THE EVOLUTION AND THE OUTLOOK OF SEISMIC GEOLOGY.

(PLATES XV AND XVI.)

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PART I: THE EVOLUTION OF SEISMIC GEOLOGY.

Introduction.—Speaking generally, the present condition of a science is so largely the consequence of an evolution by slow stages, that if the past be reviewed the present stands revealed. Zoölogy, which began with the encyclopædists as a descriptive science, passed into the comparative stage with the advent of Cuvier, and entered upon its fruitful genetic period when the modern view-point was given it by Darwin. Looking back upon this evolution, we note that the order is in every way a natural one. The facts of observation should first of all be assembled; they must next be compared with a view to establishing correspondences, and, finally, the explanation of the correspondences must be sought in genetic relationships.

Of geology it may be said, that the natural order of its evolution was exactly reversed; for the genesis of the earth and the full order of events in its history had supposedly been given to man through divine revelation. The growth of the science began, therefore, only after a measure of emancipation from the tyrrany of religious dogma had been achieved.

The Natural Development of Seismology Prevented by False Theory.—It may well be doubted if there is another branch of science which has been so long held in fetters by false theory as the branch of geology which treats of earthquakes. Had fate been more kind, it might have been the earliest to develop; for the seats of ancient culture were in earthquake countries, and it will hardly be claimed that the phenomena of earthquakings are not such as to attract the attention. Theories of cause do, indeed, date back before the beginning of the Christian era, the dominating one being that of Aristotle which connected the quakings with explosive sources of energy, conceiving that gases confined in subterranean cavities brought on quakings in their struggles to escape. For the times, this theory seemed to be well supported by facts, since earthquakes were generally manifested at the time of great volcanic eruptions, and volcanoes and earthquakes were common to the same countries. The Aristotelian theory of earthquakes acquired prestige from the adhesion to it of Strabo and Pliny among the ancient philosophers, and at the opening of the nineteenth century, through its adoption by von Humboldt and von Buch, who then dominated the field of geological thought.

The middle of the nineteenth century is a turning point in the history of nearly all sciences toward a greater exactness of observation. Academic discussions in large measure gave place to careful and painstaking observation or to laboratory experimentation. Yet almost at the moment when Darwin and Huxley were opening a new world to students of biology, the way to progress in seismology was effectually closed through the commanding authority of a pseudo-scientific work of great compass, written by the English physicist, Mallet. Darwin's great theory was an induction reached on the basis of extended observations and of meditations with an open mind; Mallet, on the other hand, approached his work firmly intrenched in a preconceived notion which the facts were assiduously, though perhaps unconsciously, twisted to confirm.

Assuming that Mallet's method had been a sound one, his elaborate observations conclusively proved the fallacy of his theory; for instead of pointing to a definite centrum, his results ranged with noteworthy uniformity between depths of 10,000 and 45,000 feet. The history of science furnishes no more striking example of a great monograph wrought out with laborious scientific method and yet absolutely lacking in scientific spirit or judgment, for with a naïve simplicity Mallet drew from his results the conclusion that, "the probable vertical depth of the focal cavity itself does not exceed three geographical miles, or 18,225 feet, at the outside." Nowhere in the two bulky volumes of his report is the possibility of a non-existence of the centrum even raised.

As was true of the famous fallacy of Werner concerning the origin of basalt, it was here the commanding position of the author which gave his theory its authority; and, although the impracticability of his method soon came to be generally recognized, the fundamental idea was destined to survive at least half a century as the standard doctrine of seismology. It was the brilliant system of Huyghens for treating the propagation of wave motion carried over bodily to seismology, which caused it to be so warmly welcomed by physicists and elasticians, to whose care this branch of science was thereafter entrusted. As late as 1899, the depth of the imaginary origin of a particular earthquake was sought by no less than four different methods with results which ranged from 21 kilometers on the one hand to 161 upon the other, these results apparently not shaking the worker's faith in the reality of the earthquake focus.

It becomes ever more clear that men of science discover in the main those facts only which their working hypotheses indicate to be important. For this reason a theory which is largely correct, grows by elimination of the false and augmentation of the true, whereas a theory essentially false yields nothing, and by discouraging effort bars the way to progress. With the aid of mathematics and by an abundance of exact observation, the more or less occult Aristotelian theory was by Mallet clothed in a modern dress and thus made respectable in the company of the modernized sister sciences. The cause of the earthquake disturbance was by the very nature of the theory hidden so deep beneath the earth's surface as to be removed from direct observation, and was, therefore, a matter suitable only for speculation.

At the opening of the twentieth century, almost fifty years after Mallet had modernized the theory of Aristotle, authors of text-books of geology quite generally disposed of the subject of earth-quakes by a treatment of the outlines of the Mallet theory in the compass of a few pages. How generally the investigation of earth-quakes was excluded from the field of research in geology is strikingly shown by the activities of the United States Geological Survey, a bureau employing the largest staff of working geologists of any in the world and including in its field subjects as diverse as paleontology and mineral resources. In the years 1868, 1872, 1886 and 1887 earthquakes of the first magnitude wrought damage to property within the national domain, and with one exception no effort was made by the national bureau to investigate these phenomena, and but little by independent geologists. Since the intellectual shock from the California earthquake of 1906, individual geologists have begun to take advantage of this opportunity for study, even though the golden opportunity had already passed.

The Process of Averaging in Mapping Isoseismals and Coseismals.—Aside from its occult and speculative basis, which removes it from the reach of direct observational studies, the centrum theory has yet assumed to adopt the observational method of modern science. The isoseismal and coseismal lines which belong to the Mallet conception of an earthquake centrum must be obtained through averaging the results of observation either of the intensity of the shocks or of the time of their arrival. In how far it has been necessary to "adjust" data in order to make the circular or elliptical curves concentric about the epicenter and represent uniformly decreasing values as they recede from it, one who has not compared the individual data will scarcely believe. A local intensity which is too large can be explained either by a soft or a wet basement, by an earthquake "bridge" or by probable error of observation; while one too small may be explained by an earthquake "shadow," by an interference of waves, etc. Many curiously anomalous data not possible of explanation on any of these grounds may be dismissed as "earthquake freaks."

As regards time of arrival of shocks, "too early" or "too late" data have not uncommonly been included among those which seemed *a priori* the most reliable. Especially good examples of such data are furnished by the studies of the Agram earthquake of 1880, the Andalusian earthquake of 1885, the Charleston earthquake of 1886, and the Indian earthquake of 1887. Out of 260 time data collected by Dutton in connection with the Charleston earthquake, 47 were rejected as "too early."

To average the determinations of an unvarying value in order to eliminate the errors of observation and experiment, is indication of a desire to secure accuracy which must be commended as eminently scientific in its nature; but to average the values of a property the distribution of which either in space or in time is likely to be significant, is, on the contrary, one of the most pernicious, as it is one of the most common and unconscious methods. Such a practice is often condoned on the ground that the data may otherwise appear to possess an accuracy beyond what they really have; forgetting, what is far more important, that through the averaging process the data lose their most significant characters. Now that so many sciences are entering upon their quantitative stages it is important that this method be corrected.

A companion fallacy to the supposed necessity for averaging data of different values is that nature in all its moods has avoided angles and straight elements in favor of the curving outline, and that in consequence results are incorrect in proportion as they bring out strong accent, or definiteness of character, or exhibit straightness of contour. In no field, perhaps, has this fault been more often committed than in topographic mapping, where it has been encouraged as tending toward accuracy. A new era is dawning, however, and the wonderfully improved maps which have been brought out in recent years by the United States Geological Survey and by European surveys have been secured through the elimination of the process of averaging and "rounding off" of angles. Significant character is thus taking the place of a lack of expression in the older maps.

In a similar way the isoseismals and coseismals, which have assumed to represent the distribution in space and in time of the seismic activity of a district, have through averaging of results removed all true expression of seismic distribution. It is likely, however, that this method will yet, at least for a number of years, effectually retard the natural progress of seismology.

The Evolution of the Fault Block Theory of Earthquakes.—It would be incorrect to state that no progress was made in seismic geology during the last half of the nineteenth century, but it would be only the truth to say that such progress as there was, was achieved in spite of and almost in defiance of the orthodox doctrine of seismology. Nine out of ten reports upon special earthquakes made during that period have included only the maps of isoseismal and coseismal lines, to which has been added a computation of the depth of the supposed origin.

It is now proposed to trace the development of the tectonic conception of earthquakes as it has grown into the fault-block theory of the present day. To the Austrian school of geologists and to its leader, Eduard Suess, must be credited the pioneer work upon the geology of earthquakes. The discovery of the localization of heavy shocks along definite lines, or the recurrence of epicenters (surface loci of heavy shocks) along such lines, has been a characteristic of the Austrian method, which dates from a paper published by Suess in 1872. Such lines in the surface, generally approximating either to a right or to a broken line, were in some cases identified with the traces of fault planes and in others were shown with much probability to be the course of such displacements. Here, then, was the first important recognition of the tectonic nature of earthquakes, and, as a consequence, the Austrian school of seismologists has since endeavored to examine earthquakes in the light of the geological structure of the affected region.

It must be regarded as quite remarkable that the recognition of this fundamental fact was reached in Austria, for the opportunities offered by the Austrian field were by no means exceptional. In fact, the great surface faults which have been a feature of great earthquakes in other districts, have there been seldom observed. In New Zealand, for example, accompanying a heavy earthquake in 1856, an area of country comprising 4,600 square miles was suddenly upraised to form a visible escarpment varying from one to nine feet in height. This event was duly described by Lyell, who, in the eleventh edition of his widely read "Principles of Geology" reported this and other similar cases apparently without seeing that they throw any discredit upon the centrum theory.

In 1884[1] Gilbert, in a brief note, explained the earthquakes characteristic of the Great Basin of the western United States as due to the interrupted jolting uplift of the mass of the mountains by vertical thrust. The stresses tending to uplift the range aided by a fissure already in existence, accumulate until they overbalance the starting friction upon the fissure, when through movement the strain is relieved and the potential energy of the system reduced. In a later note published in 1890[2] he showed that during the earthquake of 1872 in the Owen's Valley, California, the ground was moved in strips both vertically and horizontally.

In 1893 Kotô, describing the great Japanese earthquake of 1891, in referring to earlier earthquake rents within the same district said:

> The event of October, 1891, seems to me to have been a renewed movement upon one of these preëxisting fissures—the Neo Valley line of fault, by which the entire region lying to the right of it not only moved actually downwards but was also shifted horizontally towards the north-west for from one to two metres along the plane of dislocation. This vertical movement and horizontal shifting seem to me to have been the sole cause of the late catastrophe.[3]

Without the aid of surface faults, Leonhard and Volz, in 1896, expressed clearly the idea that the Silician earthquake of 1895 was the result of an adjustment among orographic blocks or *Schollen.* Their statement was:

[1] *Amer. Jour. Sci.,* Vol. 27, 1884, pp. 49–53.
[2] Mon. I., U. S. Geol. Sur., pp. 360–362.
[3] *Jour. Coll. Sci.,* Tokyo, Vol. V., 1893, p. 329.

We must, therefore, regard the cause of the earthquake of June 11, 1895, as a movement of the Nimpt complex of orographic blocks, which occurred along the southern and eastern fracture margins.[4]

The great Indian earthquake of 1897 was thoroughly examined from the geological side with results which seem to have afforded indication of the movement of the ground in individual blocks. This, however, was not the theory adopted by R. D. Oldham, who wrote the report upon the earthquake, apparently for no other reason than that it seemed to require an expansion of the affected area. In consequence, the unique hypothesis was offered that the earthquake was due to a movement upon a thrust plane beneath the affected region. The mental attitude of Dr. Oldham is brought out in the following paragraphs from his report in modification of his choice of theory:[5]

Though apparently the most probable this is not the only possible, hypothesis. The surface features of the Assam range, described in the last chapter, are compatible with, in some respects they suggest, the idea that these hills are what the German geologists call Schollengebirge, that is, mountains which have arisen from straight up and down thrusts, instead of from lateral compression, like the Alps and Himalayas. *If this be so, the faults by which the fault scarps are formed would be normal faults,*[6] and so far from there having been any compression, the elevation of these hills would have been accompanied by an extension of the surface. The state of strain, too, which preceded the earthquake would have been one of tension and not compression.

The mechanism of the production of this form of mountain is not properly understood, and a condition of tensile strain in the crust of the earth would be still more difficult to explain, but the fact of the existence of such mountains and structures cannot be gainsaid, so the possibility of the state of tensile strain they imply must be allowed.

If such is the nature of the Assam range, and of the cause of this earthquake, there would be no thrust-plane underlying it, and the focus of the earthquake would have to be regarded as a complex one. That is to say, there would be no general focus, but a number of independent ones, along each fault, and the magnitude of the earthquake experienced would be due to the simultaneous occurrence of a number of earthquakes of various degrees of severity.

Whether we regard the focus as a thrust-plane, or as a network of faults, it practically covered an extensive area.[7] The hypothesis of a thrust-plane

[4] *Zeitsch. f. Erdkunde z. Berlin,* Vol. 31, 1896, pp. 1–21.

[5] R. D. Oldham, "Report on the Great Earthquake of 12th June, 1897," *Mem. Geol. Surv. India,* Vol. 29, 1899, pp. 165–168.

[6] The italics are mine.—W. H. H.

[7] The italics are mine.—W. H. H.

is the simplest to work with, as also the most probable, and it is that which has been adopted in the following pages.

As we shall see, the fundamental difficulty which stood in the way of the acceptance of the *Schollen* idea at the time Oldham was writing, has since been removed by the "distant" studies of earthquakes (see below, p. 285), and the theory of a thrust-plane, which he chose to adopt, has remained without any support in later work.

Additional and important contributions toward the fault-block theory of earthquakes have crowded about the beginning of the twentieth century. In the year 1900, Yamasaki, in describing the great earthquake of northern Honshu, which occurred in 1896, gave as its cause the movement on two visible displacements which opened on opposite sides of the mountain mass.[8]

> Two long lines of fracture were discovered by me to be the cause of the Riku-U. earthquake. . . . They lie on the two sides of the mountain axis of the Central chain, and so this earthquake offers an example of the longitudinal quakes (*Längsbeben*) which but seldom occur.

Thoroddsen, in a report which reached the scientific world first through a German abstract of the year 1901,[9] was able to show that during each of the five heavy shocks of the South Icelandic earthquakes of 1896, a separate block of country had been shaken. These several areas were all included in a low plain walled in by a rampart of mountains, and with a single exception they were contiguous areas which did not overlap.

> Each of the heavy shocks was limited to a circumscribed area which was made evident by a mass of collapsed houses, and from this the earthquake waves were propagated outward in all directions.
>
> . . . .
>
> The ground beneath the low plain is probably separated into individual parts and the continued movement on these cross lines [across the main fissures on which the volcanoes of the island are ranged.—W. H. H.], as well as the faults between the individual parts, appear to be the causes of the many earthquakes of this district. If one studies the statistical tables of the ruined houses from each shock [given in Icelandic report.—W. H. H.] it is seen that the individual areas are somewhat sharply delimited; while upon them nearly everything was destroyed, the damage outside was relatively small.

[8] N. Yamasaki, *Pet. Mitt.*, Vol. 46, 1900, pp. 249–255, map.

[9] *Pet. Mitt.*, Vol. 47, 1901, pp. 53–56. The full report had appeared in the Icelandic language two years earlier.

Writing in 1902 Professor John Milne, who has done so much to advance seismology, gave expression to his views upon the cause of the larger and smaller earthquakes:[10]

The earthquakes to be considered may be divided into two groups—first, those which disturb continental areas and frequently disturb the world as a whole, and secondly, local earthquakes which usually only disturb an area of a few miles radius and seldom extend over an area with a radius of 100 or 200 miles.

These former I shall endeavor to show are the result of sudden accelerations in the process of rock-folding accompanied by faulting and molar displacements of considerable magnitude, whilst the latter are for the most part settlements and adjustments along the lines of primary fractures. The relationship between these two groups of earthquakes is therefore that of parents and children.

Professor Milne's studies of "distant" earthquakes had revealed the fact that the world-shaking earthquakes most frequently occur upon the floor of the ocean.

When a world-shaking earthquake takes place, and its origin is sub-oceanic, we occasionally get evidence that this has been accompanied by the bodily displacement of very large masses of material. For example, sea-waves may be created which will cause an ocean like the Pacific to pulsate for many hours.

To indicate the grand scale of the mass movements of the crust upon the continental areas, a list of twenty-two larger disturbances was compiled by Milne and the following important conclusions drawn:

If it can be admitted that world-shaking earthquakes involve molar displacements equal in magnitude to those referred to in the preceding list, . . . then, in the map showing the origins of these macroseismic effects, we see the districts where hypogenic activities are producing geomorphological changes by leaps and bounds.

The sites of these changes are for the most part suboceanic troughs. When they occur, the rule appears to be that a sea becomes deeper, whilst a coast-line relatively to sea level may be raised or lowered. For nearly all the regions of the world where they take place we have geological and not unfrequently historical evidence that the more recent bradyseismic movements have been those of elevation. This elevation, however, only refers to the rising of land above sea-level, while the mass displacements seem to be accompanied by sudden subsidences in troughs parallel to the ridges where rising has been observed. In short, at the time of a large earthquake, two

[10] "Seismological Observations and Earth Physics," *Geogr. Jour.*, Vol. 21, 1903, pp. 2, 9, 11.

phenomena are simultaneously in progress. A suboceanic trough may suddenly subside, whilst its bounding ridge may be suddenly increased in height, and the concertina-like closing of the trough may account for the sea-waves.

Dutton, in 1904,[11] included in his classification tectonic earthquakes, and by supplying data concerning the earthquake of Sonora in 1887 contributed an additional example of uplift *en bloc* of a mountain mass accompanied by a great earthquake. Of this range, the Sierra Teras, he says:

In other words, the range seemed to have been uplifted several feet between faults on either flank.

Yet the implication in the context is that these observations are hardly decisive, and in a paper read before the National Academy of Sciences in 1906[12] it is made clear that Dutton at this time still adhered strongly to a modified centrum view to which he had contributed in 1889 in his report upon the Charleston earthquake of 1886.

The Dutch geologist, Verbeek, in 1905 published a catalogue of the earthquakes of the island of Ambon in the East Indian Archipelago, together with a full account of the heavy earthquake which caused much damage upon the island on January 6, 1898.[13] His study of the distribution of the damage resulting from the latter quake brought out the fact that the shocks were largely limited to narrow zones on either side of a main fault running in a north and south direction across the island, and to similar zones about three additional faults which cross the first nearly at right angles, the stronger shocks belonging with the first mentioned displacement. Of this north and south zone he says:

The terrane most disturbed, which one designates "*the pleistoseismic area*" does not here have the form of a circle or of an ellipse, as in the case of so many earthquakes, but that of a long band relatively straight, which shows clearly that we have here to do with a *tectonic quake;* now since we have shown above in the description of the geology that there is at the south of Ambon a fault which is prolonged to the north through Ambon and southward . . . to the southern coast, it is altogether natural to attribute the earthquake to a new dislocation along this cleft or fault of the

[11] "Earthquakes in the Light of the New Seismology," 1904, p. 55.

[12] "Volcanoes and Radio Activity," Englewood, N. J., 1906, p. 5.

[13] R. D. M. Verbeek, "Description Géologique de l'isle d'Ambon," Batavia, 1905, pp. 300–323.

earth's crust. Since the formation of this cleft, which is at least of pre-Cretaceous age, doubtless movements have often occurred which continue even to our time. . . .

In the following year the Count de Montessus de Ballore, who had already become known as a seismologist of reputation by reason of his masterly essay upon the distribution of seismicity over the globe, brought out a comprehensive work entitled "Seismic Geography." In this volume, as a result of the study of no less than 170,000 recorded shocks of earthquake, their distribution within each province was analyzed by new and ingenious methods of combination. In each case the known faults of the district under consideration were discussed, and so far as possible, their relation to the seismic distribution was brought out.[14]

Much the clearest demonstration of the adjustment of portions of the earth's crust as individual blocks, and here by well-demonstrated changes of level, is to be found in a paper by Tarr and Martin upon the results of earthquakes in Alaska in the fall of 1899.[15] Some portions of the coast were found to have been elevated, and other smaller ones to have been depressed. The sea, which here cuts up the district by a number of fiords, permitted the changes of level to be measured by the height of the abandoned shore lines of 1899. In the absence of earlier soundings or of correct maps, the submerged areas were determined with much less precision, though forests now below sea level bear abundant testimony to the local direction of the earth movement. Still older abandoned shore lines, appearing as notches above the raised beach of 1899, proved that the latest elevation is but one stage in the progressive, though interrupted, general uplift of the region. Tarr and Martin's statement of their view is as follows:

Briefly summarizing the inferences which the facts seem to warrant, we conclude that in 1899 there was a renewal of mountain growth, uplifting that part of the mountain front bordering the Yakutat bay inlet to different amounts—7 to 10 feet in the southeast side of the bay, and 40 to 47 feet on the northwest side. This uplift occurred all within a little over two weeks and mainly on a single day (September 10). It was complicated by move-

[14] "Les tremblements de terre; Géographie séismologique," Paris, 1906, pp. 475.

[15] "Recent Changes of Level in the Yakutat Bay Region, Alaska," *Bull. Geol. Soc. Am.*, Vol. 17, 1906, pp. 29–64, pls. 12–23.

ments along secondary fault lines, which produced at least three (and perhaps more) major blocks. . . . The first and largest of these blocks, . . . is apparently titlted upward toward the southwest.

Accompanying this faulting was a minor fracturing apparently due to local adjustments in the tilted blocks. Doubtless this minor fracturing is much more common than our observations indicate, for it was discovered in more than half our expeditions into the interior when we went out of the valleys away from the sea coast.

The evidence accumulated for the tectonic origin of earthquakes and their inseparable connection with the process of faulting in rock strata, has shown that seismology must be considered as a part of tectonic or structural geology—that part, namely, which is concerned with the recent and present-day history of the earth. So soon as this fact receives general recognition, the field of study must be added to that now explored by geologists. For their loss in this quarter elasticians will be more than compensated by the enlarged opportunities which are now offered them for studying earth waves as they are registered at a distance upon the newly devised earthquake instruments.

Recognizing, then, that earthquakes manifest the time of operation of these larger mass movements of the earth's crust which have brought about changes in level as well as changes in horizontal position in connection with faulting, it becomes necessary to place the subject *en rapport* with the latest that has been learned in the wide field of tectonic geology. This treatment of earthquakes as a part of tectonic geology was attempted by the present writer in two monographs published in 1907 in connection with a description of the Calabrian earthquake of 1905,[16] and later, in the same year, in a treatise upon seismic geology.[17]

Having in mind the fact that the traces of fault planes are but rarely exposed to view, and in only a small percentage of cases possible of determination from purely geological studies, the investigation of the Calabrian earthquake was directed toward determining whether, (1) there are lines or narrow zones of special

[16] "On Some Principles of Seismic Geology," with an introduction by Eduard Suess. "The Geotectonic and Geodynamic Aspects of Calabria and Northeastern Sicily," with an introduction by the Count de Montessus de Ballore. *Gerland's Beiträge z. Geophysik,* Vol. 8, 1907, pp. 219–362, pls. 1–12.

[17] "Earthquakes, An Introduction to Seismic Geology," New York, 1907, pp. 1–336.

intensity of shocks, (2) whether these are repeatedly the seat of special danger from successive earthquakes, and (3) whether such lines, if they exist, are expressed in the surface of the country as earth lineaments. The investigation showed that at the time of an earthquake the surface of the country affected is peculiarly sensitized to reveal the courses of hidden faults, which, if thus made apparent, may be designated *seismotectonic lines,* and that strong seismotectonic lines correspond in position to the striking lineaments of the country. In this we find a means of deriving through the study of the topography, the tectonic geology and the seismic history, an imperfect yet none the less a valuable map to display the architecture of each seismic district.

It is a curious illustration of earlier misdirection of effort, that up to the year 1907 no detailed map of the fault system within an area disturbed by destructive earthquake had been attempted. The maps which best display the disposition of adjusted fault blocks were the small-scale charts by Thoroddsen and by Tarr and Martin. In the summer of 1907, at the writer's suggestion, the expert topographer and geologist, Mr. W. D. Johnson, of the U. S. Geological Survey, prepared accurate maps of the surface faults of certain areas disturbed during the Owen's Valley earthquakes of 1872, which maps were published in part during the same year.[18] The sudden changes of displacement on individual faults and the mosaic-like structure of the disturbed region were thus brought out with a clearness and accuracy never before attained.

Seismological science may be said to have suitably celebrated its emancipation from the bondage of the centrum theory, when in 1907 there was published from the pen of the Count de Montessus de Ballore the most comprehensive treatise upon the subject.[18a] This book recognized the adjusted fault block theory as the best available working hypothesis of the science, and with a grasp of the subject which was based upon a lifetime of study, and upon a quite unparalleled knowledge of the literature, earthquakes were so treated as to make the work the one authoritative reference book of the science.

[18] In the author's "Earthquakes," Figs. 23, 45 and 64. More complete maps will appear in a special monograph.

[18a] La Science Séismologique, Paris, 1907, pp. 579.

The common characteristic of all phases of the modern tectonic theory of earthquakes, the evolution of which we have now largely traced, is that the adjustments in position or attitude of sections of the earth's crust are regarded as *the proximate cause and not the effect of the shocks themselves.* So far as molar movements have been recognized by the advocates of the centrum theory, they have been regarded as the *direct consequence of volcanic or explosive shocks emanating from a deeper-seated origin.* Two recent papers of a somewhat speculative nature, prepared by an astronomer, have sought the cause of earthquakes in a leakage from the bottoms of the oceans.[19]

The Relation of Earthquakes to Volcanoes.—As already pointed out, the earliest of the generally accepted theories of earthquakes connected them directly with volcanic action, and this idea has survived in the centrum theory. The tendency of later study has been to indicate that while both betray a certain relationship to each other, this is not often of such a nature as to call for a quick response of the one phenomenon to the other. Regions of volcanoes are subject to earthquakes, yet some of the heaviest earthquakes have affected a region distant from any volcanic vents. Again, most great volcanic outbursts are inaugurated by light earthquakes, but great earthquakes produce as a rule no perceptible immediate effect upon the activity of neighboring volcanoes. Thus, for example, during the late Messina earthquake, which was so heavy about the slopes of Etna, that volcano showed no sympathetic response. Catalogues setting forth the seismic and volcanic activity within any province betray, however, certain periods of years during which both seismic and volcanic activity are at either a maximum or a minimum; though within these periods no close time relation of the one phenomenon to the other is apparent. In short, it would appear

[19] T. J. J. See, A.M., Lt.M., Sc.M. (Missou.), A.M., Ph.D. (Berol.), "The Cause of Earthquakes, Mountain Formation and Kindred Phenomena Connected with the Physics of the Earth," Proc. Am. Phil. Soc., Vol. 45, 1907, pp. 274–414. "Further Researches on the Physics of the Earth, and especially on the Folding of Mountain Ranges and the Uplift of Plateaus and Continents Produced by Movements of Lava Beneath the Crust Arising from the Secular Leakage of the Ocean Bottoms," *ibid.*, Vol. 47, 1908, pp. 157–275.

that both earthquakes and volcanic activity are different indications of the operation of a more fundamental geological process—mountain formation, with its concomitant manifestation in changes of level.

Going back in the direction of the ultimate cause of mountain building, we are probably correct in assuming that it is a consequence of the contraction of volume of the planet and the wrinkling of the outer shell, as that shell adjusts itself over the diminished volume of the core beneath. In the past much confusion has arisen from assuming that flexuring has taken place within the outermost shell of the earth, and that the faults discovered are an incident to the folding process *within one and the same set of beds.* Thus we have come to speak of "dip faults" and "strike faults," "longitudinal faults" and "cross faults." Later studies have shown that the processes of folding and of faulting within rocks take place under different conditions of load corresponding to different depths below the surface; and that, therefore, the folding which accompanies the rise of a mountain range is so deeply buried beneath the roots of the range that it can be laid open for study only after a blanketing layer of rock some miles in thickness has been removed. Those mountains which are growing to-day—such, for example, as the Sierra Nevadas of the Pacific border of our own country—are being pushed up in blocks which are outlined by steep faults. The elevation goes on spasmodically, and each successive uplift causes a jolt which is manifested as an earthquake more or less destructive, according as the movement is of large or of small amplitude. Deep below the surface, the rising blocks of the crust rest upon arches of folds which a future generation of geologists may be privileged to study after a layer of the present surface some miles in thickness has been carried away. Those parts of the earth's crust which are not shaken by earthquakes are, in the language of de Montessus, no longer living—they are dead.

Not only are earthquakes the indication of changes in level such as accompany the process of mountain growth, but active volcanoes are now recognized to afford evidence of the same movements. Wherever mountain ranges are now rapidly growing, there active volcanoes are to be found. The full significance of this fact is only beginning to be appreciated. Fortunately this hypothesis may be fitted to the now quite generally accepted view that the earth is essentially solid throughout, and is maintained in that condition at great depths below the surface by the high pressure from the superincumbent material. Now the arching of strata in the process of folding is competent to lift the load from underlying rocks, so that wherever their temperature is such that fusion would occur at the surface, a reservoir of molten lava is produced and will be brought to the surface from the action of gravity whenever a path is open for it. A reason is thus found for the presence of lava bodies at moderate distances only from the surface in those districts where the process of mountain building is in operation.

The Mesh-like Distribution of Volcanic Vents.—The lineal arrangements of volcanoes and the dependence of this alignment upon the existence of fissures through the crust, seems to have been one of the earliest of geological observations, so soon as the less civilized continents had been scientifically explored. In Europe the systematic arrangement of volcanoes is much less strikingly displayed, and it was there in consequence a later discovery. The credit for having first recognized this important fact of observation is generally given to von Buch, because of his classical study of the Canary Islands. It seems probable, however, that Alexander von Humboldt, his friend and colleague in the field of geological exploration, was the first to make the observation. The latter showed that the volcanoes in the Cordilleran system of South and Central America furnish striking examples of such alignment. Von Buch, in his turn, emphasized this significant relationship, but found certain volcanic districts within which the alignment of vents was not apparent, and so he distinguished *volcanic chains* from *central volcanoes*. Other explorers like Dana and Darwin soon added confirmation of a linear arrangement from the regions which they had individually visited. Dana, a member of the Wilkes Exploring Expedition, brought out the lineal arrangement of the Polynesian Islands and showed that all these were alike rows of partly submerged volcanic peaks.[20] Darwin, during his voyage on the

[20] "Manual of Geology," pp. 37, 282.

"Beagle" made observations[21] which advanced the knowledge of volcanic distribution, as we shall see, very nearly to that of the present day.

As early as 1825, that pioneer and master of vulcanology, Paulett Scrope, discussed the arrangement of volcanoes in the following manner:[22]

> The generality of volcanos have a decided linear arrangement; one vent following the other in the continuation of the same straight or nearly straight line; and when volcanos have been formed on neighbouring points out of this principal line, they are in almost all cases situated upon other rectilinear bands parallel to the first.

Later Scrope expressed his doubt of the existence of v. Buch's class of central volcanoes, for which it had been claimed no alignment could be discovered.[23] In 1844 Darwin proved the existence of neighboring parallel fissues outlined by volcanoes, and was further able to show by his studies of the Galapagos Islands that the arrangement of the vents there brought out the existence of a network of fissures composed of two rectangular series with the principal vents at the intersecting points.[24] The directions of the two series were northwest by north and northeast by east. Virlet d'Aoust had already discovered the same kind of structure in the arrangement of the volcanoes within the Grecian archipelago.[25]

Inasmuch as a mesh-like disposition of volcanic vents within a network is of the first importance in its relation to the mass displacements which occasion earthquakes, it is pertinent to examine the more recent literature of the subject with a view to establishing its truth or falsity. The newer and more accurate methods for preparing maps which have been introduced since the time of Darwin, make such a review at the present time in every way desirable. There are two regions especially which have been recently carefully studied by authorities of the first rank in the field of vulcanology. I refer to Iceland, surveyed at his personal expense throughout a

[21] "Geological Observations on the Volcanic Islands, etc.," 1844, pp. 140–145.

[22] "Considerations on Volcanos," London, 1825, p. 126.

[23] "Volcanos," London, 1862, p. 258.

[24] *L. c.*, edition of 1900, p. 131.

[25] *Bull. Soc. Geol. France*, Vol. 3, 1832–33, pp. 103–110, 201–204.

period of seventeen years by Professor Thoroddsen of Copenhagen, and the islands of the East Indian Archipelago, surveyed for the Dutch Government by the distinguished geologist, Verbeek. Of the Icelandic volcanic region Thoroddsen says:[26]

Of larger eruption fissures and crater chains I have found 87, all of postglacial origin; . . .

. . . The many fissures which are common to several districts can not possibly be entered upon a map of small scale; the terrane is often so divided by clefts that both within the flat country and upon the slopes of mountains it appears to be separated into numerous narrow strips some kilometers in length. . . .

. . . Between the numerous non-volcanic and the volcanic clefts which have poured out important streams, no difference is to be noticed; an ordinary cleft may suddenly become volcanic. . . .

. . . Where larger fissure systems cross, there are often found large

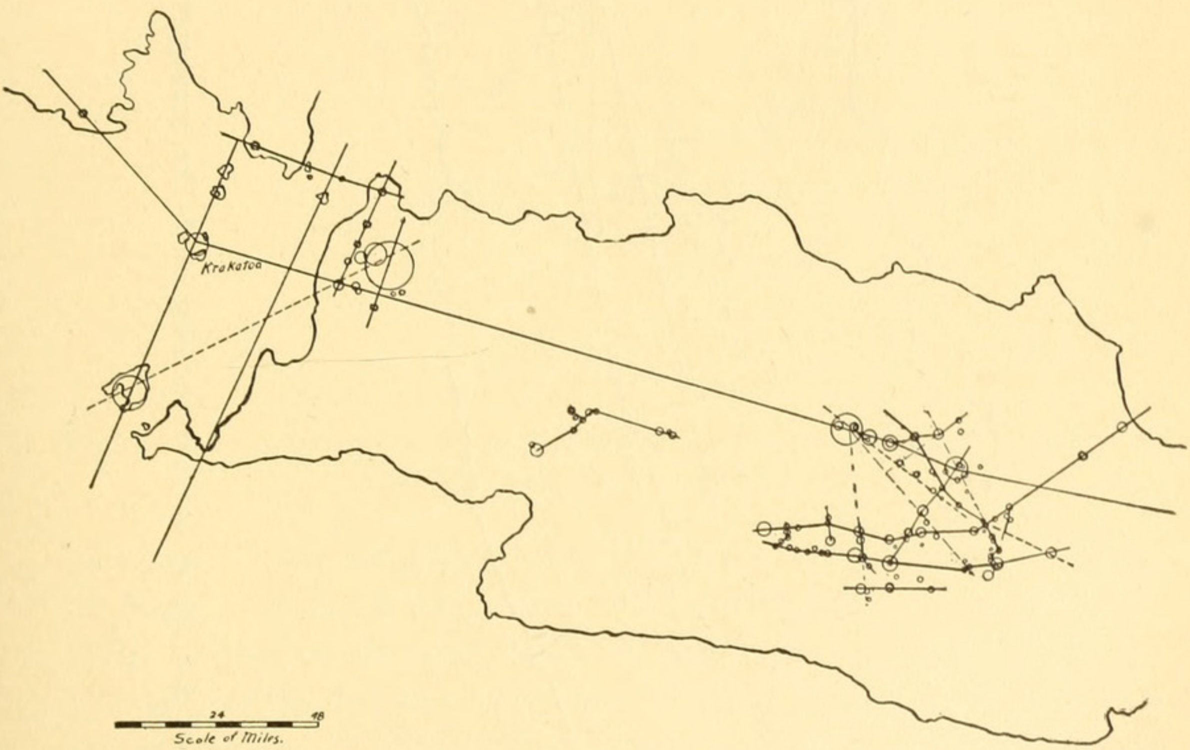


Fig. 1. Map showing arrangement of volcanoes in the western part of the Island of Java. (After Verbeek.)

volcanoes, as for example the largest volcano in Iceland, Askja, with a crater of 55 sq. km. area situated at the intersection of the southland fissure running NE.-SW. and the northland one trending N.-S.

[26] "Die Bruchlinien Islands und ihre Beziehungen zu den Vulkanen," *Pet. Mitt.*, Vol. 51, 1905, pp. 1–5, map pl. 5.

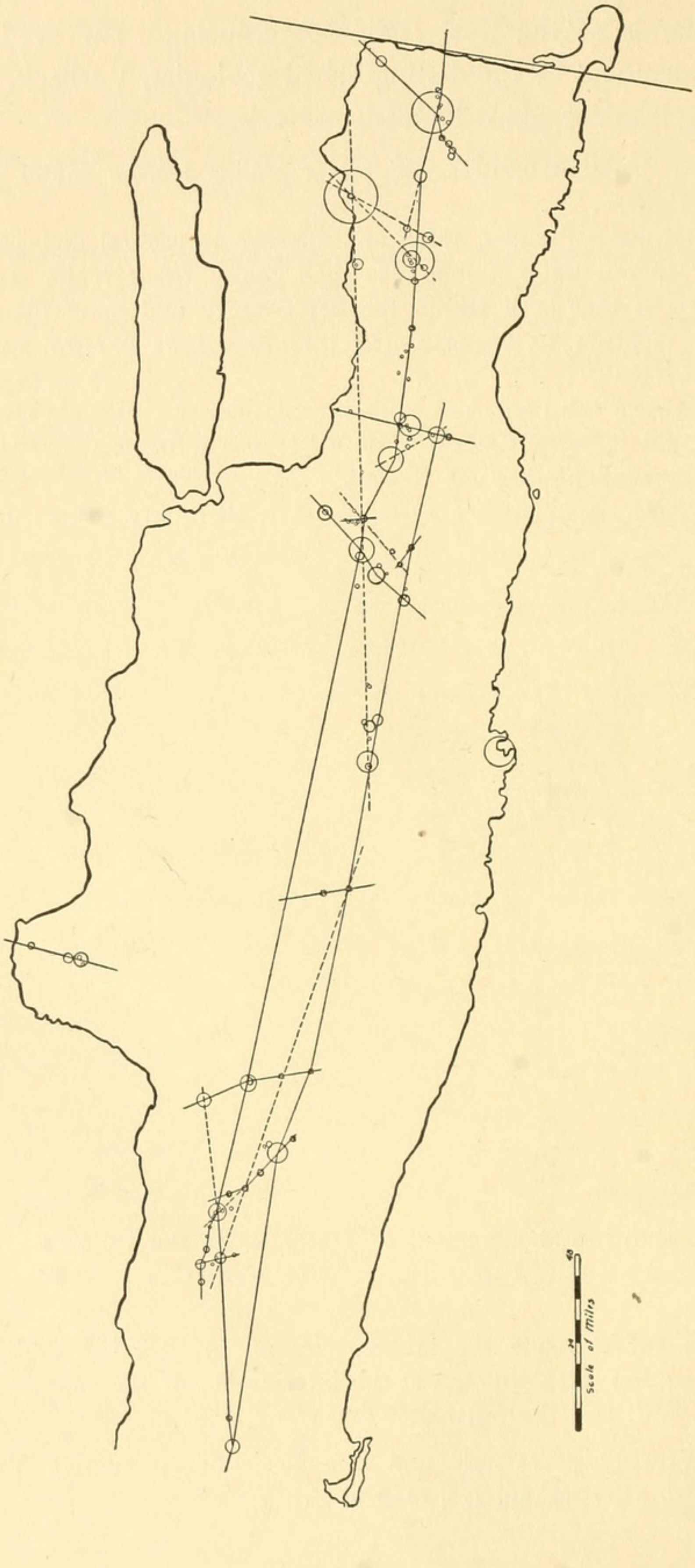


FIG. 2. Eastern portion of the Island of Java showing mesh-like arrangement of the volcanic vents. (After Verbeek.)

With the exception of the report on Krakatoa the five monographs and accompanying grand atlases which have been issued by the Geological Survey of the Dutch East Indies under the direction of Dr. Verbeek, seem to be but little known; yet they contain the results of extended and detailed surveys within one of the world's most interesting volcanic regions.[27] Nowhere have such trustworthy data been compiled which permit of a thorough study of the arrangement of volcanic vents. Clearly aligned upon fissures the map of Java displays the elements in the intersecting volcano network, as may be seen from atlas drawings reproduced in Figs. 1–2.

Though more accurately worked out, it does not appear that these instances of intersection of volcano rows is exceptional. Felix

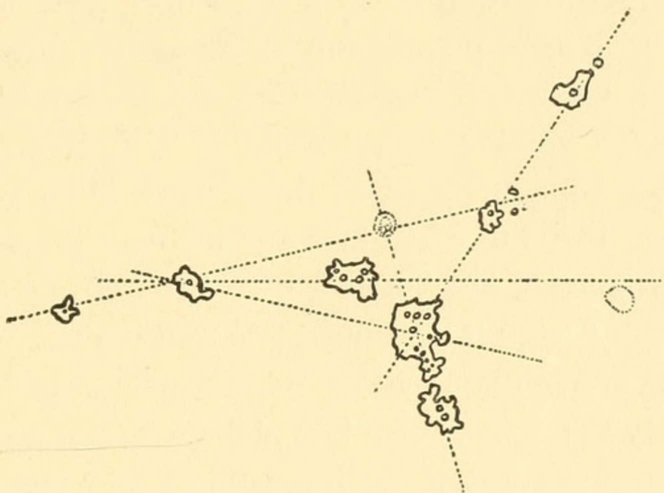


FIG. 3. Map to bring out the arrangement of volcanic islands and submerged volcanic peaks in the Lipari group.

and Lenk[28] have explained the prominence of the mighty volcanoes of Mexico, Popocatepetl, Ajusko and Nevada di Toluca, as due to their location at the intersection of important fissures, though the warrant for this has been questioned by others. The volcanic Lipari Islands of the Mediterranean, which were formerly regarded as

[27] Verbeek, "Sumatra's Westkust" (Dutch language), Batavia, 1883, 674 pp., atlas of 16 maps. Verbeek, "Krakatau," Batavia, 1885, 567 pp., atlas of 25 pls. Verbeek et Fennema, "Description Géologique de Java et Madoura," Amsterdam, 1896, two volumes, 1,183 pp., atlas of 24 maps. Verbeek, "Description Géologique de l'ile d'Ambon," Batavia, 1905, 323 pp., atlas of 10 maps. Verbeek, "Rapport sur les Moluques," Batavia, 1908. 1844 pp., atlas of 20 maps.

[28] *Zeitsch. d. deutsch. geol. Gesell.*, Vol. 44, 1892, pp. 303–326.

built up on radial fissures going out from the ruptured center of a depressed area, reveal a regular plan with the volcanic peaks and craters at the crossing points of intersecting lines, so soon as the submerged cones are brought into the problem (see Fig. 3).[29] The volcanoes of Italy and surrounding waters furnish an example of a much larger network within which the vents are located at intersecting points.[30]

What is true of the arrangement of ordinary volcanic cones within individual provinces, is repeated in the case of the monticules or parasitic cones which are built up upon the flanks of larger composite volcanoes, such, for example, as Etna.[31] To some extent a similar arrangement may be inferred on a far grander scale than any that has been mentioned, as in the longer trains of the volcanic islands. As long since pointed out by Neumayr, the volcanic island, St. Helena, is located at the crossing point of two long lines of widely separated volcanoes, one trending NE.–SW., and the other NW.-SE. (See Fig. 4). One of these, the well known "Cameroon fissure," bisects the Gulf of Guinea and includes the volcanic islands, St. Helena, Annobom, Sao Thomé, I. do Principe, and Fernando Po. On the land this fissure is continued in a striking manner by the fault bridge which ends in the Tschebitschi, 2,000 meters high, which then drops suddenly to the level of a low plain less than 200 meters above the sea. The volcanotectonic line which intersects this striking lineament at St. Helena, includes Ascension, one of the eastern cones of St. Paul's Rocks and a conical, submerged elevation upon the sea floor, almost under the tropic of Capricorn about 800 kilometers southwest of Amboland.

In addition to these two fissure directions, a third is like them strikingly characteristic of the African continent, as shown by the remarkable north and south lines of volcanoes and rift valleys in central Africa east of the Nile. To these three prevailing directions, northwest-southeast, northeast-southwest, and north-south, must be added a fourth less common direction, namely, east-west. Simmer

[29] Hobbs, *Gerlands Beiträge z. Geophysik,* Vol. 8, 1907, pp. 316–317.

[30] *Ibid.,* pp. 315–316, smaller map of pl. 3. See also Suess, "The Face of the Earth," Vol. 1, p. 144.

[31] Hobbs, *l. c.,* pp. 348–349, pl. 10.

in a noteworthy compilation[32] has shown that these directions are brought out for the African continent not only in the lines of

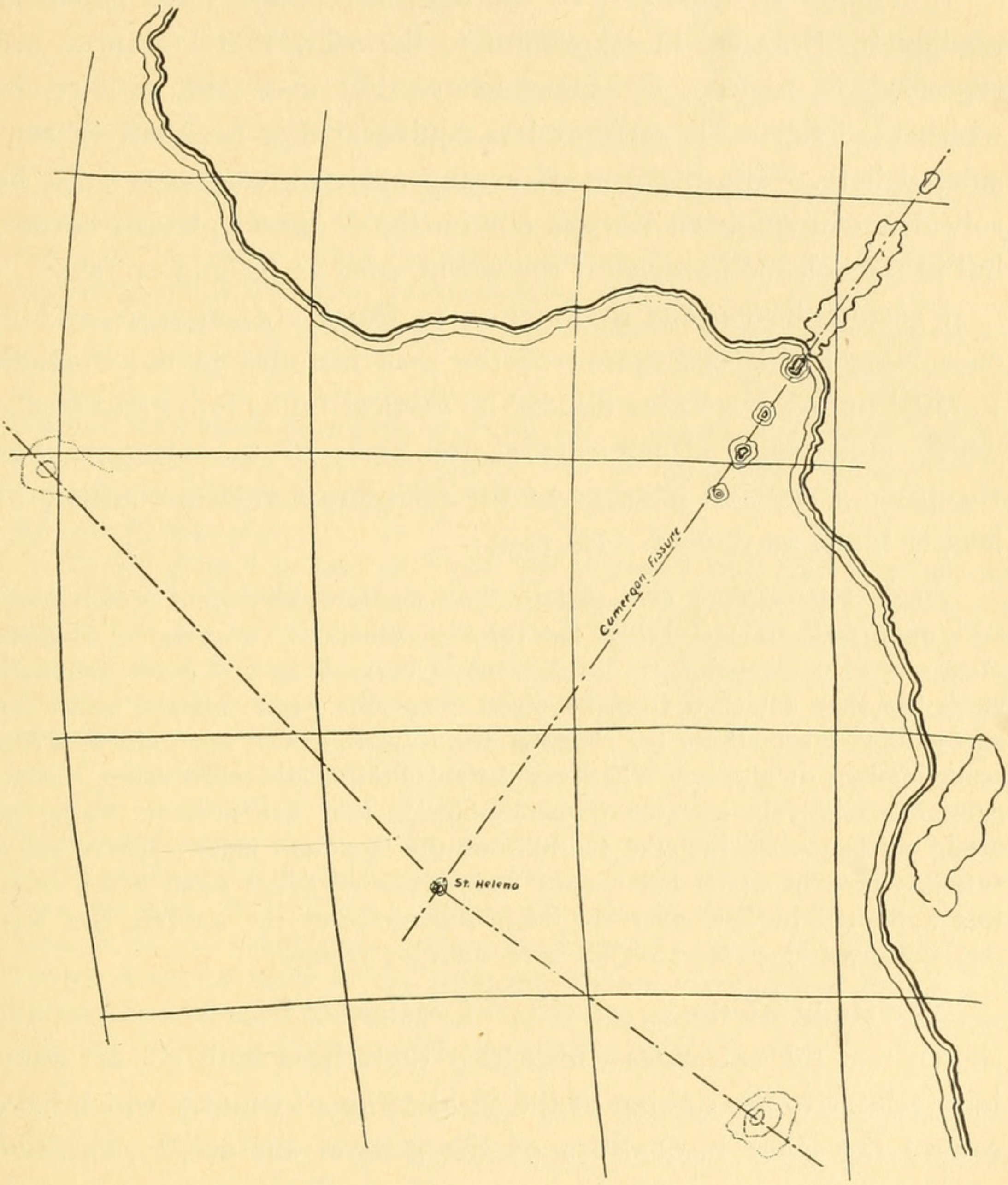


FIG. 4. Volcanotectonic lines which cross at St. Helena.

volcanoes but by the fracture systems revealed in the rocks, so far as they have been studied. It is interesting to note that these

[32] "Der aktive Vulcanismus auf dem Afrikanischen Festlande und den Afrikanischen Inseln," *Münchener Geographische Studien*, No. 18, 1906, 218 pp.

directions are also the dominant ones in the fracture system of North America.[33]

A number of papers of a controversial nature have appeared notably by Branca[34] in opposition to the view that volcanoes are aligned upon fissures, but inasmuch as they deal with districts in which the evidence is more or less equivocal they need not be considered here. The problem of arrangement of volcanoes must be solved not in southern Europe nor on the Mexican plateau border, but in the volcano gardens of the world, such as Iceland or Java.

Volcanic Extrusions in Relation to Block Adjustments.—Clarence King in his description of the area included in the Fortieth Parallel Survey,[35] an area divided by vertical faults into great blocks which underwent adjustments at the close of the Miocene, has furnished a classical instance of the relation of volcanic outflow of lava to block movement. He says:

> Single ranges were divided into three or four blocks, of which some sank thousands of feet below the level of others. The greatest rhyolite eruptions accompanied these loci of subsidence. Where a great mountain block has been detached from its direct connections and dropped below the surrounding levels, there the rhyolites have overflowed it and built up great accumulations of ejecta. Whenever the rhyolites, on the other hand, accompany the relatively elevated mountain-blocks, they are present merely as bordering bands skirting the foothills of the mountain mass. There are a few instances in which hill masses were riven by dykes from which there was a limited outflow over the high summits—but the general law was, that the great ejections took place in subsided regions.

The study of the great rifts of eastern Africa seems to have shown that the volcanoes which have there been built up, are similarly related to the sinking of the great strips of country which have caused the chief inequalities of the general surface.[36] The two

[33] Hobbs, "The Correlation of Fracture Systems and the Evidences of Planetary Dislocations within the Earth's Crust," *Trans. Wis. Acad. Sci.*, Vol. 15, 1905, pp. 15–29.

[34] W. Branca, "Zur Spaltenfrage der Vulkane," *Sitzungsber. Ak. Wiss.*, Berlin, 1903, pp. 748–756.

[35] "United States Exploration of the Fortieth Parallel," Vol. 1, Systematic Geology, 1878, p. 694.

[36] Ed. Suess, "Die Brüche des östlichen Afrika," *Denksch. Weiner Akad., Math. Naturw. Kl.*, Vol. 58, 1891, pp. 555–584.

chains of volcanoes in Mexico as mapped by Sapper[37] seem to be similarly associated with the great rift valley lying on the western border of the Mexican plateau.

It is in Iceland, however, that the most extended studies have been made of the most interesting field, in which the relation has been worked out with the greatest thoroughness.[38] Says Thoroddsen:

> One gains the impression that the form of the surface has no significance as regards the volcanic force, which breaks out above upon the ridges, as well as below in the valley, yet the volcanoes are always found associated with areas which are either sinking or have sunk.
>
> The lava stream Ögmundarhraun in Krisnoik, which dates from about 1340, was poured out from two parallel clefts. The southernmost portion of this stretch of country between the clefts after the beginning of the eruption sank about 66 meters, and one side of the western fissure rose like a vertical wall with four half craters open at the brink, the other halves having sunk. At the end of the cleft is a visible dike which leads up to the row of craters.
>
> Where great fractures or faults are present in the crust, the volcanic forces have not always made a single passageway through them, but in the vicinity on parallel clefts, often upon the high fracture margin; thus one fracture line 50 km. long extends without volcanoes from Krisnoik to Hengill, at which place the north side is sunk 200 to 300 meters; parallel with this is here found above at the margin of the cliff an almost uninterrupted series of craters which have formed not alone upon a single fissure but over several slices and small fissures running parallel to one another. A similar phenomenon is to be observed on the southern fracture margin of the peninsula of Snaefellsnes where the craters are mainly found above upon the edge of the bluff. Often, also, the reverse is the case, as for example, in the Odadahraun, where the rows of craters for the most part extend along the bases of the mountain chains, which rise as horsts from the sunken ground on either side; a like example occurs at Myvatu, although here the rows of craters occur at times above upon the ridge.

In none of these cases have we evidence that the eruptions coincided closely in time with the earthquakes which must have accompanied the movements of the earth strips between their bounding faults, but the relationship of the one phenomenon to the other could hardly be more clearly proven. Summing up the discussion, we note that volcanoes, no less than earthquakes, help us to find the positions of those fissures within the crust by which it is separated

[37] "Ueber die raümliche Anordnung der Mexikanischen Vulkane," *Zeitsch. d. Deutsch. Geol. Gesell.*, 1893, pp. 574–577.

[38] *L. c.*, p. 3.

into a mosaic of blocks, and that these lines of fracture may therefore be designated *seismotectonic* or *volcanotectonic lines* or simply *lineaments* according as they are revealed by earthquakes, by volcano rows, or by topographic and geologic peculiarities.

A Possible Explanation of "Volcanic Earthquakes."—Writing before 1885 Suess distinguished two classes of earthquakes, the dislocation and the volcanic earthquakes, and to these Rudolph Hoernes added the type of in-caving earthquakes to cover especially some of the light shocks of the Dalmatian coast. If we were to supply a complete category of earthquakes it would be necessary to add further a type of cataract earthquakes to cover the occasional fall of limestone blocks in the Niagara cataract, as well as many other minor forms, such as blast shocks in mines, etc. In point of importance two classes only stand out sharply as they were originally announced by Suess, and the present writer has been of the opinion that even these may perhaps be subclasses only of a single phenomenon. The mechanics of volcanic eruption, so far as it applies to the cone, is now so well understood that we are able to connect the outflow of lava which marks the beginning of the grand stage of paroxysmal eruption in a composite cone, with the rending of the mountain and the opening of a fissure—a distinctly tectonic movement induced by the lava as it rises under the influence of gravity, aided perhaps by the expansive power of the associated steam. I believe we have been misled into supposing that the fissures which are thus opened are necessarily radial to the cone, since this would be presumed if the mass of the cone and its basement were throughout homogenous, with no preëxisting fractures, and were acted upon by hydrostatic pressure from the central shaft only.

Etna is a giant mountain rising nearly 11,000 feet directly from the sea, its diameter is more than twenty-five miles, and since the higher portions are so largely concentrated at the center, the average thickness of visible volcanic ejectamenta over the base of the cone is only about one half mile. Apparently, therefore, this superficial layer of volcanic material may play a relatively small rôle in the rending of the entire mass which accompanies an outflow of lava. So soon as we examine the lines of parasitic craters which are distributed upon the flanks of the mountain, we find that the majority of these are not radial to the mass at all, but comprise a network. A notable instance of a line of craters not in radial relation to the central cone is furnished by the chain of Monti Segreta, Nocella, Pizzuta, Gervasi, Arso and Difeso. Nearly parallel to this chain is that of the Monti Mazzo, S. Leo, Rinazzi, Guardiola and Albano. A map of these and other monticules upon the flanks of Etna has been already published by the writer.[39] It is, therefore, not only possible, but extremely probable, that in many instances the earthquakes which so generally accompany the rending of a volcanic cone, are directly associated with the opening of, and perhaps a differential movement upon, those fractures in the basement of the mountain which are a part of the larger fracture system of the district. Lacroix has recently shown that a *network* of fissures appeared upon Etna in connection with the eruption of 1908.[39a]

The Conditions of Earth Strain During the Growth of Block Mountains.—If we consider any circumscribed portion of the earth's crust within which mountains are growing through the adjustment by individual blocks or compartments of the crust, it is necessary to assume that the superficies is increased during the process. Individual blocks may indeed be actually depressed as a consequence of the adjustment, but yet the average movement must be assumed to be upward rather than downward. Such a conclusion is, however, in contradiction of the generally accepted view that mountain growth comes about through a reduction of superficial area from secular cooling. This very obvious difficulty in the way of adopting the *Schollen* conception of mountain structure has been quite generally recognized, and we have already seen how Oldham, in seeking the cause of the great Assam earthquake, was led to reject the theory, even though the vertical faults and the differential changes in level were plainly to be observed.

In the opinion of the writer, the recent study of "distant" earthquakes by modern seismographs has removed this difficulty in the way of a general acceptance of the fault-block theory. By extend-

[39] *Gerland's Beitraege z. Geophysik,* Vol. 8, 1907, pp. 348–350, Pl. 10.

[39a] L'eruption de l'Etna en avril-mai 1908, *Revue générale des Sciences pures et appliquées.* 20e année, 1909, pp. 298–314.

ing our knowledge of surface displacements of the earth to the floor of the oceans, it has brought us a surprise; for we have learned that to these areas, by many regarded as so stable, belong a much larger proportion of the grander movements, and by presumption of the smaller ones as well. The recent study of the ocean floor through soundings, examined with reference to the loci of suboceanic quakes, has told us, further, that though the movements upon the land are generally upward, those upon the ocean bottom, on the contrary, are downward. The so-called "origins" of the oceanic quakings are most frequently the steep borders of the great sea troughs where the greatest depths have been revealed by soundings. Now it is as impossible to separate the idea of molar displacements from these great disturbances as it is to avoid the conclusion that since these troughs are now the deepest bottoms, this is a direct consequence of the repeated displacements which must accompany the quakings. It has, moreover, been a general result of direct observation, that with noteworthy local exceptions the sea-coasts are to-day undergoing elevation, and that the steeper coasts face the greater depths.[40]

It is difficult to avoid the conclusion that the general upward movement of the margins of the continental areas and the general downward movements of the near-lying oceanic floors are interrelated as parts of one general adjustment within the outer shell of our planet. This granted, there is no difficulty in conceiving of the rise of block mountains upon the continental borders, since the increase of superficies within the affected continental region is compensated by a contraction of area in portions of the sea floor which in the same general period are subsiding. A rise of block mountains to the accompaniment of an earthquake, if our theory of cause be correct, though it calls for an expansion of the surface, should reduce the superficies of the affected region *if measured on the surface of a sphere at its former level.* A renewed and sudden compression of the district is thus made possible through the action of the tangential compressive stresses within the contracting shell. The writer believes that evidence of such compression has been

[40] See, among others, G. Schott u. P. Perlewitz, "Lothungen I. N. M. S. "Edi" und des Kabeldampfers "Stephan" im westlichen Stillen Ozean," *Arch. d. deutsch Seewarte,* Vol. 29, 1906, pp. 5–11.

found in the case of most large earthquakes in the behavior of rails and bridges.[41]

Part II: The Outlook of Seismic Geology.

The Ultimate Cause of Earthquakes.—No one should be deceived into concluding that because we seem to have found some evidence of the nature of the process by which the external shell of our planet undergoes its adjustment at the time of an earth shock, we have thereby discovered the *ultimate* cause of earthquakes. That is a far deeper problem, to which the discovery of the *proximate* cause is but an initial stepping stone. It is in this field that the deeper secrets lie hidden. The outlook of the science indicates two lines of effort to be followed up. These are: (1) To make practical application of the knowledge already gained, and (2) to investigate with every possible improvement in method until we have so laid bare the laws of seisms that we may forecast the time, the place and the probable severity of future earthquakes with at least as much accuracy and forewarning as is now possible in weather prediction.

Earthquake Forecasts.—It is much to be feared that the science of earthquakes is to pass through a stage not unlike that in meteorology which ushered in the day of scientific prognostication. Judging from statements which have been published, a "Farmer's Almanac" of earthquakes and popular earthquake prophets may be looked for as a possibility of the near future. It will be well, therefore, to consider the nature of the earthquake forecasts which have been so widely advertised. Examined with care it is found that these, in so far as they have found any verification, apply to a single, though the most important, seismic zone, and that all are indefinite as to the time and largely so as to place. Dr. Omori, of Tokyo, after the California earthquake of 1906, made a forecast which he himself subsequent to its partial verification reported as follows:[42]

As to the probable position of the next great shock on the Pacific side of America I expressed my view that it would be to the south of the equator

[41] Hobbs, "A Study of the Damage to Bridges During Earthquakes," *Jour. Geol.*, Vol. 16, 1908, pp. 636–653.

[42] *Bull. E. I. C.*, Vol. 1, No. 1, p. 23.

(that is to say, Chili and Peru), as it was very likely that the seismic activity would extend to either end along the great zone in question, and as the coasts of the countries above named are often visited by strong earth convulsions.

About two months after the prediction was made occurred the Valparaiso earthquake, but at the same hour an earthquake of the same order of magnitude visited an area in the Aleutian Islands within the same seismic belt, though nearer and in the opposite direction from the one predicted. On the same grounds Lawson in a lecture read in March, 1907, said of the stretches between southern California and Central America, and between northern California and southern Alaska:

These strips, I believe, will be visited before long, and then the long line of this earthquake will be complete from Chili to Alaska.

The Guerrero earthquake in Mexico occurred only a few weeks later and bore out the geologist's faith in the soundness of his hypothesis.

The method upon which such predictions are based is already indicated in the quotations given. Briefly expressed it is the principle of immunity from shock for a considerable period after heavy earthquakes, combined with the conception of relief secured throughout an extended zone in sections by alternation. An extended zone on the earth's surface is recognized to be what might be called an orographic unit; that is to say, it is all undergoing progressive though interrupted elevation. Stresses tending to produce uplift are presumably cumulative and may be of varying amounts in different sections of the zone. The resistance to movement under the strain—whether due to the rigidity, to the vice-like compression, to the absence of suitable fissure planes on which the movement might occur, to the healing of such fissures by mineral matter, or to any other causes—may be assumed to be different in different parts of the zone. Relief of stress through sudden uplift should, therefore, occur first within some one section of the zone where stresses are greatest, resistance least, or both. The earthquakes furnish abundant proof of the general correctness of this view. Now it is simpler to assume that relief having been secured in one section of the belt, a certain lowering of the potential energy of the system of stresses is to be expected in the near-lying sections on either side, particularly since the shock tends to discharge the system of strain as would a fulminate. On the theory of probabilities the area next to be relieved should be the most distant, providing stress has there been accumulated for an equally long period. The third and fourth steps in the cycle of release of strain should in position be intermediate between the first and second on one side or the other. Later steps in the "letting down" process should affect especially the still intermediate unrelieved sections of the zone.

This method, simple as it is in theory, permits of only the broadest generalization and, as already stated, has been tested in but one zone and for one cycle of relief. This zone is the great circle belt which surrounds the Pacific Ocean, and the cycle of relief seems to have begun with the Colombian earthquake of January, 1906. Only two months after this disturbance came the Formosa earthquake, in a province between one third and one half the distance around the planet. The area of the California earthquake, which occurred a month after that in Formosa, is intermediate between the first two, though nearer the first than the second. By examination of Fig. 5, which is drawn to scale, it will be noted that the distances separating the approximate centers of these and the later disturbances in the series, generally bear out the hypothesis that each later earthquake affects an area farthest removed from those sections of the zone which have already found relief.

The rapidity with which the steps in the process of securing relief have here succeeded to one another, lends strong support to the view that the zone in question should be regarded as a definite orographic unit, and that the stress-strain conditions within all except the southernmost portions were before relief began, remarkably uniform. The planetary order of magnitude of the movements would thus seem to be clearly indicated. The section of the zone last to be relieved was, it is interesting to note, one which had been partly relieved of stress during two earthquakes six years and four years before the main cycle of relief was inaugurated. The section which separates the district of the Aleutian from that of the Californian earthquake had also been visited by earthquakes seven years and six years previous to the main cycle of relief. The portions of the zone in which the probability of heavy shocks is now most imminent, are the Japan-Kamschatka segment, the Peru-Bolivian segment, and the archipelago region to the southeast of Asia. Inasmuch, however, as between 1899 and 1903, 29, 12 and 41 heavy shocks had been registered by seismographs from the vicinity of

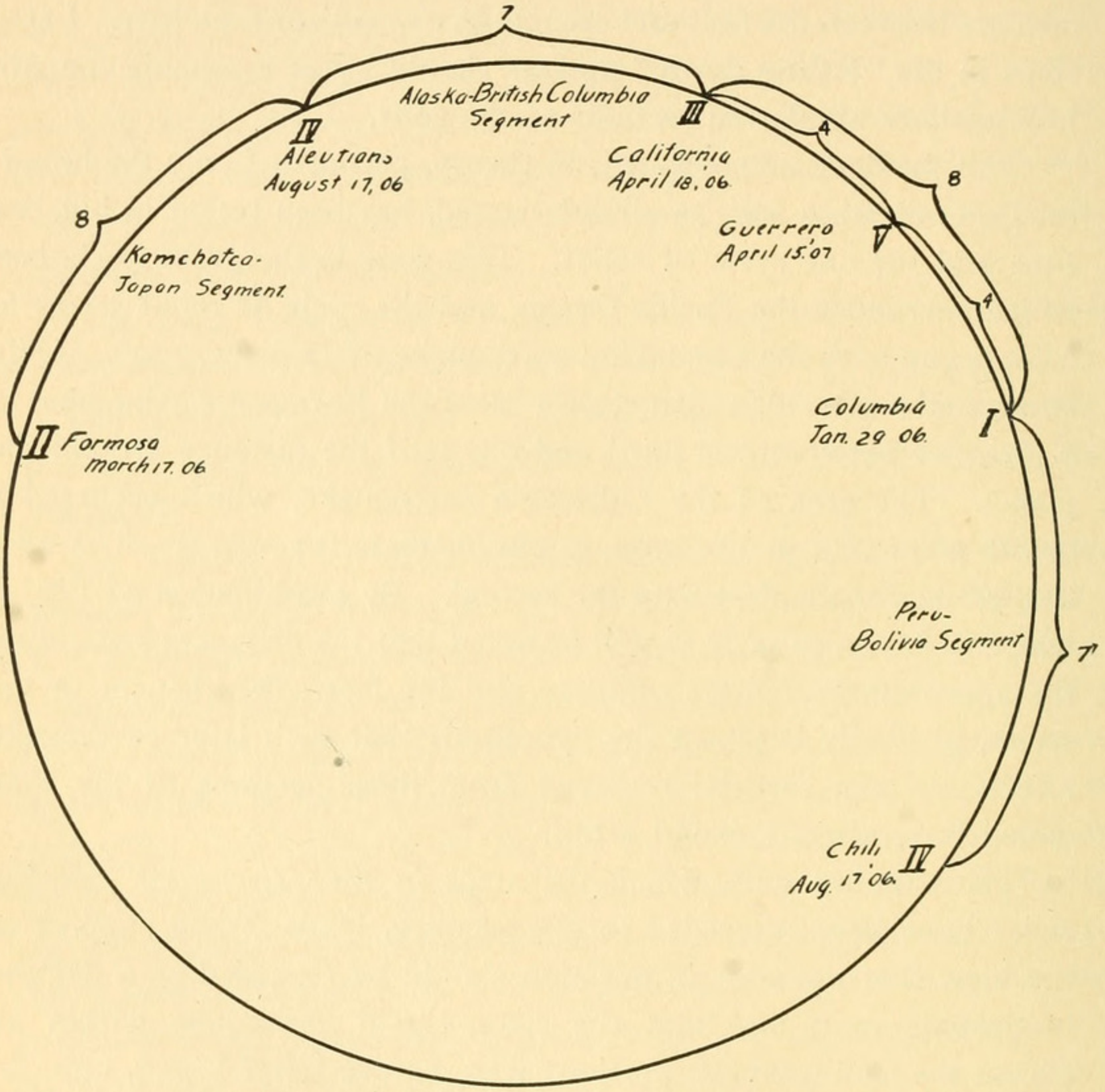


FIG. 5. Diagram showing the distances which separated the approximate centers of areas of the series of earthquakes within the circum-Pacific zone in the years 1906–7.

these three segments respectively,[43] the time may be long before the limit of strain may again be reached in them. The problem is thus far from simple and prediction would be extremely hazardous.

It should not be forgotten that prediction of any sort has thus

[43] Milne, *Geogr. Jour.*, 1903, map.

far been possible only within this circum-Pacific zone, which, at the time, is passing through a remarkable seismic history. It is little likely that any such sudden relief of strain will take place again in the same zone before a considerable period has elapsed.

Yet, outside this zone and within our own country, earthquakes of the first order of magnitude have visited the lower Mississippi Valley, the coastal plain in South Carolina and the valley of the St. Lawrence during the brief period that the country has been occupied by whites. Of these sections of country, as of most others, the only safe prediction that can now be made, is that districts already visited by historical destructive shocks, as well as some others, notably New England and the Middle States, will eventually suffer from disastrous earthquakes. To the time of such visitations we have not even a clue.

Periodicity of Earthquake Cycles.—The "letting down" of the potential energy of the system of stresses within the circum-Pacific belt, as brought out by the events of 1906–7, is, in the writer's belief, as regards its close sequence, an event without parallel in the history of seismic geology. Something approaching it appears, however, to have been in operation within a somewhat longer period in the other great seismic belt of the globe. Making all due allowance for the fact that our quite recent study of distant earthquakes has greatly extended our horizon, it still seems necessary to conclude that the present is a time of very exceptional seismic intensity.

So soon as we admit the planetary scale of these seismic disturbances and explain them as a result of mountain growth upon the borders of the continent, we are led to expect the existence of such maxima and minima of seismic intensity. If now we examine the history of earthquakes in those countries possessing the longest records, we find evidence in support of this view. The stronger earthquakes in Japan, which are on record for a period of fifteen hundred years, betray a strong tendency to group themselves. The 154 heavy earthquakes recorded in that country since the beginning of the fourteenth century may be divided more or less definitely into 41 groups separated by average intervals of 13½ years. In Kyoto a complete record has been kept for a thousand years. Here there was a strong maximum of destructive and strong earthquakes between the middle of the fourteenth and the middle of the fifteenth century, this maximum period being followed by a steady decrease to a minimum in the last half of the nineteenth century. Minor fluctuations reveal an average period of 6½ years, or about one half that revealed by the records for the Empire as a whole.[44]

The natural objection which would be raised to making use of these data for basing conclusions upon the behavior of the earth as a whole, is that the maximum of intensity in Japan may well have been compensated by a minimum in a neighboring district. What we need for basing our conclusions is a world catalogue of earthquakes extending over a sufficiently extended period. Thanks to John Milne and those who have followed his lead, we are now preparing such a catalogue, which is sure to permit of a definitive answer to the question of earthquake periodicity. Even within the first section of this catalogue, comprising as it does the thirteen years from 1892 to 1904, Milne believes he has made out a relatively short period with the maxima of world shaking in correspondence with the more abrupt changes in direction in the orbit of the earth's pole. On *a priori* grounds it is reasonable to connect seismic disturbances with sudden changes in latitude, and the further data upon the pole movement and the seismic world maxima, will be scrutinized with interest.

Possibilities of Future Prognostication.—It is too early to predict whether more satisfactory bases for future forecasting of earthquakes will be discovered, but the indications are certainly encouraging. Two, and perhaps three, lines of inquiry are already suggested. Most promising of these, is, perhaps, the study of terrestrial magnetism; for in a considerable number of instances, destructive earthquakes have been preceded by periods measured in hours and sometimes in days, within which the behavior of magnetographs was singularly abnormal. It seems likely that this change in magnetic conditions may sometimes be utilized as a warning signal. For solution of this problem the completion of the magnetic survey of the world, may be expected to contribute.

Evidence is not lacking that fore-shocks, or rather fore-tremors,

[44] Kichuchi, E. I. C. Pub., No. 19, 1904, pp. 11–13.

for they would appear to have an extremely small amplitude of vibration, are a fore-runner of most heavy earthquakes. These fore-tremors should not be confused with the preliminary tremors in the record of the distant seismograph, for they are of such small amplitude that they would probably not be registered by any instruments today constructed, except perhaps within the affected district itself. Our best evidence that such fore-tremors exist is furnished by the behavior of certain of the lower animals. In the opinion of the writer, such a body of evidence has now accumulated, that it can no longer be waved aside. Just as the sense of smell is so much more highly developed in the dog, for example, than it is in man, so there seems no valid reason for doubting that the detection of small motions by the lower animals may be by as much superior to the human sensibility. Dr. Omori has expressed his belief that seismographs will yet be made sufficiently sensitive to record these microscopic tremors. Just as a block tested in our experiments assumes very large deformations as it approaches rupture, so the earth structure may behave during a period which is as much longer in proportion as the time of augmenting the stresses exceeds that in our experiments. Judging from the recorded behavior of animals, it would not be surprising if the period during which warning may be possible on this basis, should prove to be a large fraction of a day, or even longer. If measurable deformation does occur as a result of the accumulated stresses long before the limit is reached, it may be possible in the case of those earthquakes particularly which result in horizontal shearing movements, to determine by frequent measurement of the distances which separate properly placed monuments, the approach of the strain limit. It is a subject which is at least worthy of investigation.

Since the days of Perrey, who devoted his life to an attempt to find a connection between earthquakes and lunar conditions, there have been those who have sought to connect seismic and volcanic disturbances with periods of special gravitational stress due to luni-solar phases. The most recent advocate of such a connection, is Perret,[45] who is so convinced that he has found the secret behind

[45] "Some Conditions Affecting Volcanic Eruptions," *Science*, Vol. 29, 1908, pp. 277–287.

the phenomena as to have ventured to predict for the year 1908, a grand eruption of Etna.[46] This eruption not having materialized, Perret has accepted the Messina earthquake as a substitute.[47] Assuming that his method is correct, it is possible to see how a period of seismic or volcanic activity might be predicted; the method, however, gives no clue as to what part of the earth's surface is likely to be thus affected. The predictions of the author of the theory have,

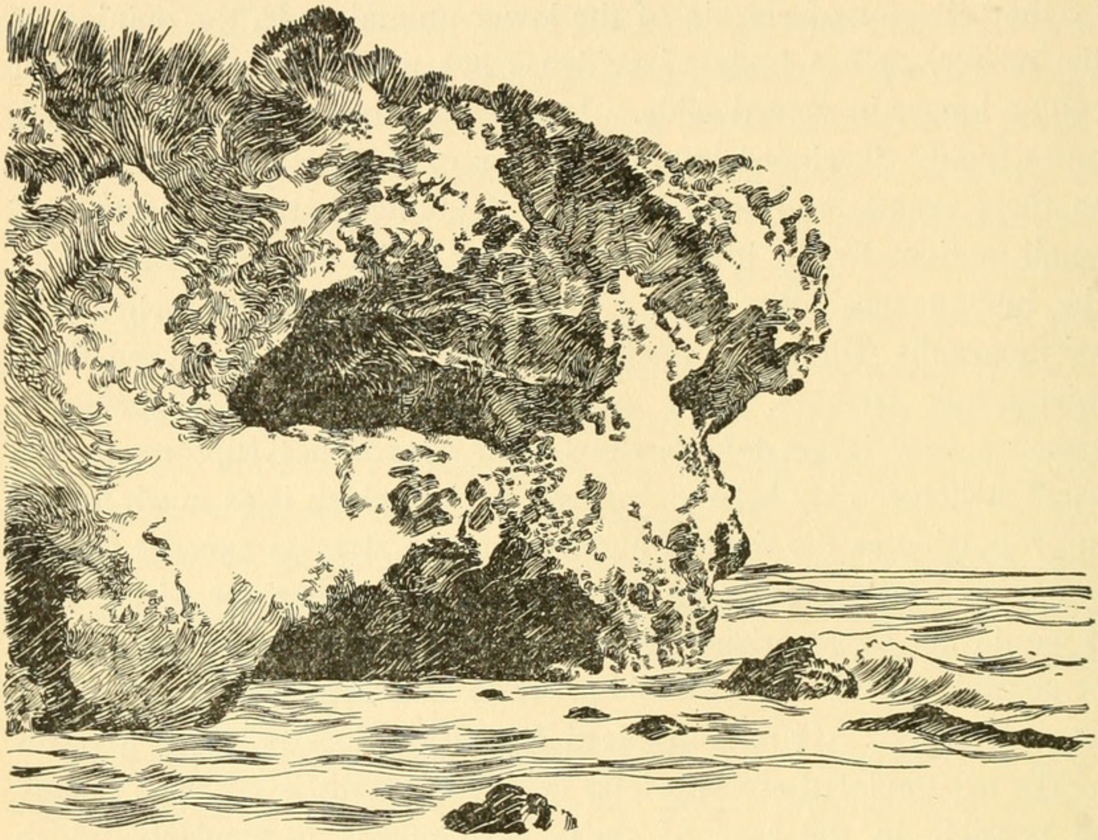


Fig. 6. Abandoned Sea Cave 10 feet above water on Coast of California. (After Fairbanks.)

on the whole, been less remarkable than the statements made by one of his supporters.[48]

Need of an Expeditionary Corps.—It may well occasion surprise that governments have been so slow to appreciate the necessity for providing means for the investigation of earthquakes. Our own government, which has shown such commendable generosity in providing the sinews for scientific investigation, has in this particular

[46] *The World's Work,* November, 1907.
[47] *Am. Jour. Sci.,* Vol. 27, 1909, pp. 322–323.
[48] Jaggar, *The Nation,* Vol. 88, 1909, pp. 22–23.

field lagged far behind other nations. In Japan since 1892 there has been an Earthquake Investigation Committee, and whenever a destructive earthquake is reported from any part of the world, Professor Omori, the secretary of the committee and its chief expert, is despatched by his government to prepare a report upon it. Under orders from the Japanese government, he is today in the vicinity of Messina engaged in a study of the latest great disaster. While these expeditions have been of value in securing information, the time has come when with the incease of our knowledge of earthquakes, something more than a reconnaissance survey is required. One man without assistants and without elaborate equipment, is today in no position to secure those more important data which alone can advance our knowledge of earthquakes beyond its present status. Today a scientific party should have at its disposal one or more surveying vessels—small gunboats or protected cruisers could be easily adapted for the purpose—provided with modern sounding apparatus and with a full equipment of necessary instruments. The crops of scientific workers should include skillful topographers and their assistants and all suitable instruments for preparing accurate topographic maps. The party should also include trained experts whose duty it should be, among other things, to map the distribution of the surface intensity of the shocks. An expeditionary vessel of the type described could be utilized upon occasion to study volcanic as well as seismic disturbances; such, for example, as the late eruptions in the Windward Islands. The seismic events of the years 1906–8, would have been more than sufficient to take up the attention of two surveying vessels with their corps of scientific workers.[49] In times of relative seismic inactivity the ships and their complements could be employed to advantage in work which will be more definitely indicated below.

A Service of Correlated Earthquake Observatories.—In addition to the study upon the ground, which may be expected to lay bare some important laws of seismic geology, there should be installed a series of stations equipped with modern seismographs for the regis-

[49] In a late number of the *Popular Science Monthly* (February, 1909) the writer has pointed out the exceptional opportunities which the recent Messina disaster has offered for study by this method.

tration of the distant as well as the nearer and local earthquakes. These stations should be well distributed over the national domain, and should include a number of stations of the first rank provided with the more sensitive type of pendulum adapted to the registration of distant earthquakes. A larger number of stations of lower rank should be provided with simpler instruments suited only for securing full data upon the local shocks. These smaller stations should be located with due regard to the more important seismic provinces of the country. The United States Weather Bureau already possesses suitable buildings for installing such apparatus, and the regular employees of the stations could be trained to add the care of the instruments to their other duties. In 1907 with the hearty approval of the heads of the various scientific bureaus of the government, the American Association for the Advancement of Science, upon recommendation of its Committee on Seismology, memorialized Congress upon the pressing need of such a service. A year later, the Geological Society of America passed a resolution of similar import, and in the same year, no positive result having been secured, the Committee on Seismology renewed its first memorial by a second resolution.[49a]

Scientific research has already gone far to remove some of the greatest scourges of human existence. Of those which are characterized by sudden and usually unexpected visitation, are pestilence, flood, conflagration, earthquake and volcanic eruption. Of these flood and conflagration must be in part laid at the door of earthquake disturbances, to which they have all too frequently been an almost inevitable sequel. They have, moreover, taken the larger toll of human life and property. As compared with epidemic diseases, like the plague and smallpox which repeatedly overran Europe during the middle ages, earthquakes and their consequences have been the less destructive of life. It has been estimated that in Europe, the plague alone carried off no less than 25,000,000 people. Yet medical science has discovered the mystery of the disease, and in sanitation and isolation provided the remedy. To meet the great dangers of conflagrations, which from time to time

[49a] See also the resolution passed by the American Philosophical Society on April 24, 1909. *Proceedings* No. 191, p. xii.

have swept over our cities, we have as yet made only partial provision, yet the remedy is known and the country does not hesitate to make an annual expenditure conservatively estimated at $25,000,000, and in addition compels its citizens to build according to approved regulations.

A single earthquake has involved us in a loss of over $350,000,000, or nearly ten times the loss from the Baltimore fire.[50] Yet the government has expended nothing in an attempt to safeguard the future by avoiding the recurrence of such disasters. In Europe within a few months an entire city has been laid in ruins with a loss of life which may reach 150,000, yet the latest information makes it almost certain that this quake was not an exceptionally heavy one, and that most of the loss of life and property might have been avoided if proper methods of construction had been adopted.

It can hardly be claimed that the comparatively recent California disaster gave us our first warning of danger, for twenty years earlier the earthquake in South Carolina caused a loss of over one hundred lives, and property to the value of between $5,000,000 and $6,000,000. The earlier earthquakes within our territory have been far heavier and the small loss of life and property is accounted for only because the districts were at the time so thinly populated. We must not, therefore, overlook the fact that the United States is an earthquake country, and this not alone in its Pacific section. Some of our largest and most prosperous cities are almost certain to pass through their trials in the future, as Charleston and San Francisco have so recently. On February 5, 1663, almost the entire valley of the St. Lawrence and large sections of New England were visited by an earthquake, which, if the country had been built up as it is today, would have caused a disaster which it is not pleasant to contemplate.

Preparation of Maps of Fracture Systems.—As we have seen, earthquakes register the movement of portions of the earth's crust between planes of fracture. In just how far these fracture planes are present in advance of the movement, and in how far they result

[50] The official figures kindly furnished by Professor J. W. Glover.

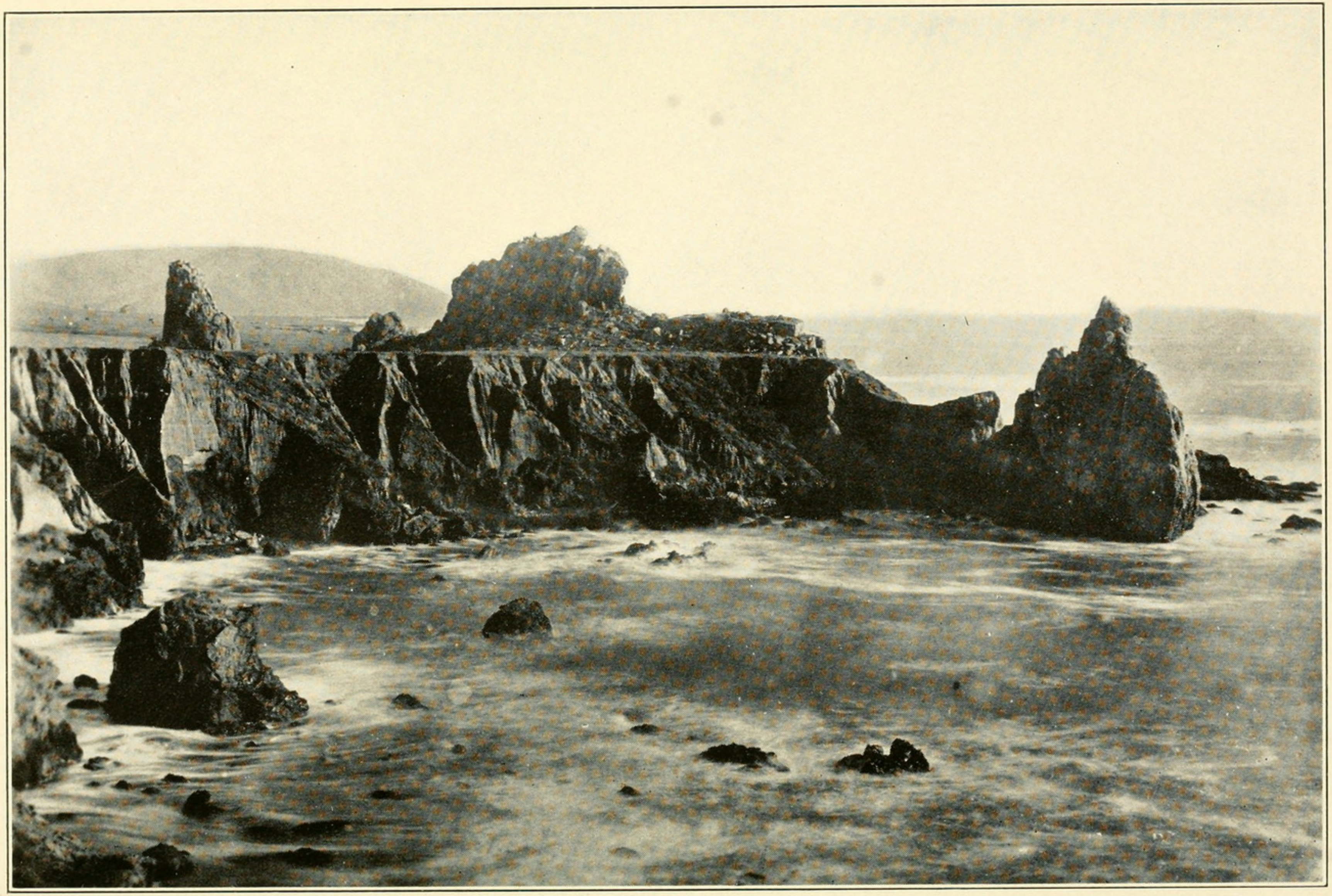
from the relief of strain at the time of the shocks, has not yet been determined. Some writers have dismissed from consideration as "secondary phenomena" most of those visible fractures which first appear at the surface during an earthquake. It seems certain, however, that many of these fractures, at least, as regards both direction and position, are dependent upon the fracture system already present in the underlying rocks; and there is, therefore, need for extended study of the fracture and fault system within the rock basement of each earthquake province. With this study might perhaps be combined the determination of the depth and the earthquake properties of each of the overlying unconsolidated deposits. Experiments are further necessary in order to determine whether large thicknesses of such deposits are controlled by the same laws as are the thinner ones.

In every district which has an earthquake history, this record should be examined to learn if possible the points, the lines, or the areas of heaviest shock. Whenever data are sufficiently complete, maps should be compared to represent the approximate distribution of surface intensity for each earthquake, and comparisons instituted.

Maps of Visible Faults and Fissures and of Block Movements for Special Earthquakes.—It has been pointed out that in the case of a single earthquake only has a map been prepared to show in detail the distribution of the surface faults and the block movements of the ground. Thirty-five years after the event which brought them into existence, these faults have been mapped in detail by Mr. W. D. Johnson, of the United States Geological Survey. It has been possible to prepare maps of portions only of the district affected, and the full results are not yet published. Within the national damain there are at least two other provinces which promise fruitful results from such a study. These are the regions affected by the Sonora earthquake of 1887, and, even more important, the country about Yakutat Bay, Alaska, so profoundly modified in its relief during the earthquakes of 1899. A scientific party with headquarters upon a surveying vessel, such as we have described, would here find almost unequaled opportunities for securing important data.

Rate of Mountain or Shore Elevation by Quantitative Methods.

Wave-cut terrace and sea arch 10 feet above present sea level on coast of California. (After Fairbanks.)



Elevated shore line exhibiting stacks on coast of California near Port Harford. (After Fairbanks.)