SCIENCE

A WEEKLY JOURNAL DEVOTED TO THE ADVANCEMENT OF SCIENCE, PUBLISHING THE OFFICIAL NOTICES AND PROCEEDINGS OF THE AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE.

FRIDAY, NOVEMBER 22, 1901.

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MSS. intended for publication and books, etc., intended for review should be sent to the responsible editor, Professor J. McKeen Cattell, Garrison-on-Hudson, N. Y.

THE GEOLOGY OF ORE DEPOSITS.

II.

WE have now traced the metals of many ores to their first positions in the veins. In order to understand other cases, we must recall the facts as to the relations of 'richness with depth.' At this point I take my illustrations from regions outside of Colorado. James Douglass says that in the Appalachian region every copper mine has diminished in richness with depth. Near the surface rich oxidized products were found. Near the level of ground-water rich belts of sulphides occurred—in some instances extraordinarily rich. Below the level of rich sulphides every old mine has passed into cupriferous pyrrhotite, a sulphide of iron bearing a very small percentage of copper. In the Sierra Nevadas, of California, Mr. Lindgren states that near the surface the values range from $80 to $300 per ton; but a little way below the level of ground-water these values fall to $20 or $30 per ton, and no exceedingly rich deposits are found. You all know the history of the Comstock lode; and of the great bonanzas found above or about the 2,000-foot level, and which did not extend deeper. In the Lake Superior region the greatest iron-ore mines in the world occur; four-fifths or more of the entire product of iron of the United States comes from that region; but at the present time vastly more iron has been taken out above the 1,000-foot level than below it. If time sufficed, similar instances from all the old mining regions of the world could be cited.

I by no means assert that the above illustrations represent an invariable rule. Indeed, this is not the case. But the illustrations undoubtedly do represent the average relation of richness and depth.

Now this story is an entirely different one from the illusion of increased richness with depth based upon the supposition that the metals for the ores are derived from the unknown depths of the earth. If that theory be true, it is natural to believe that ore deposits upon the average will become richer with depth. But if it be a pure unverified hypothesis, not supported by any facts, it is of vital importance for practical mining men to know this, since the knowledge will save them vast sums of money expended in exploration under a false theory. So far as I am aware of the facts, I do not know of a mining region in the world which supports the theory of increased richness with depth, if the unit of measure be taken as one thousand feet, if the first thousand feet be compared with the second thousand, and the second thousand with the third, and so on. In fact, nine mines out of ten, taking the world as a whole, are poorer the second thousand feet than they are the first thousand feet, and are poorer the third thousand feet than they are the second thousand feet. Many ore deposits have been exhausted or have become so lean as not to warrant working before the 1,000-foot level is reached; a large proportion before the 2,000-foot level is reached; while comparatively few ore deposits have been found to be so rich as to warrant working at depths greater than 3,000 feet.

There are, however, some ore deposits which are not known to gradually decrease in richness with depth so far as yet exploited. There are a considerable number of deposits which perhaps after a first rapid decrease in richness maintain their tenor pretty well to the depth of 1,000, 2,000 or even 3,000 feet, and some few deposits maintain their richness at even greater depths. But we cannot reasonably hope that a deposit will get richer with depth, provided we use a 1,000-foot unit for measurement. The most sanguine view which is ever justified for any deposit is that, using a 1,000-foot unit, the second shall be as good as the first, and the third as good as the second. While the above is true, there are very great irregularities in the richness of ore deposits, both favorable and unfavorable, due to multifarious causes, which I cannot possibly discuss to-night, but which I considered somewhat fully in my Institute paper.* These irregularities are especially marked in the upper 1,000 feet of a deposit; so that in many cases, if the unit of measurement were 25 feet or 100 feet, or in a few cases 500 feet even, it might be said that deposits are becoming richer with depth; although the reverse also occurs in many cases. The truth is that in the upper parts of ore deposits the variations in richness with depth are extreme, and no definite rules can be laid down in reference to them.

This rule of the diminution of richness with depth is one of averages only when considerable depths are taken into account. The factors entering into the production of an individual ore deposit are so numerous, and the irregularities are so great, that the rule cannot be asserted in advance of development of an individual mine without a study of the conditions there obtaining.

Now what is the explanation of these irregularities and of the very general diminution of richness with depth? What is the

* 'Some Principles controlling the Deposition of Ores,' by C. R. Van Hise: *Trans. Am. Inst. Min. Eng.*, Vol. XXX., 1900, pp. 102–112.

explanation in some cases of the relatively even values at different depths? The last question will be first considered.

In those instances in which the tenor is maintained or practically maintained from the surface to a great depth, the ore is believed to be the result of a single concentration by ascending waters. Such ore deposits may continue without any appreciable diminution in richness to the lowest limits to which man may expect to penetrate the earth ; but these are exceptional cases. Even ore deposits which are the result of a single concentration by ascending water may diminish in richness at considerable depth. It has been seen that in the fissure at the bottom of the valley on this chart (Fig. 6) the water ascends to the surface. It is evident that the upper part of the fissure receives the greatest supply of water, and this water to a large extent does not penetrate any great depth ; while the lower part of the fissure receives less water, but this water penetrates to a considerable depth. It may happen that the water relatively near the surface traverses the rocks containing the main supply of metals and, therefore, brings the chief contributions of valuable material, or such waters may carry the precipitating agent. In such instances the ore deposits produced by ascending water alone would diminish in richness with depth ; but such decrease would not be likely to be very rapid. Upon the other hand, if the above conditions be reversed, a deposit may increase in richness for a considerable depth ; but as a matter of fact this appears to be a very infrequent case.

As illustrations of the ore deposits of the class produced by ascending waters alone are the copper deposits of Lake Superior. These deposits, while very bunchy and extremely irregular in the distribution of copper, are wonderfully persistent in depth. The copper of the ore was deposited in the metallic form. As compared with sulphides, this material is not readily oxidized. In this district the rocks above the level of ground-water are not appreciably weathered. Doubtless there was a belt of weathered material before the glacial epochs, but if so, it has been swept away by ice erosion ; and since the glacial period sufficient time has not elapsed to weather appreciably the rocks which now lie within the theoretical belt of weathering. If there once were in this district an upper belt of weathering in which there were deposits of exceptional richness, this material has been removed. However, in this district, a first concentration by ascending waters was adequate, but it is not often that a first concentration produces deposits of such richness as those adjacent to Calumet and Houghton on Keweenaw Point ; and, indeed, this is exceptional even in the Keweenawan of the Lake Superior region ; for while concentrations of copper have occurred at many points in the rocks of this period, as yet at no other locality have those concentrations been found to be so abundant and rich as to warrant exploitation on a large scale.

I now turn to the question as to the cause of frequent diminution of richness of ore deposits with depth. The explanation of the very frequent diminution of value with depth seems to me to lie in the secondary effect of descending currents upon deposits first deposited by ascending waters. Many or most of such ore deposits are believed to be the products of two concentrations, the first by ascending, the second by descending waters. In this connection it is necessary to call attention to the fact that a large proportion of the deposits which are being exploited are below part of a slope. It may be said that the reason for this is that the low grounds are more difficult to explore and work ; but giving due allowance for this, it still seems to me that the majority, perhaps the great majority, of very rich deposits are below slopes and crests, and not below the valleys. I believe the richer deposits are below the slopes, because at these places a second concentration is possible and probable.

Returning now to this chart (Fig. 6), we shall direct our attention to the fissure on the slope. This fissure once extended up through the overlying rocks which have been removed by denudation. What has become of the ore in the part of the fissure which has been worn away? If, for instance, it carried five per cent. of copper, what has become of it? A part of it would have been scattered far and wide through erosive action; but a part of it would have been taken into solution and redeposited in the same vein deeper down. In the belt of weathering oxidized salts, such as sulphates, would form; the descending waters would carry these products downward; and it is my belief that they would react upon the solid, lean sulphides below with the result of precipitating the metals from the descending solutions. Now this has been held to be a mere unverified assumption by some geologists, but it seems to me that they have not fully considered the certain effects of the chemical laws concerned. We know if in a laboratory a solution of copper sulphate or other copper salt be placed in contact with iron sulphide, that copper will be thrown down as copper sulphide. If the copper solution be placed in contact with a lean copper-iron sulphide, a sulphide richer in copper will be produced. And if these reactions occur in the chemical laboratory, will they not as certainly occur in the laboratory of nature, although perhaps more slowly?

At this point it is to be recalled that in many ore deposits above the level of ground-water oxides and carbonates occur, while below the level of ground-water are sulphides. Moreover, at high levels these sulphides are rich in valuable metals, and usually become poorer in these metals and richer in iron sulphide at the lower levels. You will remember at Butte, Mont., at and for a distance below the level of the ground-water, are rich copper sulphurets which grade at depth into leaner copper sulphides containing correspondingly large amounts of iron sulphide. You will remember the same is true of the entire Appalachian region. You will remember that frequently above the level of the ground-water gold lodes are exceedingly rich. What is the explanation of these similar facts? What is the explanation of the exceptional or even extraordinary richness of the deposits at and near the level of ground-water, and of the low grade of galena, blende or pyrites deep below the level of ground-water? In my opinion the only plausible explanation is that the rich parts of the deposits have received two concentrations, the first by ascending waters and the second by descending waters. The metals of the rich portions of the deposits were largely contributed by the parts of the deposit above, or once above, the rich parts. In some cases portions of the depleted veins remain, as at Butte; but frequently the depleted parts of the veins have been removed by erosion. The remote source of the material was, therefore, the metals deposited by the first concentration. But let us follow the matter still further. In the majority of cases, as denudation continued, the parts of the ore deposits produced by the second concentration rise into the belt of weathering. They may there be partly or wholly transformed into rich oxidized products, or they may be depleted to extend the rich deposits below. In the concentration by descending waters the chief chemical reactions are believed to be between the oxides or salts of the valuable metals and the sulphide of iron; although, of course, similar reactions occur between the salts of silver and gold and other metals, and the sulphides of lead and zinc.

Time does not permit the consideration of the various reactions which result in the reconcentration by descending waters. These I shall be obliged to take for granted this evening, but those who care to follow the subject further may find a treatment of this part of it in my full paper upon the deposition of ores, published in Volume XXX. of the *Transactions of the American Institute of Mining Engineers.*

During the process of reconcentration erosion steadily goes on, perhaps to a depth of 1,000 or 5,000 or even 10,000 feet, or more. As denudation steadily lowers the surface of the country, the material deposited by the first concentration is picked up and gradually carried down along the vein by the descending waters. This material reacts upon the other materials, and is largely reprecipitated.

In the foregoing statements the second concentration of metals by solution, downward transportation and precipitation by reactions upon the sulphides of an earlier concentration has been emphasized. However, it is not supposed that this is the only process which may result in enrichment of the upper parts of ore deposits by descending waters. The enrichment of this belt may be partly caused (1) by reactions between the downward-moving waters carrying metallic compounds and the rocks with which they come in contact, and (2) by reactions due to the meeting and mingling of the waters from above and the waters from below.

1. The metallic compounds dissolved in the upper parts of the veins, carried by descending water, may be precipitated by material contained in the rocks below. This material may be organic matter, ferrous substances, etc. So far as precipitating materials are reducing agents, they are likely to change the sulphates to sulphides, and precipitate the metals in that form. While sulphides may thus be precipitated either above or below the level of ground-water, they are more likely to be thrown down below the level of ground-water. Other compounds than reducing agents or sulphides may precipitate the downward-moving salts in other forms than sulphides.

2. In a trunk-channel, where waters ascending from below meet waters descending from above, there will probably be a considerable belt in which the circulation is slow and irregular, the main current now moving slowly upward and now moving slowly downward, and at all times being disturbed by convectional movements. Doubtless this belt of slow general movement and convectional circulation would reach a lower level at times and places of abundant rainfall than at other times and places, for under such circumstances the descending currents would be strong. The ascending currents, being controlled by the meteoric waters falling over wider areas, and subject to longer journeys than the descending currents, would not so quickly feel the effect of abundant rainfall. Later, the ascending currents might feel the effect of the abundant rainfall and carry the belt of upward movement to a higher level than normal. However, where the circulation is a very deep one, little variation in ascending currents results from irregularities of rainfall.

In the belt of meeting ascending and descending waters (see Fig. 6) convectional mixing of the solutions due to difference in temperature would be an important phenomenon. The waters from above are cool and dense, while those from below are warm and less dense. In the neutral zone of circulation the waters from above would thus tend to sink downward, while waters from below would tend to rise, and thus the waters would be mingled. Still further, even if the water were supposed to be stagnant at the neutral belt, it is probable that by diffusion the materials contributed by the descending waters would be mingled with the materials contributed by the ascending waters.

Ascending and descending solutions are sure to have widely different compositions, and precipitation of metalliferous ores is a certain result. As a specific case in which precipitation is likely to occur, we may recall that waters ascending from below contain practically no free oxygen and are often somewhat alkaline, while waters descending from above are usually rich in oxygen and frequently contain acids, as at Sulphur Bank, described by Le Conte.* The mingling of such waters as these is almost sure to result in precipitation of some kind. Le Conte further suggests† by the mingling of the waters from below with those from above that the temperature of the ascending column will be rapidly lessened, and this also may result in precipitation.

The metals precipitated by the mingling of the waters may be contributed by the descending waters, by the ascending waters, or partly by each. In so far as more than an average amount of metallic material is precipitated from the ascending waters, this would result in the relatively greater richness of the upper part of veins independently of the material carried down from above.

In all the cases considered the precipitation and enrichment of the upper parts of deposits follow from the reactions of downward-moving waters. Their effect may be to precipitate the metals of the ascending water to some extent, and thus assist in the first concentration. But the results of these processes cannot be discriminated from the concentration resulting from an actual downward transportation of the material of an earlier concentration. In concluding this part of the subject, *it is held that the downward transportation of metals already in lodes is the most important of the causes explaining the character of the upper portions of ore deposits; and that their peculiar characters are certainly due to the effect of descending waters.*

The concentrations by ascending and descending waters have been considered as if they were mainly successive. In some instances this may be the case; but it is much more probable that ascending and descending waters are ordinarily at work upon the same fissure at the same time, and that their products are, to a certain extent, simultaneously deposited. For instance, under the conditions represented by this chart (Fig. 6) a first concentration by ascending waters is taking place in the lower part of the fissure, and a reconcentration by descending waters is taking place in the upper part of the fissure. Between the two there is a belt in which both ascending and descending waters are at work. The rich upper part of an ore deposit which is worked in an individual case may now be in the place where ascending waters alone were first acting, where later, as a consequence of denudation, both ascending and descending waters were at work, and still later, where descending waters alone are at work. The more accurate statement concerning ore deposits produced by ascending and descending waters is, therefore, that ascending waters are likely to be the potent factor in an early stage of the process, that both may work together at an intermediate stage, and that descending waters are likely to be the potent factor in the closing stage of the process.

Also, for the sake of simplicity in the consideration of the concentrations I have

* 'On the Genesis of Metalliferous Veins,' by Joseph Le Conte, *Am. Jour. Sci.*, 3d ser., Vol. XXVI., 1883, p. 9.

† Le Conte, op. cit., p. 12.

disregarded the lateral elements of the moving water. In many cases superimposed upon the vertical movements in the fissures or other openings are lateral movements, as a result of which the deposits, instead of being in vertical positions, are inclined, often much inclined, and indeed may be horizontal. Moreover, the horizontal extents of the deposits may be much greater than the vertical extents. Reduced to a simple and broad statement, *the first concentration of many ore deposits is the work of a relatively deep-water circulation, while the reconcentration is the result of reactions upon an earlier concentration through the agency of a relatively shallow water circulation. Commonly the deep-water circulation is lacking in free oxygen and contains reducing agents, and the shallow water contains free oxygen. The deep water is, therefore, a reducing, and the shallow water an oxidizing agent.*

In addition to the general factors already considered there are many special factors which have a most important, indeed, very often a controlling influence in the production of ore-chutes and in the localization of ore in certain areas and districts. Some of these factors are the complexity of openings, the presence of impervious strata at various depths, the presence of pitching folds, the character of the topography. I see, however, that my time is nearly gone, and I shall not take up their discussion this evening, but must refer those especially interested in this phase of the subject to my full paper already mentioned.* I must, however, note that impervious strata are frequently of controlling importance in the underground circulation. Often deep and shallow water circulations are separated by such strata. Often also, as the result of the removal of impervious strata by denudation, the previous deep circulation ceases and the action of the shallow circulation is inaugurated.

At this point it may be well to briefly recall the most fundamental features of the water circulation which produces the ore deposits. First comes the downward-moving, lateral-moving waters of meteoric origin which take into solution metalliferous material. These waters at depth are converged into trunk channels, and there, while ascending, the first concentration of ore deposits may result. After this first concentration many of the ore deposits which are worked by man have undergone a later concentration, not less important than the earlier, as a result of shallow descending or lateral-moving waters. In other cases, a concentration by descending, lateral-moving waters alone is sufficient to explain some ore deposits. It thus appears more clearly than heretofore that an adequate view of ore deposits must not be a descending-water theory, a lateral-secreting water theory or an ascending-water theory alone. While an individual ore deposit may be produced by one of these processes, *for many ore deposits a satisfactory theory must be a descending, lateral-secreting, ascending, descending, lateral-secreting theory.*

But there is no question in my mind that this theory is still insufficient to fully explain many of the ore deposits. No knowledge is ever complete. We move step by step, carrying a theory nearer and nearer completion. If, however, a theory be based on good work, it usually will not prove to be false; it will be found to be incomplete. Sandberger was not wrong when he said lateral secretion explained many things in reference to ore deposits. He was wrong only when he excluded other factors. He became unscientific when he carried his theory further than his observations justified. While the theory here proposed is believed to make an important advance, it will sooner or later be found to be incom-

* 'Some Principles controlling the Deposition of Ores,' by C. R. Van Hise, *Trans. Am. Inst. Min. Eng.*, Vol. XXX., 1901, pp. 112–146.

plete. I trust it will not be found to be false. But the most that I can hope for it is that it is approximately correct as far as it goes.

It is believed that the principles which have been presented lead to a new and natural classification of the ore deposits produced by underground water. As already noted, ore deposits may be divided into three groups: (1) Ores of igneous origin, (2) ores which are the direct result of the processes of sedimentation, and (3) ores which are deposited by underground water.

Since the ores produced by igneous agencies and those produced by processes of sedimentation have not been considered in this paper, a subdivision of these groups will not be attempted.

Ores resulting from the work of ground-water, group (3) above, may be divided into three main classes:

(*a*) Ores which at the point of precipitation are deposited by ascending waters alone. These ores are usually metallic or some forms of sulphurets; but they may be tellurides, silicates or carbonates.

(*b*) Ores which at the place of precipitation are deposited by descending waters alone. These ores are ordinarily oxides, carbonates, chlorides, etc., but silicates and metals are exceptionally included.

(*c*) Ores which receive a first concentration by ascending waters and a reconcentration by descending waters. The concentration by ascending waters may wholly precede the concentration by descending waters, but often the two processes are at least partly contemporaneous. The materials of class *c* comprise oxides, carbonates, chlorides, and rarely metals and silicates, above the level of groundwater, and rich and poor sulphurets, tellurides, metallic ores, etc., below the level of ground-water. At or near the level of ground-water, these two kinds of products are more or less intermingled, and there is frequently a transition belt of considerable breadth.

How extensive are the deposits of class *a* I shall not attempt to state. Indeed, I have not such familiarity with ore deposits as to entitle me to an opinion upon this point. However, a considerable number of important ore deposits belong to this class. This class is illustrated by the Lake Superior copper deposits.

The ore deposits of class *b* are important. Of the various ores here belonging probably the iron ores are of the most consequence. All of the iron ores of the Lake Superior region now being exploited are of this class.

It is believed that the ore deposits of class *c* are by far the most numerous. I suspect that a close study of ore deposits in reference to their origin will result in the conclusion that the great majority of ores formed by underground water are not the deposits of ascending waters alone, but have by this process undergone an early concentration, and that descending waters have produced a later concentration, as a result of which there is placed in the upper 100 to 1,500 or possibly even 3,000 feet of an ore deposit a large portion of the metalliferous material which originally had, as a result of the early concentration, a much wider vertical distribution.

The depth to which rich deposits of the classes produced or concentrated by descending water extend is a very important question; but time does not permit adequate discussion of it. The factors entering into the problem are very numerous and complicated. Only a single one of these will be briefly considered, and this is the topography. Where the relief is small, the vertical effect of descending solutions extends upon the average to less depths than where the relief is great. But even where the relief is moderate the descending solutions may be effectual to a considerable depth, as shown by the Lake Superior iron mines. And where the topographic forms are those of great and sharp relief, there the descending waters go to very great depths. In the San Juan region, for instance, are wonderfully steep slopes and very great canyons. Here the water descends a long way on its downward course before it turns laterally and upward on its way to the valleys. I have visited the San Juan region during the past week with other geologists, and in some cases we saw the effect of descending water to a depth of 3,000 feet below the surface. It has already been explained that in the early history of this region the conditions were ideal for a first precipitation of ores by ascending waters. They are now no less ideal for a reconcentration by descending waters.

If the classification advocated be based upon facts, it gives valuable criteria to mining men for the exploration and exploitation of their mines. Many millions of dollars have been lost needlessly in exploitation by not understanding or paying attention to this matter. In many cases it can be ascertained to which of these three classes an ore deposit belongs.

The character of a deposit in most cases will determine this. Where the ores are deposited by ascending waters alone it has been pointed out that this is favorable to their continuity to great depth. Therefore, where a given ore deposit has been shown to belong to this class, the expenditure of money for deep exploration may be warranted, although, as already pointed out, such deposits may decrease in richness with depth. Where a deposit is produced by descending waters alone, the probable extent in depth is much more limited. In such cases, when the bottom of the rich product is reached, it would be the height of folly to expend money in deep exploration. Where the ore deposit belongs to the third class, that produced by ascending and descending waters combined, there will, again, be a richer upper belt composed of rich oxidized and sulphureted deposits which we cannot hope will be duplicated at depth. To illustrate: It would be very foolish, at Ducktown, Tenn., to sink a drill hole or shaft into the lean cupriferous pyrrhotite with the hope of finding rich sulphurets such as those which were mined near the level of groundwater. Those who have spent money in deep prospecting of the lean pyrrhotite in the Appalachian range will doubtless agree to this statement. Deposits produced by two concentrations may grade into the class produced by ascending water alone, and after the transition the deposit may be rich enough to warrant exploitation at depth; but if such work be undertaken it must be done with the understanding that the rich upper products will not be reduplicated at depth. It therefore appears to me that the determination to which of the classes of ore deposits produced by underground waters a given ore deposit belongs has a direct and very important practical bearing upon its exploration and exploitation.

In conclusion, I hold if mining engineers and superintendents understand the work of underground water, understand why and how ore deposits are made, less money will be expended in fruitless exploration; money will not be wasted in searching for deposits at places where nature never placed a deposit. Therefore, it seems to me to be the part of wisdom for a mine owner or manager to make a complete scientific investigation of a deposit of which he has charge in order to ascertain to which of these three classes the deposit belongs; and then to carry out the exploration and exploitation according to the principles which apply to the particular case.

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