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ALBANY, N. Y.

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M. CLARKE, DIRECTOR

GENESIS OF THE ZINC ORES OF THE EDWARDS
DISTRICT, ST LAWRENCE COUNTY, N. Y.

By C. H. SMYTH JR

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ALBANY

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EXCHANGE

N 63

The University of the State of New York

State Museum, May 17, 1918

Hon. Thomas E. Finegan

Acting Commissioner of Education

DEAR DOCTOR FINEGAN:

I beg to transmit herewith for publication as a bulletin of the State Museum, a manuscript entitled Genesis of the Zinc Ores of the Edwards District, St Lawrence County, N. Y., which has been prepared at my request by Dr C. H. Smyth, jr. The manuscript is brief and of somewhat exigent character and I trust that early publication may be effected.

Very respectfully yours

JOHN M. CLARKE

Director

THE UNIVERSITY OF THE STATE OF NEW YORK
THE STATE DEPARTMENT OF EDUCATION
COMMISSIONER'S ROOM

Approved for publication

the 20th day of June, 1918

Thos. E. Finegan

Acting Commissioner of Education

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GENESIS OF THE ZINC ORES OF THE EDWARDS DISTRICT, ST LAWRENCE COUNTY, N. Y.

By C. H. SMYTH, JR

INTRODUCTION

Several years ago, while examining the geology of the Canton quadrangle with Mr J. C. Martin, the writer made a brief visit to the Edwards zinc mine which, at that time, consisted of little more than a few shallow prospects. The data and specimens then collected were laid aside in the hope that some further and more favorable opportunity for a study of the deposits might be forthcoming.

Subsequent rapid development of the district led Mr D. H. Newland, assistant state geologist, to give it a thorough examination and the chief results of this work were stated in a paper published by him.¹

In a correspondence growing out of this publication, Mr Newland suggested that the writer join him in the preparation of a report on the district, intended primarily for those interested in its mining development, and the present paper has resulted from this suggestion. Its appearance as a separate contribution, long subsequent to the publication of Mr Newland's report,² is due primarily to the exigencies of the war situation, and is most regrettable.

While availing himself of his acquaintance with the geology of the region within which the Edwards district lies, as well as the data and specimens collected in the visit to the mine, above referred to, the writer has depended primarily upon the data and collections generously placed at his disposal by Mr Newland, thus incurring a debt which is gratefully acknowledged.

¹ Newland, D. H., The New Zinc Mining District near Edwards, N. Y.; Econ. Geol. 1916, 1:623-44.

² Newland, D. H., The Zinc-Pyrite Deposits of the Edwards District, New York; N. Y. State Defence Council, Bul. 2, 1917.

NATURE OF THE PROBLEM

The problem of the genesis of the ores falls into three parts, involving different methods of study. First, and most fundamental, is the study of the general geology of the region in which the deposits occur; for here, as elsewhere, the ores are merely a minor and special product of the geological agents and conditions controlling the development of the region as a whole. Second, is the determination of the form, size and structure of the ore deposits themselves and their relations to the immediately surrounding rocks. Third, is the laboratory study of the ores, their chemical and mineralogical composition and the interrelations of the minerals in a minute way, as shown by microscopic examination.

In the paper above referred to, Mr Newland has discussed the first two phases of the problem at length and the third phase more briefly. The latter is here considered with more detail and, as will be seen, the conclusions reached are in close agreement with Newland's.

RESUMÉ OF GEOLOGICAL FEATURES

The area whose general geology underlies the problem is, broadly speaking, the whole Adirondack region, which has been studied by a number of geologists, during a long period, with the resultant determination of the major features of its geological history.

More specifically, it is the belt of rocks within which the ore deposits lie, together with the closely adjoining formations, whose history is involved in that of the ores; and the results of the study of these rocks have already been given by Mr Newland. But, as is evident, these rocks can be clearly interpreted only by comparing and correlating them with the formations of the larger region.

The salient facts of the geology of the Edwards district, from the standpoint of the genetic problem, may, to advantage, be repeated in this immediate connection.

The ore deposits occur in a belt of thoroughly metamorphosed limestone, with minor amounts of schist, quartzite etc. On the north this limestone is overlaid by schists, apparently part of the same sedimentary series and, like the limestone, thoroughly metamorphosed. These schists are cut by dikes of pegmatite and granite and thoroughly injected by granitic material, often taking on the character of typical injection gneisses.

To the south of the limestones (which, with the schists and

Exchange

quartzite, are classed as of Grenville age) there is an extensive area of granite which is younger than, and intrusive in, the sedimentary rocks.

All these rocks are of Precambrian age and, while the sediments were, of course, deposited at the surface, they were subsequently buried to great depth, folded and metamorphosed from ordinary limestones, shales and sandstones into crystalline limestones, or marbles, schists, gneisses and quartzites. This metamorphism in part preceded, to a large degree was contemporaneous with and, to a relatively slight degree was subsequent to, the intrusion of the great mass of granite and the injection of granite and pegmatite into the sediments.

Later erosion exposed, at the surface, the whole series of rocks whose mineral composition and physical character had been determined by agents and conditions prevailing at considerable depth, doubtless some thousands of feet. Any attempt to interpret the history of the rocks must necessarily be based upon this deep-seated origin of their dominant features.

As the denuding agents which exposed these rocks at the surface act with extreme slowness, it is obvious that the period of erosion must have been an exceedingly long one. It was finally terminated by the submergence of the denuded area beneath the sea of early Paleozoic time; and the surface of the Precambrian rocks, rugged, but with low relief, was buried beneath Paleozoic sediments, beginning, in this vicinity, with the Potsdam sandstone.

Later the region was again raised above the sea and erosion wore away the veneer of Paleozoic rocks, excepting scattered remnants, and once more exposed the rugged surface of the Precambrian.

Apparently there has been no subsequent marine submergence of the region, the conditions of denudation persisting to the present time.

Thus, in the vicinity of the ore deposits, the rocks show a clear record: First, marine conditions, with the deposition of thick masses of sediment; second, a deep-seated folding, with accompanying intrusion and injection of granite and intense metamorphism; third, long-continued erosion, exposing at the surface the metamorphosed sediments and igneous rocks of deep-seated origin; fourth, the marine submergence of the region and consequent burial of the Precambrian rocks to a moderate depth beneath Paleozoic sediments, but with neither metamorphism nor igneous intrusion of any moment; fifth, the relevation of the region above sea level and the erosion of the Paleozoic sediments.

GEOLOGICAL HISTORY OF THE ORE DEPOSITS

Clearly, there is here represented a very wide range of conditions, both physical and chemical, and in any attempt to decipher the history of the ore deposits it is necessary to determine their relations to these varying conditions. If this could be done completely, the genesis of the deposits would be completely explained, but as the conditions, so briefly outlined, involve unlimited complexity in detail, no such complete solution of the problem can be obtained.

An obvious first step is to determine, if possible, whether the ore deposits have been involved in all the changing conditions of the region or in only part of them. In other words, are the deposits of the same age as the limestones in which they occur and which have passed through all the changes sketched above? Or, are the deposits younger than the limestones and, if so, how much younger, in terms of the varying conditions of the region?

These questions are to be answered by shifting the study from a consideration of the geology of the whole district to a closer examination of the ore deposits themselves and, in particular, their form and structural relations.

If the ore deposits were of the same age as the limestone, they would conform to the dominant original structure of the latter or, in other words, the ores would occur as stratified beds or lenses, intercalated parallel to the bedding of the limestone. This is clearly not the case, the ores having the form of veins or irregular masses which cut across the stratification of the limestone and are evidently the result of deposition long subsequent to that of the sedimentary series.

The ores, then, were not formed under the conditions first recorded in the geology of the region, that is, conditions of marine sedimentation; nor, obviously, could they have been formed during the vastly later, second marine period, since in the latter event they would be interstratified with Paleozoic sediments.

With these periods of sedimentation eliminated, there remains to be determined, if possible, the date of ore formation in terms of the other stages of the geological record.

The form of the deposits—veins and irregular masses cutting across the stratification of the sedimentary wall rocks—is proof of their deposition by underground circulation, but to fix the time of deposition, other factors must be considered and particularly some of the more detailed features of the deposits as related to the larger geological features of the region.

The ore bodies sometimes are sharply defined, with well-marked walls, but in other cases are irregularly shaped portions of the limestone more or less permeated with blende and pyrite, which gradually decrease in quantity as the ore body passes into normal limestone.

APPEARANCE AND CHARACTERISTICS OF THE ORES

The ore is a compact, granular aggregate of the sulphides, pyrite, blende and, sometimes, a little galena, with varying amounts of calcite, diopside, tremolite, phlogopite, serpentine, talc, a little barite and occasional films of greenockite of secondary origin, and, while differing from the ordinary crystalline limestone of the region in containing the sulphides, does not differ materially from it in structure, so far as is apparent to the naked eye. In consequence of this, a casual inspection of the ore gives the impression that it has passed through the entire process of metamorphism which has given to the limestone its present character. As will be shown later, this is not the case, but, instead, the minute texture of the ore, the relation of the sulphides to the normal constituents of the limestone and many details observable only with the microscope all point to the conclusion that the ore deposits were formed at considerable depth—probably some thousands of feet—during the metamorphism which has so profoundly modified the sedimentary rocks of the region. If this conclusion is correct, it fixes the age of the ore deposits as Precambrian and as comparatively late in the series of events recorded in the Precambrian rocks of this region. Indeed, it appears that since the ores were formed they, and the surrounding country rocks, have suffered no radical modification of any kind. On the contrary, during the vast period of time that has elapsed, the region has been so free from rock folding and igneous intrusion that the ore deposits have retained their original character, excepting slight modifications of a superficial nature which have not affected the deposits as a whole.

If the foregoing view is correct, the ores are of extreme antiquity and, roughly speaking, comparable in age with the noted zinc deposits of Franklin Furnace, N J., though differing greatly from these in mineralogical composition.

As the above conclusions are based not only upon the larger relations already discussed but also upon the more minute details to be ascertained only by microscopic study, the results of the latter need to be considered.

Thin sections have been studied ranging from rich ore, through leaner varieties, to the country rock nearly or quite free from the sulphides. As would be gathered from casual examination, the mineral composition of the ore is relatively simple and the microscope adds little to the list of minerals already given. Mention may be made of a peculiar mineral of vermicular habit, which occurs in small quantities and conforms, except in its pleochroism, to Termier's¹ leverrierite, classed by Dana as a variety of muscovite.

The country rock is a crystalline aggregate of calcite with varying amounts of silicates such as diopside, tremolite, phlogopite, talc, serpentine and alteration products of doubtful nature. Of these minerals, calcite is, as a rule, the dominant one and forms the main mass through which the others are scattered. These latter may, however, so increase as to predominate, while again they may almost wholly disappear.

So far as calcite, diopside, tremolite and phlogopite are concerned, no marked order of formation is evident and it would appear that they must have crystallized nearly simultaneously as products of one set of conditions. It is necessary, however, to recognize the fact that the calcite, besides having a distinctive behavior to be discussed later, is a mere recrystallization of the original calcite of the limestone, while the silicates did not exist before the establishment of the conditions under which this recrystallization took place. Some idea as to what these conditions were may be derived from the study of the general geology of the region.

It has already been seen that the country rock of the zinc ores is a crystalline limestone of sedimentary origin, having been deposited either as a chemical precipitate or an accumulation of the calcareous shells of marine organisms. In its original state, it doubtless resembled many limestones of the Paleozoic or later formations, while its present highly crystalline condition is due to changes effected by metamorphism. This has resulted in a complete recrystallization of the rock, with the production of new structures and new minerals, so that, doubtless, the limestone as it now exists is quite different in appearance and in mineral composition from what it was before the metamorphism.

¹ Termier, P., Note sur la Leverrierite; *Bul. Soc. Fr. Min.*, 1890, 13:325-30, and *Sur la Composition Chimique et les Propriétés optiques de la Leverrierite*, *ibid*, 1899, 22:27-31.

GENERAL DISCUSSION OF METAMORPHISM

Metamorphism is a deep-seated process involving heat, pressure and the presence of enough water to act as a medium of solution and recrystallization though, as a rule, there is probably little free circulation of water and, in consequence, little active transfer of material from point to point. At least, this is the case when metamorphism is of the type that results from the burial of rocks to considerable depth, with consequent increase of temperature and pressure, the latter often differential, with resultant rock flowage. Under these conditions, metamorphism is primarily a recrystallization of material already present in the rock, with little change of bulk chemical composition, though there may be, and usually is, a radical change of mineral composition. The latter is particularly true in the case of sediments which, having formed at the surface, are often largely composed of minerals which are unstable at great depth and, consequently, break down and yield their material to build up new minerals stable under the new conditions. Even such stable minerals as quartz and calcite, though surviving to form part of the metamorphic rocks, undergo complete recrystallization, while, in other cases, they may lose their identity, their constituents being merged in other minerals.

Another type of metamorphism results from the intrusion of igneous magmas, with their accompanying hot gases and vapors and great variety of mobile and potent chemical agents. Under these conditions, great changes of chemical, as well as mineral, composition may be effected in the country rock, involving the removal of original material and the substitution for it of new material on a large scale.

Metamorphism of the first type is apt to be much more widespread than that of the second type, while either one may be superimposed upon the other, resulting in extreme complexity.

Of whatever type it may be, metamorphism is, as already implied, merely a readjustment to new conditions. Every rock is an aggregate of minerals and each mineral is stable only within certain limits, both physical and chemical. When these limits are passed, the mineral ceases to be stable and readjustment follows, by recrystallization, paramorphism or complete chemical rearrangement, with the formation of a rock of different mineral composition. The limits of stability vary widely in different minerals, as does the rate of readjustment. Often, readjustment lags greatly behind the change of conditions so that a rock may retain, for many geological

ages, the character acquired under one set of conditions in spite of exposure to a totally different set of conditions.

For sedimentary rocks, formed at the surface, with low temperature and pressure, the changes effected by metamorphism are distinctly constructive. It is a process of integration and tends to convert relatively soft, incoherent, fine-grained rocks, of fragmental texture and composed of simple minerals, into hard, dense, coarse-grained, highly crystalline rocks composed of complex minerals.

Thus, the crystalline limestone that contains the zinc deposits is a coarse, compact marble, carrying crystalline silicates, very different from an ordinary unmetamorphosed limestone, drab, blue or black, and containing more or less mud or sand instead of the silicates crystallized *in situ*. Even more striking is the contrast between the schists and gneisses, on the one hand, and the muds from which they were derived, on the other.

METAMORPHISM AND THE ORE DEPOSITS

As to the kind of metamorphism that has brought about the changes in these rocks, there can be no doubt that both types, so briefly sketched above, have been active in it, though there is room for difference of opinion as to which type predominated. But recent studies in the neighboring Lake Bonaparte quadrangle indicate that limestones of the diopside-tremolite type here represented are largely the product of igneous intrusion or, in other words, the metamorphism is chiefly of the "contact" rather than the "dynamic" type. But it is contact metamorphism that, on account of heavy cover, widespread intrusion and abundant injection of magmatic material, has operated over such a large area as to be regional, rather than local, in its effects.

Were the metamorphism purely dynamic, it would follow that the silicates represent only new combinations of the original siliceous impurities with the lime and magnesia of the limestone. But, assuming the metamorphism to be largely contact, it follows that part or all of the silicates may be derived from magmatic sources. The absence of typical pneumatolytic minerals, such as tourmaline and fluorite, would seem to argue against this idea, but experience in other parts of the region suggests that most of the silica and perhaps part of the magnesia have been introduced in hot gases and solutions derived from the igneous magmas that have intruded and so thoroughly injected the sedimentary series. To give the various lines of evidence upon which this conclusion is based, would transcend the present limits.

But whether or not this conclusion is right, one thing is clear, namely, that the calcite of the limestone, in its present coarsely crystalline condition, and what may be distinguished as the *primary* silicates, diopside, tremolite and phlogopite, were formed during this period of metamorphism. They are compounds that are stable under metamorphic conditions of the kind that controlled the recrystallization of the limestone. These conditions gradually changed to others under which the silicates in question were no longer entirely stable and they underwent a partial or complete alteration, to establish equilibrium under the new conditions. This alteration produced *secondary* silicates, talc and serpentine, which, together with unchanged portions of the original silicates, have persisted to the present time (in spite of radical change of conditions) except at, and close to, the immediate surface, where the agents of weathering have completely broken down the rocks.

If the varying intensity of the metamorphic processes were represented by a curve, with a vertical coordinate for intensity and horizontal coordinate for time, its summit would indicate the formation of diopside, tremolite and calcite, this aggregate of minerals constituting the typical products of metamorphism. Minerals formed during the period represented by the ascending portion of the curve would tend to be destroyed or recrystallized at its summit, and might or might not be present in the rock now.

The minerals formed under maximum intensity of metamorphism, at the summit of the curve, are, as a rule, stable through a wide range of conditions and thus persist to a large extent throughout the descending portion of the curve. But even these yield considerably to the new conditions and, thus, the descending portion of the curve represents the alteration of diopside and tremolite into talc, serpentine, etc., which, though also silicates, are evidently later than, and derived from, the primary silicates first named.

This relation between the two sets of silicates is one that has been clearly established in a large number of cases, in many different regions and in rocks of various ages, being perfectly familiar to all students of rocks although, even now, the details of the complex changes involved are obscure.

In the present case, as in others, microscopic study of thin sections of the rocks shows plainly the time relations of the earlier and later minerals. A granular aggregate of calcite and diopside, in which the two minerals are essentially of the same age, having crystallized in interlocking grains, often shows the diopside in every

stage of alteration to serpentine. The two minerals are easily distinguished and the serpentine can be seen developing around the margin and along the cracks of the diopside, gradually spreading until the latter mineral is entirely replaced by the former. (Plate I, figures 1 and 2.)¹ Had the process of alteration gone to completion, in every instance, it would, of course, have destroyed all trace of the original mineral, but, even in this event, experience in other localities would have suggested that the serpentine had resulted from the alteration of some older silicate.

The obvious result of the process, so briefly outlined, is to change a diopside limestone into a serpentine limestone, and this is what has happened in the present case.

The composition of diopside may be represented by the formula $\text{CaMgSi}_2\text{O}_6$ and of serpentine by $\text{H}_4\text{Mg}_3\text{Si}_2\text{O}_9$ and it is clear that in the alteration of the former to the latter a decided chemical change takes place, involving the elimination of CaO and SiO_2 and the addition of OH . This change may be represented as follows:

The equation is not to be taken literally as showing the precise chemistry of the process, but serves to indicate the general nature of the change and, particularly, that the process involves hydration, in which respect it is similar to many processes by which anhydrous silicates undergo alteration. Indeed, hydration is one of the most frequent effects of such mineral alteration.

If the above equation could be accepted as an exact statement of the alteration process, it would be possible, by using the specific gravities of the minerals, to determine the relative volumes of the diopside and the serpentine. It is evident that when one mineral alters to another, the second mineral may occupy more or less space than the original mineral, depending upon the relative amounts of material added or removed and the relative densities of the two species. Or, it is possible that these different factors may balance each other so that the secondary mineral occupies the same volume as the primary mineral.

Hydration is very commonly attended by increase of volume and decrease of density and, in the case of serpentine, this increase of volume is large. Indeed, when a rock is largely composed of a mineral, such as olivine, which alters to serpentine, the consequent

¹ The writer is indebted to Mr W. E. Cockfield, fellow in geology, Princeton University, for the accompanying photomicrographs.

Plate 1

Figure 1 Diopside altering to serpentine x95

Figure 2 Diopside, fresh, partly altered and completely altered to serpentine, with blende molded on all varieties x95

Figure 1 Replacement of calcite by serpentine influenced by the cleavage of the calcite x95

Figure 2 Replacement of calcite by serpentine influenced by the cleavage of the calcite x95

increase in volume may cause marked mechanical disturbance in the mass, with resultant slickensiding. On the other hand, when the calcite of a limestone is altered to the denser dolomite, the decrease in volume renders the rock porous and may thus convert it into a water-, gas-, oil- or ore-bearing formation.

In the present case, it is evident from the study of thin sections that the serpentine, resulting from the alteration of diopside, fills the entire space originally occupied by the latter mineral. Moreover, it is evident, both from microscopic study and from mere inspection of hand specimens, that the serpentine developed not only by the alteration of grains and crystals of diopside, thus forming pseudomorphs, but also filled cracks in the rocks and replaced calcite, in this way often segregating in large masses. Clearly, then, the formation of serpentine is a more complex process than the mere alteration of diopside in place for, when serpentine fills fissures in the limestone, it is evident that all the constituents of the mineral must have been in solution in, and deposited by, the water circulating through the fissures. In some large masses, as well as in many microscopic grains, serpentine has been deposited from solution, replacing calcite which goes into solution as the serpentine is deposited. In so far as the limestone is magnesian, it may contribute a portion of the MgO to the serpentine, but it is probable that most of the MgO is furnished by the solutions, which may get it either from the older silicates or, more probably, from a magmatic source. Thus, the serpentine of the ore deposits and country rock is, in part, an alteration *in situ* of diopside (and to less extent tremolite) and, in part, a deposit from solution, either in cracks or replacing calcite. Between the two methods of origin there is a marked contrast. In the first case, the diopside itself furnishes most of the material of the serpentine and may be said to "alter" into serpentine, which is an "alteration product" of diopside. The calcite, on the other hand, supplies little, if any, material for the serpentine which takes its place and, thus, the latter can not be called an alteration product of the former. The relation between the two minerals is that of "replacement," not alteration, the serpentine "replacing" the calcite.

In alteration there is always some more or less close chemical relation between the primary and secondary minerals involved in the process. In replacement, on the other hand, this is not the case, and one mineral may be replaced by another of totally dissimilar composition. The replacement of pure calcite, calcium carbonate, by serpentine, a magnesium silicate, is of this nature.

As to the external form of the serpentine, it is that of diopside grains, when it simply replaces the latter, and these are commonly rounded or irregular. In cracks, the serpentine, of course, conforms to the opening and, thus, appears in straight or sinuous veins or as a network of these. As a replacement of calcite, serpentine sometimes develops along the cleavage of the latter (plate 2, figures 1 and 2) but, more commonly, is bounded by a series of intersecting curves which may, however, be very jagged in detail (plate 3, figures 1 and 2). When present in small amount, it occurs in isolated globular, reniform or irregularly rounded masses (plate 4, figure 1), sometimes connected by veins (plate 4, figure 2) and as these spread and coalesce, it increases up to a point when there is merely a little calcite filling the interstices between adjacent masses of serpentine (plate 5, figures 1 and 2). More rarely, serpentine clearly replaces minerals other than calcite as, for instance, barite (plate 6, figure 1).

Between the two types of serpentine, no sharp line can be drawn, and there is no reason why a mass of serpentine resulting from the alteration of diopside in place, should not grow larger by the addition of more serpentine from circulating solutions. As a matter of fact, in many cases, grains of pseudomorphous serpentine have been enlarged by the addition of replacement serpentine which, with its characteristic scalloped margin, lies outside the smoothly curved margin of the pseudomorphous grain. Examples of this relation are shown in plate 6, figure 2 and plate 7, figure 1. The illustrations do not show the line of separation between the two types of serpentine but its smooth curve is indicated by the form of the contact between pseudomorphous serpentine and sulphides as contrasted with the scalloped edges of replacement serpentine.

The practical distinction between the two genetic varieties is difficult, however, save in typical cases, which are the exception rather than the rule.

Talc is much less abundant in the ores and wall rocks than serpentine and, being easily confused with white mica, is more difficult to identify. Like serpentine, it appears in two forms—as plates or tufts in calcite and as an alteration of the anhydrous silicates. In the former, it has evidently been deposited from circulating solutions and has replaced an equivalent amount of calcite. In the latter, the original silicate, being unstable under the conditions present, broke down in a manner closely analogous to that leading to the formation of serpentine. So far as rather limited data indicate, the latter mineral is formed very largely from diopside, and the talc

Plate 3

Figure 1 Serpentine replacing calcite with development of characteristic scalloped boundary between the two minerals. A residual tongue of calcite projecting into serpentine near center x50

Figure 2 Characteristic form of replacement serpentine, with residual masses of calcite scattered through it x70

Plate 4

Figure 1 Replacement serpentine with short vein extending from it between two distinct individuals of calcite x110

Figure 2 Calcite about one-half replaced by connecting masses of serpentine x50

from tremolite. The nature of the change in the latter case may be expressed by the following equation:

It is noticeable that, in the cases of both diopside and tremolite, the active agents of alteration suggested by these equations are the same—water and carbon dioxide.

As talc is less hydrated than serpentine, it might be expected to form at a higher temperature, that is, higher up on the descending portion of the curve of metamorphism; and such is the fact, talc being distinctly the older of the two minerals. This is shown by the way in which serpentine eats into, or cuts squarely across, tufts and plates of talc and, even more strikingly, by crystals of tremolite or diopside, altered to talc, traversed by a network of serpentine. In these cases, serpentine has grown at the expense of, and replaced, talc and, to this extent, talc has been an intermediate stage in the production of serpentine. The same may be true of the large nodules of talc surrounded by serpentine.

The alteration of diopside to talc may be represented as follows:

The further stage of alteration of talc to serpentine may be represented as follows:

While, however, the alteration of diopside to serpentine sometimes passes through the intermediate stage talc, this is evidently not essential to the process as, in nearly every section where the change can be seen, the passage is direct from diopside to serpentine.

Aside from the minerals briefly described, the wall rocks contain nothing of moment except occasional scattered grains of the ore minerals. As the latter increase in quantity, the rock gradually passes into ore, there being, often, no sharp line of demarkation between the two. In consequence, thin sections of the ores present the same minerals as those of the wall rock, with the addition of the metalliferous sulphides. The latter are blende (sphalerite), the sulphide of zinc; pyrite, the sulphide of iron; and galena, the sulphide of lead. Of these three minerals, the first two are of commercial value in the deposits here considered.

In thin sections, the pyrite and galena are both opaque, the former being brass yellow and the latter lead gray in reflected light. The blende is translucent and ranges from deep reddish brown through light yellow to nearly colorless. As seen with the naked eye, these minerals, excepting, perhaps, the galena, which is present in such

small quantity as to be negligible, appear to be intercrystallized with the anhydrous silicates, diopside, tremolite etc., as if formed at the same time. But under the microscope, it is seen that the relations of the minerals can not be so simply expressed and it is evident that the sulphides belong to a later period of mineral formation. Furthermore, it is evident that there is a distinct order of succession in the formation of the sulphides, pyrite being the oldest, blende next and galena youngest, although there is no reason for believing that there is any great age difference. On the contrary, the sulphides, aside from minor amounts to be referred to later, may be safely ascribed to one period of mineralization.

ORDER OF SULPHIDE DEPOSITION

The relative ages of the sulphides appear in the fact that, when in contact with one another, blende is always molded upon pyrite. This might be explained by the very evident stronger tendency of pyrite to develop crystal form, were it not for the added facts that blende often entirely surrounds pyrite and sometimes fills cracks in it. In a very few cases the relation of blende and pyrite suggests the possibility that the former has replaced the latter, as described by Teas,¹ but in no instance seen by the writer was this explanation capable of proof.

Galena occurs as scattered aggregates, often of skeletal form, growing upon the other sulphides and evidently younger than either. It is, indeed, probably more widely separated from them in age than they are from each other, and may be, in part, a secondary concentration.

As already indicated, pyrite often shows a marked tendency toward crystal form. On the other hand, many grains are quite irregular. Blende invariably occurs in grains and masses, with no suggestion of crystal form.

As to both minerals, however, it is evident that, instead of crystallizing simultaneously with the anhydrous silicates and contemporaneous calcite, they have been formed subsequently, space for them being afforded not by open cavities but by replacement. In other words, calcite and silicates have been dissolved and pyrite and blende deposited in their place *pari passu*. The sulphides eat their way into the older minerals, from margins and cracks, spreading in all directions, and gradually change a diopside-tremolite

¹ Teas, L. P., The Relation of Sphalerite to other Sulphides in Ores; Trans. Am. Inst. Min. Eng., Feb. 1918, p. 1921.

Figure 1 Residual calcite between coalescing masses of serpentine x83

Figure 2 Characteristic forms of remnants of calcite when serpentine replacement is almost complete x110

Figure 1 Serpentine replacing barite and inclosing residual masses of the latter mineral x150

Figure 2 Smoothly rounded pseudomorphous serpentine enlarged by replacement serpentine with characteristic scalloped margin. Pyrite molded upon the pseudomorphous margin x83

limestone into a zinc ore (plate 7, figure 2). In this process, the calcite is more readily attacked than the silicates and, often, sulphides are molded upon silicate grains, having replaced the calcite by which the latter were originally surrounded (plate 8, figure 1). But the silicates themselves, in spite of their relative stability, do not escape and may repeatedly be seen to have undergone replacement (plate 8, figure 2, and plate 9, figure 1).

The pyrite, on account of its earlier development and stronger tendency toward assuming crystal form, takes on a rather massive and compact character, seldom appearing in veinlets or skeletal crystals, although these latter do sometimes occur. The blende is, also, often in fairly regular, equidimensional grains, but again occurs in irregular patches and stringers, evidently introduced after the crystallization of the rock as a whole, and eating into the other minerals.

During this process of sulphide deposition, the rôle of the calcite is quite different from that of the primary silicates and requires further consideration. The silicates mark a definite phase of metamorphism, their formation having been confined to a limited period when temperature was at or near the maximum. The recrystallization of calcite, on the other hand, doubtless began long before the formation of the silicates and continued throughout the whole subsequent period of mineral formation, as calcite fills veins in all the other minerals.

Thus, the age relation of calcite to the sulphides is not as simple as is that of the anhydrous silicates, some of it being older than, some contemporaneous with, and some younger than, the sulphides. And, thus, while the sulphides show a clear molding upon or, less often, replacement of, the silicates, they are often intercrystallized with calcite, though again evidently replacing it. In the former case, blende occurs in compact, equidimensional grains; in the latter, it has a more irregular and branching habit, whose replacing relation is clear. This suggests the formation of the mineral during a considerable period of time, involving a corresponding change of physical conditions.

One effect of this change of conditions, suggested by the data in hand, is a progressive change of composition of the blende, as indicated by color. The older blende, intercrystallized with calcite, is very dark colored, while, as the mineral loses its compact habit and takes on more and more a replacing character, it becomes lighter colored. Exceptions occur, it is true, but, in general, the rule

seems to hold good. The extreme result of this tendency appears in a distinctly younger, colorless blende, which re-cements and borders cracked grains of the older, dark-colored variety.

So far as these observations go, they indicate that, during the period of blende formation, there was a decrease in the supply of iron (which had its maximum in the preceding period of pyrite formation) or else that the changing physical conditions reduced the capacity of iron for entering into the composition of blende. The obvious change of conditions would be a decrease in temperature and it is of interest to recall in this connection Berg's¹ statement that the blende formed by contact metamorphism is always the dark-colored, ferruginous variety.

The natural conclusion in the present instance is that the dark-colored ferruginous blende, intercrystallized with calcite, as well as nearly all the pyrite, represents conditions approximating those involved in the formation of the typical contact silicates, which gradually gave way to lower temperature conditions, with resultant formation of lighter colored, less ferruginous blende, taking on more and more, in its relation to calcite, the character of a replacing mineral, its deposition being subsequent to the major part of the calcite recrystallization.

Doubtless, the actual space now occupied by the dark blende, as well as the light, was originally occupied by calcite, but, under the high temperature conditions prevailing when the dark blende was deposited, the calcite was undergoing such general recrystallization that the two minerals assumed the relation of contemporaneous crystallization.

RELATION OF SULPHIDES TO SECONDARY SILICATES

Of interest in itself and bearing directly upon the question just considered as to the age relations between the sulphides and the primary silicates and calcite, is the problem of the relative ages of the sulphides and of the secondary silicates, serpentine and talc.

With reference to this problem, one thing is clear: In many sections, grains of blende and pyrite occur which have been broken and the cracks subsequently filled by serpentine (plate 9, figure 2). In these cases, it is obvious that the serpentine is younger than the sulphides. But this evidence is not conclusive as to the general age relation between the sulphides and serpentine, since this vein ser-

¹ Berg, Georg, *Die Mikroskopische Untersuchung der Erzlagerstätten*, 1915, p. 123.

Plate 7

Figure 1 Smoothly rounded pseudomorphous serpentine with added replacement serpentine, and with blende molded, upon the former. Serpentine replacing calcite along cleavage x70

Figure 2 Blende replacing calcite x32

Plate 8

Figure 1 Blende molded upon smoothly curving diopside x70

Figure 2 Blende replacing tremolite x150

pentine may be younger than the main part of the mineral. As a matter of fact, there is evidence that, to some extent at least, the serpentine is analogous to both the blende and the calcite in that it formed either through a long period or at two distinct times, probably the former.

At first sight, it would seem that the structural relations between the various minerals, as shown by the microscope, would determine their relative ages, but the value of this criterion is destroyed by the alterations and replacements that have occurred.

As previously stated, there are two types of serpentine, pseudomorphous and replacement, and it is the latter that veins the sulphides. On the other hand, blende may occasionally be found veining the pseudomorphous serpentine. This might be taken as evidence that the sulphides are younger than the pseudomorphous serpentine while older than the replacement serpentine. But this relation can not be proved until it is shown that the blende was actually deposited in cracks in serpentine and not in cracks in diopside, which was subsequently altered to serpentine. Moreover, most, if not all, of this blende, veining serpentine, is of the younger type.

One of the most striking phenomena shown by the microscope is the molding of the sulphides upon serpentine. This may be seen in nearly every section where the two minerals are in contact (plate 6, figure 2; plate 7, figure 1; plate 10, figure 1). It is obvious that the sulphides were deposited around an older mineral which controlled their form. At present, the controlling mineral is commonly serpentine, but it is not evident whether the sulphides were deposited around serpentine itself or around diopside which has, subsequently, altered to serpentine. While, in most of these cases, as just stated, the form-controlling mineral is entirely serpentine, there often still remains a residual core of unaltered diopside, pointing clearly to the origin of the serpentine (plate 10, figure 2). These cases make particularly clear the difficulty of determining whether the serpentinization preceded or followed the deposition of the sulphides, as the actual structural relations of the minerals would be the same in either event.

The frequent presence of veins of serpentine passing, from the central mass of serpentine, out through the surrounding sulphides seems, at first glance, to point definitely to serpentinization after deposition of sulphides. But on closer examination it becomes evident that the serpentine of these veins is often not continuous

with that of the central mass, but is separated from it by a faint but sharp marginal line, which materially weakens this evidence.

The presence of abundant cracks in the sulphides suggests yielding to the expansive force of growing serpentine and, consequently, the earlier formation of the sulphides. These cracks, however, are not radial around serpentine grains but commonly occur in parallel systems traversing the whole width of sections, without reference to serpentine. Furthermore, it very often happens that, under the strain that has produced these cracks, a core has separated from the adjacent sulphide and the intervening space has been filled with the vein serpentine. It is noticeable, however, that the serpentine itself is not cracked.

Clearly, if the serpentine had a distinctive form of its own, which controlled that of the sulphides, all difficulty would be removed. But unfortunately this is not the case. It is true that one can not examine the sections without being impressed with the conspicuously rounded margins of the serpentine grains. These are so frequent as to give the impression that they may be taken as characteristic and peculiar to the mineral and thus, since they control the form of the sulphides, establish the earlier formation of the serpentine. But this conclusion is negated by the well-known frequency of similar rounded forms of primary silicates in crystalline limestone. Indeed, a section of the country limestone contains perfectly fresh diopside in grains whose forms are precisely of the type shown by the serpentine (plate II, figure 1). If the surrounding calcite were replaced by sulphides and the diopside then altered to serpentine, the resulting relation would be just what is shown by the ore (plate I, figure 2). At the same time, the latter is equally true if the alteration of diopside to serpentine preceded the deposition of the sulphides; which shows the difficulty of a positive determination of the age relation of the minerals. If the serpentine is strictly pseudomorphous after diopside, its form relation to sulphides gives no light on their relative ages, since the form is that of diopside and its alteration to serpentine might precede or follow the deposition of sulphides, without affecting their structural relation.

The most promising line of evidence leading toward a definite conclusion would seem to be afforded by the replacement serpentine. As previously stated, this is serpentine which is not an alteration of diopside *in situ* with retention of form but, instead, has been deposited by solutions, replacing calcite. This serpentine occurs in rounded and reniform masses, often with jagged margins and with

Plate 9

Figure 1 Blende replacing tremolite x150

Figure 2 Cracks in blende filled with serpentine and younger blende, the latter not distinguishable in the photograph x110

Figure 1 Blende molded upon serpentine of smoothly rounded form.
Serpentine also fills a vein in blende x110

Figure 2 Blende molded upon pseudomorphous serpentine with large
core of diopside x95

veinlike extensions which frequently connect adjacent masses (plates 3, 4 and 5). In its typical development it is sharply contrasted with the pseudomorphous serpentine, though more often the practical distinction between the two varieties is difficult.

Cases of the molding of sulphides upon replacement serpentine have not been frequently observed, but several occur that seem to be of this nature (plate 11, figure 2). In this type of serpentine, the form is its own and not inherited from an older mineral, and hence, if this form controls the deposition of the sulphides, it is evident that they are younger than the serpentine. Even if the replacement serpentine always starts with the alteration of diopside, if the former spreads beyond the limits of the latter mineral, the form becomes that of serpentine and plays the same rôle with reference to sulphides that it would if no diopside entered into the process.

This evidence then, so far as it goes, indicates that the sulphides were actually molded upon, and are therefore younger than, serpentine; but, as a matter of fact, the blende in these cases is nearly always of the very light-colored, younger type and thus is of no value in this connection. Even in the rare cases of apparent molding of early sulphides on replacement serpentine, the relation may be due to replacement of the former by the latter, implying an age relation just the reverse of that suggested at first glance.

Figure 2, plate 6 and figure 1, plate 7 are of interest in this connection. The molding of pyrite, in the former, and of blende, in the latter, on the smoothly curved surface of grains of pseudomorphous serpentine is very marked, while equally marked is the contrasting scalloped margin of the replacement serpentine, which has been added to the pseudomorphous serpentine. Though not shown in the photograph, the smooth curve of the latter is continued inside of the replacing serpentine, making a clear line of demarkation between them. So often are these relations repeated, that it seems necessary to conclude that the blende was deposited upon the rounded grains before the growth of the replacement serpentine. This being the case, it is evident that the relations described give no positive evidence as to the relative ages of blende and pseudomorphous serpentine, but, since both varieties of serpentine are the product of essentially the same conditions, it is probable that they are of the same age and younger than the dark blende.

But while it is true that the actual space relations of the minerals give no positive evidence of their relative ages, still the generally rounded form of diopside in the limestone, the molding of sulphides

upon these grains in all stages of alteration, from perfectly fresh to complete pseudomorphs of serpentine, the very frequent veining of blende by serpentine, the absence of cracks in the serpentine, and the character of the blende itself, all point to the deposition of the major part of the blende before the period of hydrothermal alteration, although, as elsewhere stated, some of the younger blende seems clearly contemporaneous with the serpentine.

In other words, the main deposition of blende, dark colored and ferruginous, occurred at relatively high temperature as compared with that of the hydrothermal alteration, but, during this latter stage, limited quantities of blende continued to be formed, containing less iron and having a correspondingly lighter color.

To revert to the curve as representing time and temperature conditions, diopside and related minerals being at its summit, indicating the period of intense metamorphism, there can be no doubt that the ores belong on the descending portion, which is also true of the hydrous silicates. The former, according to the foregoing interpretation, begin higher up and extend, though perhaps with a break, beyond the point at which the latter begin. Indeed, it is probable that the youngest, light-colored blende was deposited late in the period of hydrothermal alteration.

If the curve were continued down far enough to represent weathering conditions and their products, the gap between these and the hydrous silicate would, it is thought, be much greater than between the latter and the diopside.

SPHALERITE OF LATER DEPOSITION

While a very large proportion of the blende belongs to the one continuous period of formation, there is, as stated above, a relatively small amount of distinctly later deposition. In many cases, grains of the ordinary deep reddish, brown blende have been fractured and subsequently recemented by a further deposition of the same mineral. This later blende is distinguished from the earlier by being pale gray or colorless, and it may occur as narrow borders or projections on the margins of the cracks or may become quite compact, entirely filling the cracks and forming a margin around the whole cemented mass. When grains of the latter type are viewed by reflected light, they present the appearance of a breccia made up of dark-brown, angular fragments of older blende cemented by the nearly white, younger blende.

While a difference of age between the dark and light blende is

Plate 11

Figure 1 Characteristic rounded grain of diopside in crystalline limestone x32

Figure 2 Apparent molding of blende upon replacement serpentine x110

Plate 12

Figure 1 Light-colored blende replacing calcite under control of its cleavage x70

Figure 2 Light-colored blende replacing barite x205

manifest, the magnitude of this difference is by no means obvious; but there seems to be good reason for believing that the light blende marks a late stage of the main period of ore formation rather than a widely separated recurrence of ore-forming conditions.

This is indicated by the intimate association of the light blende with the younger serpentine. The two minerals are so closely mingled in veinlets cutting the older mineral as to suggest very strongly their essentially contemporaneous deposition, the blende being, if anything, a little older than the serpentine. As previously stated, cracks in the older blende are usually filled with calcite or the younger serpentine and there was evidently an abundant supply of these minerals, amply sufficient to fill all cracks. If this had happened, it is hardly possible that the younger blende, always in small amount, could have found its way into these cracks and replaced serpentine and calcite. On the contrary, the conclusion seems unavoidable that the younger blende was deposited in the cracks slightly before, or simultaneously with, the other minerals.

Occasionally the light blende, in contrast with the dark, replaces calcite with a marked development of the rhombohedral form (plate 12, figure 1). This occurs when cleavage cracks have formed in the calcite as a result of the same disturbances that crushed the older blende, these cleavages controlling the flow of solutions and deposition of the blende. The phenomenon is a very minor one, marking a late stage in the period of ore formation. Very rarely, the light blende may be found replacing barite (plate 12, figure 2).

In only one case, so far as seen, does the light blende become the dominant type of ore, and here its history seems to be quite unlike that sketched above.

The ore in question occurs near Sylvia lake and was opened up many years ago as a source of iron. It has turned out to be the oxidized portion of a zinc deposit and, in depth, the hematite is giving place to pyrite, while blende is appearing in some quantity. As might be expected, calcite has been removed by the free circulation of ground waters to which the ore has been subjected, and samples from the bottom of the pit are an aggregate of vein quartz, hematite, pyrite and blende. This is very different from the ordinary zinc ores but the difference is doubtless due largely, if not wholly, to secondary causes. The deposit has been subjected to the attack of circulating superficial waters and largely made over by them. Much material has been removed in solution and what remains has been dissolved and reprecipitated.

There seems to be no doubt that the blende has shared in this process and, consequently, in its present condition is a precipitation from descending surface waters.

In other words, the blende of this deposit is ascribed to such conditions as produce the "secondary enrichment" of copper ores rather than to the much deeper seated conditions represented by the other zinc ores of the region. Obviously, if this interpretation is correct, the blende in question is vastly younger, in its present state, than the blende of the other deposits.

As this younger blende is all light colored, it might be taken as evidence that the small quantities of light blende in the other deposits were of the same late and superficial origin. Reasons have already been given for believing that this is not the case and an added argument against this supposition is afforded by the fact that, in the one case where it appears to be evidently applicable, the conditions implied by it have completely changed the character of the ore deposit, making it wholly dissimilar to the ordinary zinc ore elsewhere in the region. The latter shows no features that suggest any extensive action of superficial waters such as have so thoroughly made over the Sylvia lake deposit.

Thus, while the latter deposit shows that there has been, in this particular instance, a transfer and redeposition of blende by superficial waters, acting geological ages after the primary deposition of the mineral, this does not indicate that the same action is accountable for the small quantities of light-colored blende associated with primary blende in the ordinary ore deposits. While this light-colored blende is, obviously, somewhat younger than the dark mineral, the age difference appears to be slight and both types are regarded as belonging essentially to one period of ore formation or, in other words, to continuous and practically uniform geological conditions. Any solution and redeposition of blende that has occurred is ascribed to the action of the normal vein-forming solutions rather than to superficial waters of later date. This is, however, a question in regard to which there is room for much difference of opinion and Newland ascribes the later blende to superficial waters.

To summarize briefly: The ore deposits are of high-temperature type, with the sequence—anhydrous silicate, sulphides, hydrous silicates, or, in more detail, (1) diopside, tremolite, (2) pyrite, (3) blende, (4) galena, (5) talc, (6) serpentine, controlled by decreasing temperature. Throughout the process of mineral forma-

tion, calcite was subject to repeated solution and recrystallization. The whole assemblage of minerals is regarded as formed during continuously changing conditions, starting with those of contact metamorphism and, finally, arriving at those normal for the depth involved, uninfluenced by outside agencies, and with no time interval of magnitude sufficient to admit of radical change of conditions and consequent pronounced discontinuity in the series. Excepting one locality, where blende has undergone rearrangement and redeposition by superficial waters in recent geological time, the deposits were formed, essentially as they now exist, in Precambrian time.

If the evidence as to the relative ages of sulphides and serpentine were interpreted as indicating the reverse of that accepted above, making the sulphides younger than the serpentine, the sulphides would be relatively low-temperature minerals as compared with the conditions to which their formation has been ascribed.

As will be seen later, this view is in harmony with that held by several investigators with reference to certain analogous deposits and there is much to be said in its support. Nevertheless, it is felt that, while the evidence available does not amount to a demonstration, it does point clearly to the earlier date and higher temperature for the formation of the sulphides.

Obviously, the alternative views are variants of a single hypothesis rather than fundamentally distinct.

COMPARISON OF ORES WITH ZINC ORES OF OTHER REGIONS

Thus far the zinc ores have been treated exclusively in their relation to geological conditions prevailing in a rather limited area, but it is desirable to consider them from the standpoint of similar ores in other regions.

Broadly speaking, there are two main genetic types of zinc ores; those associated with sedimentary rocks only, chiefly limestones, like the deposits of the Mississippi valley; and those associated with igneous rocks, like the many zinc-bearing bodies of the Cordilleran region. Naturally, with the latter type, sedimentary rocks, also, are commonly present.

Deposits of the first type are generally interpreted as formed through the concentration, by circulating meteoric waters, of zinc originally disseminated in the sediments, though some investigators maintain that, even in these deposits, the zinc is of direct magmatic

origin. As to the second type, the evidence is so strong that the zinc is deposited by vapors or hot waters of magmatic origin that there is a very general acceptance of this theory of the genesis of the deposits.

In the case of the Edwards deposits, if the sulphides gave evidence of having been deposited before metamorphism, it might be argued that, since they occur in limestone, they belonged to the first type, their association with igneous rock being a mere coincidence. But, as the ores were introduced after the development of the metamorphic silicates by the intrusion of granite, and during a later stage of the metamorphic process, the conclusion is well-nigh unavoidable that this intrusion of granite was the cause of ore formation, while similar genetic relations in a large number of cases, elsewhere, give added strength to the hypothesis.

Blende is not, like some minerals, exclusively of high temperature origin but, on the contrary, may form under a wide range of conditions according to Lindgren,¹ from contact metamorphic conditions nearly to surface conditions. It is a fact, however, as previously stated, that the dark-colored, ferruginous blende is a variety particularly characteristic of contact zones; but while this may be taken as a suggestive indication, it can hardly be regarded as conclusive. The mere presence of blende gives no positive evidence as to the conditions under which it was formed. On the contrary, these conditions must be determined by a study of the geology of the ore deposit as a whole and the mineral association of the blende.

When, as often happens, blende occurs in nonmetamorphosed limestones, associated with ordinary low-temperature vein minerals, the natural inference is that the blende was gathered from a disseminated condition in the sediment and deposited by meteoric waters. When, however, as in the present instance, blende occurs in contact metamorphic rocks, intimately associated with contact minerals and their hydrothermal alteration products, a magmatic source for the mineral is strongly indicated.

In the Edwards deposits, as shown above, the blende is later than the typical contact metamorphic minerals (diopside, tremolite etc.) formed at high temperature, and precedes the alteration products of these minerals (talc, serpentine etc.), which are formed at lower temperature, in the later stages of contact metamorphism.

If a long interval be assumed between the sulphides and the

¹ Lindgren, Waldemar, *The Relation of Ore-Deposition to Physical Conditions*; *Econ. Geol.* 1907, 2:122.

hydrous silicates, a material modification of the hypothesis might be advanced. This would leave the sulphides as deep-seated and moderately high-temperature minerals, as they are here regarded, but would interpret the talc and serpentine as much later and relatively superficial in origin, the product of cold superficial waters or even of weathering.

The question as to the conditions under which talc and serpentine are formed is one whose thorough discussion would far transcend the limits of this paper. On the one hand, it is argued that they are products of weathering; on the other, that they are due to the action of magmatic waters on magnesian silicates. As thus baldly stated, both views are rather extreme, but the writer, as may be gathered from the foregoing pages, is strongly in sympathy with the latter. It seems highly probable that the formation of talc and serpentine is a process that goes on below, rather than in, the "belt of weathering" within which latter these two minerals, while relatively resistant, are by no means end products, but tend to break down into simpler compounds. There is no doubt that talc and serpentine are formed below the belt of weathering by both magmatic and meteoric waters. When once formed, the minerals are stable and may be regarded as end products, so far as these conditions are concerned.

Many years ago the writer took the ground¹ that the extensive talc deposits of the Edwards district were formed by deep circulation although, with less knowledge of the geology of the region than we now have, appeal was not specifically made to magmatic waters. With the addition of the latter factor, this hypothesis as to the origin of the talc still holds good, and as the zinc ores occur in the talc belt and under practically identical geological conditions, it has direct bearing upon the present case.

After what has already been said it is, perhaps, hardly necessary to state that the hypothesis here offered for the genesis of the ores regards the granite magmas as the source, not only of the heated vapors and solutions that served as transporting agents for the ores, but, also, of the actual materials of the ores themselves, both the sulphur and the metals. During the cooling of the magmas, the gases and solutions were given off, carrying the sulphur and metals and depositing them in the limestone by replacement. The ores are of magmatic derivation, marking a late stage in the history of the

¹ Smyth, C. H. jr, The Genesis of the Talc Deposits of St Lawrence County, N. Y., School of Mines Quarterly, 1896, 17:333-41.

granitic intrusions, and were formed wholly under deep-seated conditions and as a product of magmatic agencies.

This hypothesis is essentially identical with that applied by the writer¹ some years ago to the pyrite deposits of St Lawrence county, although, in the latter case, the intervention of superficial agents was recognized as a not improbable contributing factor. Further consideration of these deposits has served to accentuate the potency of magmatic agents in their formation and to eliminate superficial conditions, thus bringing their origin into close agreement with that of the zinc ores. The two groups of ores have much in common and their history seems to be essentially the same. Certain striking differences, however, exist in the character of the typical deposits, as to composition and wall rock.

The first of these differences appears in the fact that the zinc ores thus far found always carry considerable pyrite, while the typical pyrite ores, on the other hand, are nearly free from blende. The writer found, at the Stella pyrite mines, two vugs, obviously of late date as compared with pyrite ore, lined with crystals of blende and quartz; while Mr Newland has seen one specimen of pyrite ore which was a granular aggregate of pyrite and blende, but the rarity of these exceptions serves to accentuate the rule.

A second difference in composition between pyrite and zinc ores lies in the fact that the former are notably rich in graphite, while the zinc ores contain little or none, in spite of the fact that they occur in crystalline limestone, a rock that, throughout the region, often carries graphite.

As to wall rock, the zinc ores are always in limestone, while the typical pyrite ores are always in schist or gneiss, even when limestone occurs within a few feet. This latter fact is paralleled by many cases mentioned in the literature, but no entirely satisfactory explanation of it has been given.

As to the constant occurrence of the zinc deposits in limestone, it would appear that, as zinc elsewhere shows a strong tendency to be concentrated in limestone, this rock must, on account of its chemical nature, exert a precipitating action on zinc compounds. The possible nature of such action will be referred to later.

This influence of the limestone suggests an explanation of the absence of zinc in the typical pyrite ores: Zinc and pyrite solutions carrying the constituents of both types might traverse purely siliceous rocks, like the schists, and deposit pyrite, but not blende,

¹ Smyth, C. H. jr, On the Genesis of the Pyrite Deposits of St Lawrence County, N. Y.; N. Y. State Mus. Bul. 158, 1912, p. 143-82.

because of the absence of calcium carbonate to act as a precipitant of the latter. Thus, in the schists, there would be formed deposits of pyrite free from blende. In the limestone, on the other hand, zinc would also be precipitated as blende, together with the pyrite, forming the pyritiferous blende deposits.

This explanation leaves out of account the graphite of the pyrite ores, but this mineral constitutes a problem much too large to be considered here and has, moreover, no direct bearing upon the genesis of the zinc ores.

An obvious practical conclusion to be drawn from the foregoing is that, in seeking new zinc deposits in the district, the prospector should confine himself to limestone areas while, if his search is for pyrite, he should examine regions of Grenville schist and, particularly, the so-called "rusty gneisses." It seems also to be true that pyrite is more apt to appear in limestone than is blende in schists.

From all that has been said, it is evident that the zinc ores are intimately related to the pyrite deposits. Indeed, it may be inferred that the zinc, pyrite, talc and, possibly, graphite deposits of the region are, from the genetic point of view, closely interrelated.

As to the distribution of the zinc deposits, it might be expected that, if they are derived from the granite magma, they would occur near the contact between granite and limestone; and such is usually the case. But, in view of the magnitude of the granite intrusions as compared with that of the limestone belts, and the fact that the zinc compounds have, probably, been transported in solution rather than as vapors and, thus, were capable of traveling long distances before being deposited, there is no reason why, mechanical conditions being favorable, ore deposits should not occur anywhere in the limestone. It is considered highly probable that no part of the limestone has escaped the influence of the granite intrusion.

The actual localization of the ores is, unquestionably, due, as their form shows, to fractures or planes of weakness in the limestone, through which the ore-bearing solution circulated. These fractures were not wide, open fissures but were mere cracks or narrow sheer zones admitting the solutions, which were thus enabled to attack and replace the wall rock, with the resultant formation of the ore deposits.

CHEMISTRY OF ORE DEPOSITION

Any attempt to determine details as to the chemistry of ore deposition must, of necessity, be highly speculative, and yet an effort in this direction seems justifiable.

In this connection, the work of Goldschmidt¹ on the zinc deposits of the Christiania region, Norway, is of much interest. As the deposits in question occur in Paleozoic rocks which have not undergone the pronounced regional metamorphism which characterizes the Adirondack rocks, it is possible to work out the history of the minerals in much greater detail than in the Edwards district and, in spite of marked differences between the two regions, Goldschmidt's conclusions with reference to the one have a direct bearing upon the other.

The Christiania ores, according to Goldschmidt, are of contact origin, and are formed in limestone as a result of the intrusion of various igneous rocks but, particularly, granite. The ores occur either directly at, or adjacent to, the contact between the igneous rocks and the limestones or in bodies some distance away from the contact, which are localized by the presence of fissures or channels in the rocks at the time of the intrusion. Evidently, it is to the latter type that the Edwards ores are analogous.

In the Christiania deposits, there is a much greater variety of minerals, both ores and silicates, than at Edwards, and there is further, an abundance of pneumatolytic minerals, or minerals formed by gaseous magmatic emanations, which are conspicuously lacking at Edwards. Evidently, in the Christiania district, the contact metamorphism was more localized and more intense than at Edwards and involved the action of abundant "mineralizers" such as fluorine, chlorine etc.

According to Goldschmidt's interpretation, the blende and other metalliferous minerals were deposited at a temperature near that of the high-temperature silicates, although the sulphides are stated (page 218) to be somewhat younger than the silicates, as is the case with the Edwards deposits.

While, at Edwards, no direct clue has been found as to the probable reactions involved in the transfer of the zinc from the granite to the limestone, Goldschmidt (page 251) maintains that, in the Christiania district, the metal was originally present in the granite magma as sulphide and was converted into chloride by magmatic hydrochloric acid, according to the equation

The zinc chloride, having a boiling point of only 700 C., was volatilized and, together with the other magmatic gases, traversed fissures in the surrounding rocks, permeating their walls. When these gases came in contact with limestone, any free acid would be

¹ Goldschmidt, V. M., *Die Kontaktmetamorphose im Kristianiagebiet*, 1911, p. 40-55, 63-65, 86-90, 211-20.

fixed by calcium, while zinc chloride and hydrogen sulphide would remain and react according to the equation

In the absence of calcium carbonate (calcite,) the reaction would take place chiefly from right to left. With calcium carbonate present, however, hydrochloric acid would be fixed as calcium chloride so that the reaction would proceed from left to right, till the supply of either zinc chloride or calcium carbonate was exhausted. Thus, the limestone is replaced by blende, the latter being less volatile than zinc chloride and remaining when formed.

This explanation of the genesis of the Christiania ores indicates why the zinc ores occur in limestone, since the calcium carbonate of the latter is an essential factor in the precipitation of the zinc sulphide.

While it is not maintained that this explanation of the chemistry of ore deposition in the Christiania region can be transferred bodily and without modification to the Edwards deposits, there can be little doubt that it indicates, in a general way, the nature of the process by which the ores of this district were formed.

As already stated, there is reason for believing that the materials of these ores were transported in solution rather than in gaseous compounds, as was the case with the Christiania ores. This conclusion is based on field relations and on the absence of pneumatolytic minerals in the deposits. The evidence on this question is, however, far from satisfactory and it is quite possible that future study may show the constituents of the sulphides to have been transported in a volatile state.

The importance of chlorine in ore concentration, Goldschmidt bases upon the abundance of scapolite (a chlorine-bearing silicate) among the contact minerals. No scapolite has been noted in the Edwards ores, but it is a frequent and abundant mineral of the contact zones throughout the region and may, very probably, occur in the immediate vicinity of the ores. Thus, the presence of sufficient chlorine to play a vital rôle in the process of ore formation is entirely possible; indeed, the entire absence of scapolite would by no means negative the possibility of the chlorine. But even if the zinc were actually transported as some compound other than chloride, the process might still have much in common with that outlined by Goldschmidt.

For blende deposited at a much lower temperature than that assigned to the Christiania ores, approximating that of the formation of serpentine and talc, the zinc may have been transported as carbonate or bicarbonate rather than as chloride.

In this event, the precipitation as blende may be represented as follows:

These equations are, of course, not to be taken too literally, but they show how simple reactions may account for both the precipitation of the zinc as the relatively insoluble sulphide, and the simultaneous removal of the calcite by its conversion into the soluble bicarbonate of calcium, both of which operations enter into the process of replacement. Thus, it is possible that, in the late stages of ore deposition, carbonic acid played a rôle that, in the earlier stages, was taken by chlorine or some other agent of similar potency. At the same time, the anhydrous silicates might react as follows:

For an exhaustive discussion of the chemistry of natural zinc solutions, Siebenthal's¹ recent work should be consulted.

In seeking zinc ore deposits, other than those of the Christiania region, similar to those of the Edwards district, it is natural to turn first to the very important ore bodies of Franklin Furnace, N. J., which have in common with the Edwards ores their Precambrian age, occurrence in crystalline limestones, and association with granitic intrusions. They differ from the Edwards ores, on the other hand, as well as from those of all other localities, in the fact that the zinc occurs in primary oxides and anhydrous silicates and not as sulphide.

This fact, together with the complexity of their geology and their great commercial importance, makes the ores of exceptional interest and has led to their repeated study by geologists; but the problem of their origin is not yet completely solved. Detailed investigation,² however, has led to an explanation of the ores quite similar to the one here advanced for the Edwards ores; and it is interesting to note that Goldschmidt (page 252) says that the Franklin ores have

¹ Siebenthal, C. E., Origin of the Zinc and Lead Deposits of the Joplin Region; U. S. G. S. Bul. 606, 1915, p. 54.

² Spencer, A. C., Franklin Furnace Folio, (No. 161), Geol. Atlas U. S., U. S. G. S. 1908, p. 8. Also, The Mine Hill and Sterling Hill Zinc Deposits, Sussex county, New Jersey; Geological Survey of New Jersey, Ann. Rep't of State Geologist for 1908, 1909, p. 49-52.

been formed by the same process as the Christiania ores, but by gases exceptionally poor in hydrogen sulphide.

Mr Newland, in the paper previously cited, refers to the similarity between the Edwards ores and those of Long Lake, Ontario, which have, however, been considered¹ as deposited before the metamorphism of the wall rock and subjected to this process with the latter. If this interpretation is correct, it implies a decided genetic difference between the ores of the two localities but, in spite of this, there is marked resemblance in mode of occurrence, age and geology of the country rocks.

As a matter of fact, zinc ores of the age and character of the Edwards deposits are distinctly rare, as Mr Newland has pointed out.

From the genetic standpoint, the arsenic-gold ores of Reichenstein in Silesia have much in common with the Edwards ores, though there are great differences in detail, both mineralogical and geological.

In a recent discussion of these ores, Beyschlag and Krusch² have arrived at conclusions the substance of which follows:

1 The ore deposits are due to granite intrusions into limestones.

2 An older period of contact metamorphism, during which diopside and tremolite were formed, was followed by a younger period of serpentinization effected by magmatic thermal waters.

3 Contrary to the earlier views of Wienecke, who advocated two periods of ore formation, one during the high-temperature metamorphism and the other during the thermal water period, there was but one period of arsenic deposition, that of the thermal water period, and the ores replaced not only calcite but also diopside of the earlier period.

4 All observations indicate the contemporaneity of the arsenic ores and the main mass of the serpentine, while smaller quantities of a younger serpentine occur filling cracks in the older minerals.

Thus, the hot waters that produced the serpentine also deposited the arsenic ores, as well as the gold which they carry.

The parallelism between these views and those here expressed as to the origin of the serpentine is obvious, and while the deposition

¹ Uglow, W. L., *Ore Genesis and Contact Metamorphism at the Long Lake Mine, Ontario*; *Economic Geology*, XI, 1916, p. 231-45.

² Beyschlag, F. & Krusch, P., *Das Arsenerzvorkommen von Reichenstein, Die Erzlagerstätten von Frankenstein und Reichenstein in Schlesien; Abhandlungen der Königlich Preussischen Geol. Landesanstalt, Neue Folge, Heft 73, 1913, pp. 55-92.*

of the ore is placed in the later and lower temperature stage of serpentinization, rather than, as at Edwards, in the earlier, high-temperature stage following diopside formation, the entire process of mineral formation is ascribed to deep-seated conditions and magmatic agencies rather than to the more superficial conditions and agencies by which the formation of the serpentine is often explained.

At Schwarzenberg, in Saxony, pyrite-blende deposits occur in silicate aggregates formed by the contact metamorphism of limestones by granite. The metamorphic silicates are considerably altered and an entire bed may be converted to chloritic or serpentinous aggregates.¹ The sulphides which have formed after the primary silicates and, apparently, after these have been altered to hydrous silicates, surround and penetrate them, as in the ores at Edwards.

Very similar are the zinc ores of Räfvåla, Sweden, where again the sulphides surround and penetrate the corroded contact silicates. Here, again, according to Beck² the sulphides are later than the silicates but with no definite evidence as to how much later.

Many ores of copper, lead, zinc, gold and silver, occurring in the Cordilleran region, are related in origin to the Edwards zinc deposits, though, as a rule, of vastly later geological date, much greater complexity of mineral composition and, probably, formed at less depth. But in the derivation of the ore-bearing solutions from granitic, monzonitic or other magmas, and the deposition of the metals in limestones, by replacement, at and near the contacts, there is very marked resemblance of a fundamental kind. Descriptions of the western deposits are so numerous that extended reference is out of the question, but the exhaustive reports of Lindgren,³ Lindgren, Graton and Gordon⁴ and of Ransome and Calkins⁵ may be mentioned.

In these western ores, the sulphides are often so intergrown with contact metamorphic minerals as to lead to the conclusion that they

¹ Beck, R., Ueber Erzlagerstätten von Schwarzenberg; Zeits. d. Deutsch. Geöl. Ges., 1900, 52, pp. 58-60; also, Erzlagerstätten, 3te Auflage, 1909, 1, pp. 124-28.

² Beck, R., Ueber die Gesteine der Zinkblendelagerstätte Långfallsgrube bei Räfvåla in Schweden; Tschermak's Min. & Pet. Mitth., 1901, 20, pp. 382-89.

³ Lindgren, W., The Copper Deposits of the Clifton-Morenci District. Arizona; Prof. Paper U. S. G. S. No. 43, 1905.

⁴ Lindgren, W., Graton, L. C. & Gordon, C. H., The Ore Deposits of New Mexico; Prof. Paper U. S. G. S. No. 68, 1910.

⁵ Ransome, F. L., & Calkins, F. C., The Geology and Ore Deposits of the Coeur D' Alene District, Idaho; Prof. Paper U. S. G. S. No. 62, 1908.

are contemporaneous, but in some cases the sulphides are younger than the silicates although, judging from the published descriptions, they follow the sulphides rather closely.

Similar genetic conditions are shown in the ore deposits of the Suan mining concession, Korea, recently described by Higgins.¹ Here again silicates, such as diopside and phlogopite, developed before the sulphides and the latter "replaced the calcite in preference to the silicates."

From these examples, whose number might be greatly increased, it is evident that, from the genetic standpoint, the zinc ores of the Edwards district belong to an important and widespread type of deposits, the essential feature of which is their occurrence as replacements of limestone effected through the influence of hot gases and solutions evolved by intruding granitic, or related, magmas.

¹ Higgins, D. F., *Geology and Ore Deposits of the Colbran Contact of the Suan Mining Concession, Korea*; *Economic Geology*, Vol. XIII, 1918, pp. 1-34.

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