the Lower Miocene to *Hipparion* and *Pliohippus* of the Upper Miocene and Pliocene. The Oligocene Equidæ are three-toed, but the side toes are less reduced, and reach to the ground in the ordinary step, thus helping to support the weight. Their teeth are short crowned, without cement, and as in all their descendants the three last premolars are like the true molar teeth. A small splint-bone on the outer side of the fore foot represents the remains of the fifth digit; this splint in the later Tertiary horses is reduced progressively to a tiny nodule, and in the

Pleistocene and modern *Equus* has completely disappeared. In the Eocene Equidæ, the fifth digit of the fore foot is complete and functional, so that the fore limb is supported on four toes, of which the outer one is smallest, and the middle or third digit a little larger than the others. The hind foot has three toes, of which the central one is but a little the largest, and in the earliest stage of *Eohippus* from the base of the Lower Eocene we find tiny splints which are vestiges of the first and fifth digits in the hind foot, thus indicating an earlier five-toed ancestor. The teeth are very short crowned, and the premolars are at first small and simple in construction, but become progressively more like the true molars.¹

Although thus remarkably complete, our western American series of Tertiary Equidæ does not appear to be as direct and uninterrupted as that of the camels, oreodonts, or peccaries, known to be of Neartic evolution, since they were confined to North America. The successive stages appear suddenly, as though by migration from a moderately distant centre of dispersal. The European series is much less complete and direct during the Early and Middle Tertiary. In the Pliocene and Pleistocene it is not less progressive and complete than the American series. This is probably due to the fact that Europe was largely archipelagic and separated from eastern Asia until the Pliocene, when it became continental and fully accessible to migrants from that source. Whether the centre of dispersal of the Tertiary Equidæ was in northeastern Asia, as indicated on the diagram, or in northwestern North America, can be decided only when we know the Tertiary mammal faunas of

¹It is currently stated that in *Eohippus* (Lower Eocene) no premolars are molariform; in *Orohippus* (Middle Eocene) one premolar ($p \frac{4}{4}$) is molariform; in *Epihippus* (Upper Eocene) two premolars ($p \frac{3-4}{3-4}$) are molariform; and in *Mesohippus* (Lower Oligocene) and its successors three premolars are molariform. This is approximately true of the lower teeth, but inaccurate as respects the upper premolars. Their evolution might better be stated as follows: *Eohippus*, premolars non-molariform; *Orohippus*, $p \frac{3-4}{3-4}$ submolariform, p^2 non-molariform; *Epihippus*, $p \frac{3-4}{3-4}$ molariform, p^2 submolariform; *Mesohippus*, $p \frac{2-4}{2-4}$ completely molariform.

Fig. 30. Geological and Geographical Range of Ancestors of the Horse. The dotted lines with arrows represent the author's views of the affinities of the successive genera.

one or both of these regions—*terra incognita* at the present day. The present distribution, combined with what is known of the past distribution, appears to me to indicate on the whole as the most probable centres of Perissodactyl dispersal, northeastern Asia for the Equidæ, eastern Asia for the Tapiridæ, and western Asia for the Rhinocerotidæ.

Artiodactyla. The ruminants or higher Artiodactyla are today the most progressive and successful of the many kinds of terrestrial animals which have been evolved to feed upon plant food. The cattle, sheep and goats, antelopes and deer include most of the existing hoofed animals of the world. They are all rather nearly related, and their evolution took place chiefly during the later Tertiary. Their centre of dispersal seems to have been in Asia, whence successive invading types entered North America and flourished here, giving rise to more or less

peculiarly differentiated groups. Among these were the Antilocaprids or prong-horn antelopes now living on our western plains, which seem, according to Dr. Merriam's recent discoveries, to be descended from a group of handsome little antlered animals, the Merycodonts or deer-antelope. These in turn were preceded by more primitive invading stages, *Blastomeryx* of the Lower Miocene, *Leptomeryx* of the Oligocene.

But much more abundant in the Cordilleran Tertiaries are the peculiarly American groups of camels and Oreodonts. The camel family evolved in North America and its ancestral stages can be very fully and exactly traced in the western formations, as far back as the Upper Eocene, below which they are merged with the ancestry of other groups. They are unknown in any

Fig. 31. The different groups of ruminants all originated either in the Palæarctic or Nearctic region, but rapidly spread into the regions southward. The later and higher types are today almost cosmopolitan, while some of the older types have disappeared from the country of their origin, or become extinct.

Fig 32 Skeleton of *Merycodus*, Deer-Antelope of the American Miocene. A collateral ancestor of the existing Pronghorn Antelope.—Am. Mus. Photo No. 35177.

other continent until the Pliocene, when they invaded South America and Asia and Africa, surviving in those continents today, although extinct in North America since the Middle Pleistocene.

Although the modern camels, especially the Old World species, are adapted to desert life, it does not appear that their Middle Tertiary ancestors were so. They appear to have taken the place in part of the antelopes and other Old World rumi-

nants, which were late in arrival and few in numbers in the New World.

But by far the most abundant of the fossil mammals of our Middle Tertiary are the Oreodonts or "ruminating hogs," as Dr. Leidy very appropriately called them. These animals had somewhat the proportions of pigs in body and legs, but a short muzzle, with cropping teeth like those of a horse, while the grinders were of the ruminant pattern, and stout tusks like a

Fig. 33. Evolution of the Camel. Series of hind feet, illustrating progressive stages in the reduction of the lateral digits, consolidation of median metatarsal bones, into a "cannon-bone" and spreading of the toes into a broad, padded foot, in adaptation for long journeys over desert sands. The maximum size in this family was reached in the Pliocene, at which time they also invaded the Neotropical and the Palaëartic regions. The stages represented are: *Diacoderis*, Lower Eocene; *Protylopus*, Upper Eocene; *Poebrotherium*, Oligocene; *Protolabis*, Middle Miocene; *Procamelus*, Upper Miocene; *Pliauchenia*, Pliocene; *Camelops*, Pleistocene; *Camelus*, recent. All but the last are North American.—Photo from panel in Am. Mus. Nat. Hist.

peccary, except that the lower pair were the first premolar teeth instead of the canines. These Oreodonts were peculiar to North America, and their skulls and skeletons have been found in great numbers in the Oligocene and Miocene formations. Some of the later kinds exceeded the largest living pigs in size; most of them were the size of a peccary or smaller.¹

¹ The above are the facts. Perhaps it would be more interesting to say that great herds of Oreodonts roamed about the shores of the Tertiary lakes. But I don't believe that there is any evidence that the Oreodonts

Fig. 34. *Oreodon*, a primitive type of Ruminant common in the Cordilleran Oligocene. Although specialized in a few features, this animal retains most of the characters of primitive ruminants.—Am. Mus. Nat. Hist. Photo No. 35163.

These higher Artiodactyls are traced back to more primitive non-ruminating kinds, with teeth adapted to crushing instead of grinding their food, and probably more omnivorous in their diet. Such types were more common in the Middle Tertiary, although they still survive, little altered, in the pigs and peccaries of today. The pigs are of Old World descent, unknown to the American Tertiary; but the peccaries are found in our Cordilleran formations. Other groups of this more primitive division are the Entelodonts of the Oligocene, huge beasts, whose body and limbs were proportioned like a buffalo, having a great head with long powerful jaws and teeth that are suggestive rather of a gigantic flesh-eating than of a herbivorous animal. Dr. Leidy called these animals "carnivorous hogs," but modern palæontologists, in view of the general organization of the skeleton, the size of the beast, and method of wear of

went in herds—although it is likely enough—and as for the Tertiary lakes I believe they are mostly a myth. I do not mean to depreciate theories and interpretations. But they should not be stated as facts.

the teeth, are disposed to believe that these savage-looking teeth were used chiefly in stripping leaves from branches, rooting for edible tubers, and other such peaceful purposes.

Contemporaries of these Entelodonts were the Anthracotheres, more piglike in proportions and affinities, and perhaps ancestral to the hippopotamus.

The primitive Artiodactyls, from which all these various later kinds are derived, are found in the Eocene formations, both in Europe and North America, and can be traced as far down as the Lower Eocene, to tiny ancestors with teeth which are not easily distinguished from those of the contemporary ancestors of monkeys, carnivores, insectivores, and other orders of placental mammals. The skull and skeleton show indeed that even at this early time the Artiodactyls were pretty clearly distinguished from other mammals. But in the Paleocene, where we might expect to find them merging, the ancestors of this order have not yet been discovered, or at all events have not been recognized as such.

Proboscideans. It is only in the later Tertiary that the ancestors of the elephants and mastodons appear in North America. They are of Old World origin, and Africa is generally assigned as their place of evolution and dispersal, since the oldest and most primitive ancestral stages are found in the early Tertiary of Egypt, while they do not appear in Europe until the Lower Miocene, nor in North America until the Middle Miocene.

The earliest American Proboscideans are already of huge size, and highly specialized, but less so than their successors. They have a pair of tusks in each jaw, and retain a strip of enamel on the ivory of the outer side. In other respects they are much like the mastodon, which succeeded them in the Pleistocene, and differs in its larger size, the practical loss of the lower tusks and elongation of the upper tusks in a great sweeping spiral curve. The mammoths, which appear first in the Pleistocene, are much more progressive and specialized, closely related to the modern elephants and resembling them in proportions and characters. They are commonly said to have

the study of the evolution of the Proterid. The study of the evolution of the Proterid is a very important part of the study of the evolution of the animal kingdom. The study of the evolution of the Proterid is a very important part of the study of the evolution of the animal kingdom. The study of the evolution of the Proterid is a very important part of the study of the evolution of the animal kingdom.

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Fig. 35. Skulls of *Proterid* and *Proterid*, early stages in the evolution of the Proterid. Note the progressive specialization of the Proterid. Note the progressive specialization of the Proterid. Note the progressive specialization of the Proterid.

The study of the evolution of the Proterid is a very important part of the study of the evolution of the animal kingdom. The study of the evolution of the Proterid is a very important part of the study of the evolution of the animal kingdom. The study of the evolution of the Proterid is a very important part of the study of the evolution of the animal kingdom.

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Fig. 35. Skulls of *Palaeomastodon* and *Trilophodon*, early stages in the evolution of the Proboscidea. Note the progressive specialization of tusks and grinding teeth and increase in size. *Palaeomastodon* from the Oligocene of Egypt is the oldest unquestionable proboscidean. *Trilophodon* from the Middle and Upper Miocene marks the earliest appearance of the Proboscidea in North America. Specimens in Am. Mus. Nat. Hist. Photo No. 35438

reached a much larger size than the modern elephants and to have had much larger tusks, but this is doubtful. The elephants we see in captivity are most of them young and the Indian species seldom has large tusks even when adult. But there are records of African wild elephants which very nearly equal the record of size in fossil mammoths, whether as to height of the animal or length of its tusks. And the fossil records are much more numerous, for the ivory trade has for centuries past weeded out the largest and finest of African tuskers and the recorded measurements are only in recent years.

The first appearance of Proboscideans in the western Tertiaries is in the Middle Miocene¹ (Mascall, Deep River, Pawnee Creek), associated with *Merychippus* and *Dromomeryx*, invading types, and with *Alticamelus* and other types which appear to have been evolved in North America. Their earlier appearance in Europe at the base of the Miocene would seem to indicate that their centre of dispersal was relatively distant from this country, either in northern Africa or southwestern Asia. That it was in Ethiopia proper seems to me less probable. Here again a knowledge of the earlier Tertiary faunas of southwestern Asia, which is beginning to come to hand, will afford the evidence for a decision. But southwestern Asia, we may recall, was in large part an area of disturbance and submergence in the early Tertiary, the Indian peninsula being the chief stable area; the same appears to be true of a large part of northern Africa. These facts would militate against these regions affording an effective centre of dispersal at that time.

Amblypoda or *Dinocerata*. These hoofed quadrupeds represent, so to speak, one of the early, crude attempts at fashioning gigantic animals out of the primitive placentals of the Paleocene. Again and again in the Tertiary of every continent we find gigantic races being evolved out of one or another of its herbivorous mammals. The advantages of great size in the

¹ Their reported occurrence in the Lower Miocene (Upper Harrison) is based upon fragments of teeth which I do not regard as positively determinable.

Fig. 36. Skeleton of *Dinoceras* (= *Uintatherium*), an Amblypod of the Middle Eocene. Original in the American Museum of Natural History. In the evolution of animal mechanism this represents an early and rather crude attempt at fashioning a gigantic mammal. The crudity is apparent in the details of joint construction, imperfection of apparatus for masticating food, and in the imperfect correlation of the animal's activities conditioned by the small size of the brain.

superiority over the attacks of enemies, or the competition of smaller rivals, are obvious enough. The disadvantages lie in the greater mechanical perfection of limbs and body and the larger proportionate amount of food which are required to maintain the larger animal as a going concern. Imperfect organization and insufficient food must needs set a definite limit to the practicable size that a race may attain, and render its existence and survival precarious anywhere near that limit. While many other causes may have operated to cause the extinction of the numerous kinds of gigantic animals, these factors must always have been present to set limits to their size, and render their survival difficult, especially with any change in the environment.

Obviously, the less perfect the general organization of the animal, the lower is the maximum limit of size which the race can attain. The largest of the Eocene quadrupeds would scarcely impress us as gigantic today. Yet they had the characteristics that today are associated with most gigantic animals; the massive proportions, the ponderous post-like limbs, and short stubby padded feet, adapted to support great weight but not to attain great speed.

In these features, adaptations always associated with relatively large size, the Amblypoda resembled the elephants. But here the resemblance stops. The characters of the skull, the teeth, are altogether different; the detailed construction of limbs and feet differs widely in spite of the general resemblance.

In *Coryphodon* of the Lower Eocene, the large front teeth flare out widely, suggesting the hippopotamus; the cheek teeth have a series of chopping crests, more as in the tapir; there is no indication of a trunk, but the muzzle was probably thick and flaring as in the hippo. The animal was as large as a grizzly bear. *Uintatherium* or *Dinoceras* of the Middle Eocene was very similar in limbs and feet; the cheek teeth have somewhat the same pattern, but the muzzle was quite different, with a pair of large flattened tusks and no other upper front teeth. The skull has two pair of stout horns, one near the back, one over the eyes, and a third pair sometimes appears at the tip of the nasal bones. This animal was of larger size, some species equalling a rhinoceros. It was confined to America, and indeed has never been found outside of Wyoming, where the discovery of its remains almost simultaneously by Professors Leidy, Marsh, and Cope gave rise to a historic controversy, the echoes of which were long heard in palæontologic discussion. The *Coryphodon* was of wider range; first found in England and France, it is much better known from skeletons found in Wyoming and New Mexico, and probably inhabited all the Holarctic realm.

Among the Paleocene mammals we find what appear to be early stages in the evolution of the Amblypod type. *Pantolambda* and *Periptychus*, although not direct ancestors of

Coryphodon and *Dinoceras*, tend in their direction and are evidently related.

Rodentia. Rodents are today by far the most numerous of all quadrupeds. Yet they do not rank high in intelligence, nor does their physical organization appear to be as perfectly elaborated as in several other orders. Their great success in the struggle for life is commonly ascribed to their fecundity, but this does not appear to me to be a very satisfactory explanation. It is wholly out of accord with the general evolutionary history of higher animals, which shows throughout a progressive decrease in fecundity in the higher and more dominant groups. And the fecundity of rodents, while greater than that of higher types, is not greater than that of less successful orders of their own rank, the Insectivora, for instance. But there is no doubt that the rodents during the Tertiary have increased in relative abundance while the insectivores have diminished. I suspect that their success is due rather to their greater adaptability to varied and changing environment, especially to the habit so common among them of storing up supplies of food, and to their readiness to combine in social groups and colonies.

However this may be, there is no doubt as to their increasing abundance and variety during the Tertiary. The earliest rodents appear in the Lower Eocene (Wasatch group) in *Paramys* and its allies, already quite distinct from other orders of mammals and without any known ancestors in the Paleocene. From this primitive group may be derived by partly divergent and partly parallel specialization all the widely varied races of the later Tertiary, although the direct ancestry can be traced only in a few instances. The rabbits (Lagomorpha) are an exception to this statement. They appear quite suddenly in the Oligocene and are not derivable from any Eocene group; it is doubtful whether they have anything to do with the remainder of the rodents. On the other hand, the mice, squirrel, and porcupine groups are clearly derivable from the *Paramys* group of the Eocene. Mice (*Eumys*) allied to the harvest mice of Europe appear first in the Oligocene, squirrels (*Sciurus*) about the same time, while porcupines (*Erethizon*) are unknown

PHYLOGENY OF THE EDENTATES

Fig. 37. Phylogeny of the Edentates. Showing their early appearance in North America and later evolution and expansion in South America into diverse, specialized and oftentimes gigantic types, some of which subsequently reinvaded North America.

in North America until the Pleistocene, and are probably of South American origin.

There are numerous problems of migration and affinity among rodents which cannot be discussed at present.

Edentates. The sloths, anteaters, and armadillos are survivors of an order of mammals that played a large part in the Tertiary history of the New World. They appear to have evolved in South America during the Tertiary while that continent was separated by ocean barriers from the northern world. They attained by the end of the Tertiary a great variety of form and habits and many of them reached gigantic size. The great ground sloths, *Megatherium*, *Myodon*, etc., and the tortoise-armadillos, *Glyptodon* and its allies, are well known. Towards the close of the Tertiary they invaded the northern continent and are found in the Pliocene and Pleistocene of the western United States.

Compared with the animals of the northern world, these invaders from the south seem singularly clumsy and inept in bodily structure, and not high in brain development. Yet we find that they were not immediately swept away before the competition of the northern herbivorous mammals when the two continents became united, as was the fate of the marsupial carnivores which had evolved in South America during the period of separation to take the place of the absent placental Carnivora, or of the peculiar groups of hoofed animals which replaced the northern ungulates. On the contrary, the Edentates maintained themselves and apparently flourished for some time in competition with the northern herbivora, and were even able to invade North America and flourish there for two geologic epochs.

The explanation is perhaps that the adaptive evolution of the Edentates progressed along different lines from that of any of the higher-brained and more active mammals. They seem to have been primarily fossorial or digging animals, and all of the later races evidently made great use of their digging capacities. Whether, as Owen long ago suggested, the great digging claws enabled them to uproot trees and secure food

otherwise inaccessible to a terrestrial animal, or whether they dug for roots or food inedible or distasteful to other herbivora, they evidently did not have to compete with northern races of precisely similar adaptation. Their final disappearance we may ascribe either to their inability to withstand the attacks of their carnivorous enemies, or, more in conformity with the evidence as it stands, to the appearance of primitive man in the New World.

Fig. 38. Groundsloths. Sketch. Restoration by Erwin Christman, based on the group of fossil skeletons in the American Museum. The animals are supposed to be engaged in a concerted attempt to uproot and tear down a tree, in order to feed on the foliage. This is in accord with the theory of their habits outlined by Owen. The genera represented are *Lestodon* and *Mylodon* of the Pampean formation.

Although chiefly South American, there is some evidence that the Edentates were derived from an earlier northern ancestry. For in the early Eocene and Paleocene of the Western States are found what appear to be specialized survivors from the

same common stock that gave rise to the South American Tertiary Edentates. *Metacheiromys* of the Bridger seems to be distinctly related to the armadillos, although with no bony armor and without functional teeth, except for a pair of upper and lower tusks. It is preceded in the Wasatch by a less specialized ancestor, *Palæanodon*. The Tæniodonta or Gano-donta of the Paleocene and Eocene are a group of more doubtful affinities. They have several characteristic Edentate peculiarities and may be an archaic side branch of the order. These early Tertiary northern types are probably older than any known South American ancestors of the Edentata, and they are certainly more nearly related to the common stock from which all placental mammals seem to be derived.

Insectivora. The modern Insectivora are all small, and generally scarce animals of lowly organization but mostly of highly specialized habits. A great part of them inhabit the tropical or southern regions, the marginal portions of the earth's surface, and most of them either have some unusual mode of life, like the subterranean moles and shrews, or some special means of defense like the spines and rolling into a ball characteristic of the hedgehog. These unusual specializations have enabled them to survive among their higher mammalian competitors. The various groups of insectivores are not nearly related to each other, and it is not easy to find characters by which to distinguish the order as a whole. In short, the Insectivora are what we should expect to find in a primitive and ancient group that has long passed its prime and is on the verge of extinction.

Such being the case, we are not surprised to find that the insectivores are a much more important order in the early Tertiary, and especially in the Paleocene and Eocene than now; that relatives of types now confined to southern latitudes are found in the early Tertiary of the north, and that several of the higher orders of mammals, when we trace their ancestry back to the early Tertiary, converge towards the Insectivora, and appear to be derivable from them and at first not easily distinguishable.

In the Paleocene fauna we find it very difficult to distinguish between insectivores, primates, and early carnivores. Artiodactyls, Perissodactyls, and rodents, when they first appear at a somewhat later stage, seem to be derived from a similar stock, so that Huxley's generalization of fifty years ago, namely, that the Insectivora represent most nearly the central primitive type of the placental mammals, seems confirmed by fossil discoveries.

Fig. 39. Skeletons of *Metacheiromys* (lower) and modern Armadillo (upper). The discovery of this little Edentate in the Eocene of North America affords evidence that this order so characteristic of the South American Tertiary came originally from the north.—After Osborn.

The Eocene insectivores are much more numerous relatively to other groups, and include larger animals, than is the case in the living fauna. In the Cordilleran Tertiary we find ancestors of the modern moles, shrews, and hedgehogs of the

north as well as relatives of the solenodons, tenrecs, and golden moles now limited to tropical and southern regions. But the evidence is lamentably fragmentary, and the ancestry in most instances is rather approximate or collateral than direct.

Date of Evolution of Mammalian Orders, Families, Genera and Species. At the beginning of the Eocene the placental orders are well differentiated. The families are not.

The Perissodactyla, Artiodactyla, Rodentia, Primates, Insectivora, Carnivora, have each their characteristic form of astragalus, and some if not all of their other ordinal peculiarities fully developed. There are, it is true, a few genera, like *Hyopsodus*, difficult to place, although the skull and skeleton are known. But for most of the fauna there is no uncertainty as to the ordinal relations of each genus except from incomplete materials. The Artiodactyl, Perissodactyl, or Primate astragalus is just as characteristic and distinct in *Eohippus* as in the modern horse, in *Diacodexis* as in the modern camel, in *Pelycodus* as in the modern lemur.

The teeth are for the most part widely different from those of their modern descendants, yet they usually show more or less clearly the characteristics common to the order. The modern horse, tapir, and rhinoceros, widely different as they are in teeth, have yet a certain degree of fundamental resemblance in tooth pattern, which we find foreshadowed in the Eocene Perissodactyls and in no other mammals of that time. The ordinal characters of modern fissipede Carnivora are all present or foreshadowed in the Creodonta of the family Miacidæ. The ordinal characters of Artiodactyla appear to be all foreshadowed or present in the Dichobunidæ, although these have been less carefully studied in this country.

The modern placental families are, broadly speaking, not differentiated in the Eocene, and are first clearly distinguished in the Oligocene. The more recent and more progressive families are not clearly distinguished until the Miocene or even later. I do not mean by this to say that the *phyla* are not distinguishable, but that the differences do not amount to family distinctions until after the Eocene.

Fig. 40. Date of Evolution of the Orders, Families, Genera and Species of Mammals.

Eohippus, *Systemodon*, and *Heptodon*, of the Lower Eocene, supposed ancestors of horses, tapirs, and rhinoceroses, are very close together in tooth characters and hardly separable in skull or skeleton characters. They are distinct genera, but they would not be placed in different families were it not for their supposed ancestral position. Nor in my judgment are there any important points in *Eohippus* that would suggest family relationship to *Equus* if we had not the intermediate stages of the phylum as a guide. It could just as well be ancestral to tapirs or rhinoceroses. In *Mesohippus* of the Oligocene, on the other hand, the family characters are clearly foreshadowed. Although it is three-toed, as in the rhinoceros, the reduction of the lateral digits is already considerable. Although it has short-crowned,

crested teeth as in tapirs, yet the pattern is clearly approaching that of *Equus*. We should not hesitate to refer it to the Equidæ rather than Tapiridæ or Rhinocerotidæ.

With the Miacidæ again, the genera do not show clear affinities to any particular families of modern Carnivora. Mostly they combine the primitive characters of all, and it is only through the intermediate stages in the later Tertiary, if at all, that we can attach any Miacid genera to the phylogeny of a modern family. In the Oligocene, on the other hand, some of the modern families are already distinct, and others are foreshadowed more or less clearly.

The same holds true of the Artiodactyla. The Dichobunidæ of the earlier Eocene may be regarded as structurally ancestral to all of the later Artiodactyla.¹ But none of the special characters of the later families have yet appeared. Even the selenodont division is not distinct until the Upper Eocene. The extension of one or two family phylogenies into the Eocene rests upon the evidence of intermediate stages. The distinctive family characters (excluding primitive or semi-primitive characters) of Camelidæ are not present in the Eocene *Protylopus* any more than those of Equidæ are in the Eocene *Eohippus*. In the Oligocene we find them either present or foreshadowed in *Poebrotherium* and those of peccaries and tragulines are almost equally clear in *Perchærus*, *Hypertragulus*, etc. The higher ruminant families are not clearly distinguishable until well on in the Miocene.

Among the rodents we find the early Ischyromyidæ, with fully developed ordinal characters, but structurally ancestral to any or all of the Simplicidentate families. In the Oligocene some at least of the modern families are clearly defined; the ancestry of others is traced back into that epoch rather on the evidence of intermediate stages than because the family distinctions have appeared at that time.

¹ I make this statement with hesitation, as it does not conform with the conclusions of Dr. Stehlin, for whose views I have the highest respect. But I have in mind especially the tritubercular Dichobunidæ of the Lower Eocene.

The differentiation of the modern genera is of course of later date, from Miocene to Pleistocene.

While the placental orders are clearly distinct in the Lower Eocene, it is no less clear that they are, relatively speaking, nearly allied. The common pattern of the teeth, derived from or still retaining the tritubercular form which is obscured or unrecognizable in most of the later Tertiary mammals, is here clearly revealed. The details of skull construction, of limbs and feet, support the broader evidence that all are derived from a common ancestry, tritubercular, pentadactyl, plantigrade, and probably arboreal or partly so, at no very remote date. I conclude that they converge to that common ancestry not long before the beginning of the Eocene, probably in the later Cretaceous.

As between marsupials and placentals there are no clear signs of approximation. The Insectivora, indeed, which retain various metatherian characters lost in the more specialized placental groups, play a much larger part in the Eocene fauna than in those of today. But the Eocene Insectivora do not any of them approach the marsupials more closely than do some of the modern insectivores. Some of them are transitional to other placental orders, but I have not observed any evidence of transition to marsupials. Nor is there any such evidence among other placental orders. The early Eocene marsupials are very imperfectly known, but what is known of them shows no closer approach to placentals than a generalized modern marsupial would present. The subclass characters, small and great, are fully developed in them so far as the material at hand shows.

At what time the marsupial-placental split occurred it is difficult to say. The Jurassic-Comanchic mammals certainly do not show a clear distinction between the two groups foreshadowing in any positive way the marsupials and placentals; their evidence, however, rests upon insufficient material. With material equally incomplete, it would certainly be impossible to come to correct conclusions as to the ordinal differentiation of the Lower Eocene mammals. And the lack of intermediate

stages makes phyletic associations a very doubtful clue to follow in attempting to arrange their affinities.

The evidence is then so inadequate that any conclusions would be speculative, and unworthy of association with the well-grounded conclusions as to the time of epochs to which the differentiation of the placental orders, families, and genera date back. To summarize:

The placental orders date back to the late Cretaceous.

The placental families date back to the Oligocene or later.

The placental genera date back to the Miocene or later (mostly later).

Modern species rarely date back earlier than the Pleistocene.

It is to be observed that the higher, more specialized and usually dominant families are those of more recent origin. This is true also of genera and species, and probably of orders, if our knowledge were more complete.

Apparent exceptions to these generalizations are mostly to be explained by a different concept of the term family which has prevailed in the current classification of certain groups, or by provisional reference of imperfectly known primitive genera. In one or two cases incorrect correlation is accountable.¹

Summary and Conclusion. This closes our review of the Cordilleran records of the history and evolution of the higher quadrupeds. We find that the evolution of most of the dominant races of placental mammals is well represented, sometimes by series of direct or nearly direct descent, sometimes by a succession of stages not directly descended each from its predecessor, but derived by successive invasions from some more or less distant centre of dispersal, usually Asiatic. We find that at the dawn of the Tertiary in the Paleocene, the placental mammals suddenly appear in force, but the different modern orders are not clearly separated until the beginning of the

¹ *E.g.*, *Prohyracodon*, a Rhinocerotid from the "Middle Eocene," is more probably Lower Oligocene. Certain Santa Cruz rodents belong to modern families, but their age is Miocene, not Eocene, as was maintained by Ameghino.

Eocene. During the Eocene, the different families of modern mammals become differentiated and are clearly distinct at the beginning of the Oligocene. The modern genera of mammals date back to the Miocene or later. The modern species seldom date back further than the Pleistocene.

In two of the lower groups of vertebrates, the crocodiles and turtles, the record is nearly as complete as in the mammals. But it is of less interest as their changes in evolution and adaptive specialization were relatively small. As regards the birds, the lizards, the fresh-water fish, the land and fresh-water invertebrates, the records are very scanty, and quite inadequate to trace the evolutionary history and dispersal of the various races. I believe that the fragmentary data can be made to fit in fairly well to the principles of evolution and dispersal that are shown to prevail among the mammals. But except among the birds and lizards the amount of progressive evolution and deployment was probably small during the Tertiary.

To conclude, the western Tertiary formations afford a record more complete than in any other region of the history and evolution of the higher quadrupeds. It is a record not merely of many kinds of extinct animals or races more or less peculiar and interesting, but of the origin and history of those which today are dominant over most of the world. It carries us back to the source of the modern families of mammals, almost but not quite to the source of the modern orders. Its interpretation, clear and unmistakable in many of its broader outlines, is full of complexities and unsettled problems in detail. For the solution of these problems we have need: *first*, of more material, for the best of our extinct faunas are very inadequately known, and the opportunities for future collecting are inexhaustible; *second*, of more careful and thorough research on the extinct animals already known, their comparative anatomy and relationships, their environment and habits, the conditions and causes which resulted in their preservation as fossils; *third* and most necessary, critical sifting and testing of all our interpretations and theories, weighing the validity and trying the scope of our hypotheses, and detecting their inconsistencies where compared

and followed to all their logical conclusions. Such critical synthesis, as distinguished from mere compilation, is the hardest thing to get in this day of extreme specialization. We are all of us trying to make new discoveries, to formulate new theories. The cry is all for new data. But it seems to me that even more than new facts we need a more thorough and critical study of accepted theories and hypotheses in the light of known facts. The methods and ideals which have so revolutionized our understanding of human history in the last century will equally serve to broaden our comprehension of that great period in the history of life whose records and documents are found in the Cordilleran Tertiary.

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