Some Principles Controlling the Deposition of Ores.*

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PART I.—GENERAL PRINCIPLES.

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PART II.—APPLICATION OF PRINCIPLES TO ORE-DEPOSITS.

PART I.—GENERAL PRINCIPLES.

INTRODUCTION.

THE following paper upon the principles controlling the deposition of ores is adapted from a treatise on Metamorphism, to be published hereafter as a Monograph of the United States Geological Survey. In the present paper the argument can be made only in outline. The argument is especially fragmentary in the treatment of the general principles controlling the circulation of underground water.

It will be held in this paper that the deposition of most ores is but a special case of the general work of groundwaters, of exceptional interest to man. In order to understand the special problem, it is necessary to have a profound knowledge of the general principles controlling the circulation and work of groundwaters. In the treatise from which this work is adapted I have attempted to treat this subject more fully and broadly than has heretofore been done. From this treatise so much is abstracted as seems absolutely necessary in order to understand the special application of the work of groundwaters to the genesis of ore-deposits. Where points are not covered with sufficient fullness, I beg the reader to suspend judgment until he sees the full treatise.

In the treatise, as well as in the following paper, I have of course drawn upon the knowledge contained in the writings of all previous workers. No general treatise upon a broad subject is the work of a single man. It is the conjoint product of all previous workers and its writer. In the following discussion of ore-deposits I am indebted to all who have contributed ideas to this subject, from the great Bischof to Sandberger and Posepny. I have tried to give full credit to all by numerous references; but I cannot be sure that I have done full justice in every case. A comparison with the writings of others will show that I am in accord with Prof. Joseph Le Conte upon more points than with any one else.*

Ore-deposits may be divided into three groups, viz.: (A)

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* *Trans. Am. Inst. Min. Engineers*, vol. xxiv., p. 996. "On the Genesis of Metalliferous Veins," by Jos. Le Conte: *Am. Journ. Sci.*, 3d series, vol. xxvi., 1883, p. 1 *et seq.*

ores of direct igneous origin, (B) ores which are the direct result of the processes of sedimentation, and (C) ores which are deposited by underground water.

Ore-deposits of direct igneous origin are probably of limited extent. Certain very basic igneous rocks have been worked as iron-ores. In Norway are sulphide ores of various metals which Vogt* holds to be a direct segregation from a magma. Emmons† has also favored the idea of at least a first concentration of the metallic contents of ore by processes of differentiation from igneous rocks, more particularly basic ones. In many cases where ore-deposits, and especially sulphides are supposed to be igneous, the question may pertinently be asked as to how far aqueous agencies have worked in connection with the igneous agencies. I suspect, in most cases, that even if a first concentration has been accomplished by magmatic differentiation, that a second and more important concentration has been performed by underground waters, and this position I understand Emmons also to hold. Upon the question as to how far some ore-deposits are the direct processes of igneous agencies I do not propose here to enter.

To a limited extent ores are also the direct result of processes of sedimentation. As an instance of such ores may be mentioned some placer deposits. Possibly some ores are due to sublimation.

However, in so far as ores are of igneous origin, or are the direct result of the processes of sedimentation, or are the results of sublimation, they are excluded from the scope of the present paper. I intend here to consider only the third group of ores, —those produced through the agency of underground waters.

My first and fundamental premise is that the greater number of ore-deposits are the result of the work of underground water.

THE THREE ZONES OF THE LITHOSPHERE.

In another place‡ I have shown that the outer part of the crust of the earth may be divided into three zones, depending

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* J. H. L. Vogt: *Zeitschr. für prakt. Geol.*, Jan. and Apr., 1893; Oct., 1894; Apr., Sept., Nov., Dec., 1895.

† *Trans. Am. Inst. Min. Eng.*, vol. xxii., pp. 53–95. "The Mines of Custer County, Colorado," by S. F. Emmons: *17th Ann. Rept. U. S. Geol. Surv.*, part ii., 1896–96, pp. 470–472.

‡ "Principles of North American Pre-Cambrian Geology," by C. R. Van Hise, *16th Ann. Rep. U. S. Geol. Surv.* for 1894–5, pt. i., p. 589 *et seq.*, 1896.

upon the character of its deformation: an upper zone of fracture, a lower zone of rock flowage, and a middle zone of combined fracture and flowage.

Zone of Fracture.

The zone of fracture is that near the surface. In this zone the rocks are not deformed mainly by flowage, but by fracture. They are adjusted to their new positions mainly by rupture and differential movements between the separated parts. When rocks are deformed in the zone of fracture the ruptures which occur are those of faulting, jointing, differential movements between the layers (or accommodation), fissility, and brecciation. The so-called folds in the zone of fracture are chiefly the result of numerous parallel joint-fractures across the strata with slight displacements at the joints, giving each block a slightly different position from the previous one, and thus as a whole making a fold. For instance, the folds of the rigid rocks in the Alleghenies are not in the main true flexures, but a series of slightly displaced blocks.

Zone of Flowage.

In the zone of rock-flowage the deformation is by granulation or recrystallization, no openings being produced, or at least none except those of microscopic size.* This conclusion rests upon arguments which cannot here be fully repeated. However, it may be said in passing that the conclusion that a zone of rock-flowage exists at moderate depth is based, first, upon deduction from known physical principles as to the behavior of solid bodies under pressure, and second, upon observation. It is well known that when a rigid body, such as rock, is subjected to stress greater than its ultimate strength, it must rupture or flow. If a rock be subjected to a stress in a single direction greater than its ultimate strength in that direction, and the rock is not under pressure in other directions, rupture occurs. However, if we suppose that the rock be subjected to stresses greater than the ultimate strength of the rock in all directions, and that the difference in the stresses in different directions is greater than the ultimate strength of the rock

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* "Principles," *cit.*, p. 594, *et seq.*

under the conditions in which it exists, then if openings could be produced by a rupture, they would almost immediately be closed by pressure. In other words, at a certain depth below the surface of the earth, if we could suppose that cracks and crevices are formed by the deformation to which the rocks are subjected, the pressures in all directions being greater than the ultimate strength of the rock, these cracks and crevices would be almost immediately closed.

Since this conclusion was reached, Adams has actually deformed marble under the conditions supposed to exist at moderate depth below the earth, with the result that the rock changed its form without rupture and with no perceptible openings or cracks.*

Before the above inductive reasoning or Adams' experiment was made, I had become convinced from observation that at moderate depth rocks are deformed with fracture and differential movements between the solid particles (*granulation*), and by continuous solution and redeposition by underground water (*recrystallization*).† It was calculated that for all but the very strongest rocks, flowage must begin at a depth not greater than 12,000 meters,‡ for at this level the weight of the superincumbent mass is greater than the ultimate strength of the rocks.

Factors Influencing Depth at Which Flowage Occurs.—In the case of anticlinal arches a portion of the load may be removed by the supporting limbs, and thus the depth of the level at which the zone of flowage occurs beneath the arch be theoretically somewhat increased. However, it is highly probable that lateral stresses and increased temperature which always accompany rapid deformation, more than compensate for any removal of load. Time is another important factor. It is well known that a stress which in a short time is insufficient to rupture material may, if long continued, result in its deformation by flowage. The geologist has this factor, time, to a larger extent than scientists in any other subject, and it is a factor which he has con-

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* Experiments in the flow of rocks are still being made at McGill University by Frank D. Adams. A preliminary account was presented to the Geol. Soc. Am., Montreal meeting, 1897. This is summarized in "Science," vol. vii., 1898, pp. 82-83.

† "Metamorphism of Rocks and Rock Flowage," by C. R. Van Hise. *Bull. G. S. A.*, vol. ix., 1898, pp. 295-313, 318-326.

‡ "Principles," *cit.*, p. 592.

stantly to keep in mind. How important this factor is may be illustrated by the deformations of rocks as result of very moderate long-continued pressures. In some cases, in cemeteries, marble slabs have been placed horizontally and suspended at the ends. In the course of a score or more of years such slabs are found to have sagged in the middle a very considerable amount. If the slabs had at the outset been bent to this extent they would have undoubtedly been ruptured. The change in form is only possible by rock flowage, either through a differential movement of the solid particles with reference to one another or by solution and redeposition, *i.e.*, recrystallization, or the two combined. The consideration of time leads me to believe that the limit of 10,000 to 12,000 meters placed as the level at which flowage of the strong rocks must occur is probably too great, and observations upon deformation in the cores of mountain masses which have been deeply denuded confirm this conclusion. Rocks, even of the strongest kind, have in many instances been deformed by flowage rather than by fracture, when at depths much less than 10,000 meters.

Other factors, such as igneous intrusions or orogenic movements, increase the heat and pressure acting on the rock, and thus tend to diminish the depth at which flowage occurs.

If this reasoning is correct, it follows that all fissures must disappear at some depth, and that the maximum depth is limited by the depth of the zone of fracture for the strongest rocks.

Zone of Combined Fracture and Flowage.

There is a zone of combined fracture and flowage below the zone of fracture, because rocks have varying strengths, because there is great variation in the rapidity of deformation, in the temperature at which the deformation occurs, in the moisture present, and in various other factors. A weak rock, for instance a shale, may be deformed by flowage at a much less depth than a strong rock, such as a granite. Thus the belt of combined fracture and flowage is of considerable thickness, possibly as thick as 5000 meters. In this zone we have all combinations of the phenomena of fracture in the various ways above mentioned, and of flowage by granulation and recrystallization.

It is highly probable that the openings of the zone of fracture gradually decrease in size as depth increases, until in the zone of flowage the openings are, as already explained, microscopic or non-existent. If a gradation such as indicated exists, it is a necessary corollary that the deformations of the zone of fracture must have their equivalents in the deeper seated zone of flowage and flexure. This point I have fully developed in other places.* It is explained that in depth faults are replaced by flexures, and that any deformation of a large mass of a given rock from one form to another by fracturing may be paralleled by similar changes of form in the zone of flowage, the result being there accomplished by granulation of the mineral particles or by recrystallization, or by both.

It might be thought that the above general statement is a deduction which cannot be confirmed by observation, but such is not the case. Many rocks which have been deformed in the zone of flowage or in the zone of combined fracture and flowage, as a consequence of denudation have reached the surface, and one is able to observe all the transition phenomena of deformation between the zones of fracture and flowage. These I have somewhat fully described in another place.† An excellent illustration of the deformation of a rock mainly by flowage, but in a subordinate way by fracture, is the Berlin rhyolite-gneiss, described by Samuel Weidman.‡ The formation of this rock was mainly that of recrystallization, but many of the mineral particles were granulated. Also many minute joint crevices were formed which were subsequently filled by cementation.

It follows from the above reasoning that fissures may disappear at different depths below. Where there are fractures with large displacements, fissures are likely to extend to very considerable depths. In proportion as the displacements are small, the fissures are likely to disappear below at less depths. Furthermore, as has already been explained, certain rocks are deformed by flowage at a much less depth than are other rocks. Therefore, in a region in which there is a great shale

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* "Principles," *cit.*, p. 676; "Metamorphism," *cit.*, pp. 313–318.

† "Principles," *cit.*, pp. 601–603; "Metamorphism," *cit.*, pp. 312–313.

‡ "A Contribution to the Geology of the Pre-Cambrian Igneous Rocks of the Fox River Valley, Wisconsin," by S. Weidman. *Bull. Wis. Geol. and Nat. Hist. Surv.*, No. III., pt. 2, 1898.

or slate formation at a moderate depth, a strong fissure in more brittle rocks at the surface may disappear as it encounters the shale formation, being replaced there by a flexure. I have little doubt that considerable fissures thus disappear at a depth less than 1000 meters.

Illustrations of the disappearance of fissures with depth are found at various places. In the gold belt of the Sierra Nevadas, Lindgren* says it is "an incontestable fact that many small veins close up in depth."

Not only may fissures die out below, but fissures may disappear above, the fault along the fissures being replaced by a flexure in the overlying stratum, which yields by flowage. This is beautifully illustrated by the Enterprise mine, of Rico, Col., described by Rickard,† where faulted fissures in sandstone and limestone disappear above, at the place where shale is encountered, the shale accommodating itself to the fractures below by monoclinal flexures. (See Fig. 9, p. 128.)

The marked effect which the character of the country rock may have upon the nature of a fissure is well illustrated in the Cripple Creek district, where, according to Penrose,‡ the fissures in the hard rocks are sharp, clean-cut breaks, while in the soft rocks they are ordinarily a series of very small cracks, constituting a displacement of a kind which I call a distributive fault. Well illustrating this are mines which are partly in hard and partly in soft rock. "The vein on which the Buena Vista, Lee Smuggler, and Victor mines are located occupies a sharp, clean-cut fissure, partly in the massive rock and partly in the hard breccia; but when it passes into the soft, tufaceous breccia on the east slope of Bull Hill the fissure is represented only by faint cracks occupied by no vein of importance. In this case the force which caused the fissure overcame the cohesion of the harder rock sufficiently to make a clean break, but in the more plastic rock it overcame cohesion only to the

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* "The Gold-Quartz Veins of Nevada City and Grass Valley, California," by Waldemar Lindgren, 17*th Ann. Rept. U. S. Geol. Surv.*, pt. ii., 1895–96, p. 162.

† "The Enterprise Mine, Rico, Col.," by T. A. Rickard, *Trans. Am. Inst. Min. Engineers*, vol. xxvi., 1897, pp. 906–980.

‡ "Mining Geology of the Cripple Creek District," by R. A. F. Penrose, Jr., 16*th Ann. Rept. U. S. Geol. Surv.*, pt. ii., 1894–95, p. 144.

extent of causing a series of faint fractures without any one well-defined break."*

This point of transition between the zone of fracture and the zone of flowage and the dying out of fissures below is dwelt upon in order to exclude the hypothesis of filling of fissures from the bottom. If fissures gradually decrease in size and finally die out, the streams which make their way into the fissure must enter from the side or from above. For further development of this point, see pp. 54–56.

In closing the subject it may be said that in all cases where rocks have been deformed in the zone of rock flowage, or in the zone of combined fracture and flowage, and are now at the surface, there will be superimposed, upon the effects of the deep-seated deformation, the deformation by fracture, resulting from earth movements during the time the rock is slowly migrating through the zone of fracture to the surface.

THE WATER-CONTENT AND OPENINGS IN ROCKS.

Since the ore-deposits considered in this paper are the work of underground water, and since the flowage of underground water is mainly through the openings in rocks, it is necessary to consider the condition of the water in the openings and the character of the openings which may occur in rocks.

As to the content of water the zone of fracture may be divided into two belts, an upper belt above the level of groundwater called the belt of weathering and a lower belt below the level of groundwater called the belt of saturation. Above the level of groundwater the openings in the rocks are ordinarily only partly filled with liquid. Under different conditions, which need not here be discussed, the water in the openings varies from an exceedingly small fraction of that required to fill the openings, to saturation.

Condition of Water in the Zone of Fracture.

In the belt of saturation, from the level of groundwater to its base, if it be limited to a depth of 10,000 meters, the H_2O is in liquid form, as water. The water is, however, for much of the belt superheated. If the increment of increase of tempera-

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* *Loc. cit.*, p. 144.

ture be taken as 1° C. for every 30 meters, the critical temperature of water, 364° C., would be found at a depth of 10,920 meters. At any given place the water is subject to the pressure of the superincumbent column. The question as to whether hydrostatic pressure increases sufficiently fast to prevent the water from passing into the form of gas needs to be answered. Supposing the temperature of the water were 100° C., or just at the boiling-point at the surface of the earth, the most unfavorable assumption to holding the water as a liquid in the zone of fracture, it would still be true that the water would be in the form of liquid in this zone, as is shown by the following table based upon this supposition, column (1) being temperatures, column (2) being pressures necessary to hold H_2O as a liquid at these temperatures, column (3) being depth in meters at which the pressures would be produced, column (4) being the depth which would be required to produce the temperatures on the supposition that the increment of the increase of temperature is 1° C. for every 30 meters, and column (5) being the actual temperatures which exist upon this supposition at the depths represented by column (3):

(1.) Temperatures.	(2.) Pressures Corresponding to Temperature of Col. 1.	(3.) Depth Necessary to Produce Pressure of Col. 2.	(4.) Depth Necessary to Produce Temperature of Col. 1.	(5.) Temperatures Actually Existing at Pressures and Depths of Cols. 2 and 3.
Deg. C.	Atm.	Meters.	Meters.	Deg. C.
120	2	20	3,600	100.66
180	10	100	5,400	103.33
225	25	250	6,750	108.33
265	51	510	7,950	117.00
310	99	990	9,300	133.00
340	148	1,480	10,200	149.33
365	205.5	2,055	10,950	168.33

From this table it will be seen that the hydrostatic pressure at various depths is far in excess of that required to hold the water in the form of a liquid; or, looked at in another way, for any given depth the temperature is not sufficiently high to allow the water at that depth and pressure to exist in the form of a gas.

Therefore, where the increase of temperature is normal, the pressure at any point down to the level at which the critical temperature of water is met is clearly much more than adequate to prevent the water from changing to steam. Where magma is intruded in the lithosphere, the temperature may become so high that this statement will not hold. This, however, is the exceptional, not the usual, case. Furthermore, it is conceivable that as result of deformation itself the temperature of the rocks might rise so high as to convert the water present into the form of steam. This possibility will not be discussed. However, it is believed to be probable from investigations upon metamorphism that this condition of affairs rarely if ever obtains, since, as I have elsewhere explained, long before the critical temperature of water is reached, solution and deposition of rock material, or recrystallization, readily takes place, and in this change the work converted into heat is far less than in mechanical granulation.*

The Openings in Rocks.

The openings in rocks include (1) those which are of great length and depth, as compared with their width, and thus are essentially flat parallelopipeds; (2) those in which the dimensions of the cross-sections of the openings are approximately the same, and therefore resemble tubes of various kinds, and (3) irregular openings.

(1) The openings of the first kind are those of faults, of joints, of fissility, and of bedding partings. The openings of this class are likely to be continuous for considerable distances. This is true to the largest extent of fault openings, is true to a less extent of joint openings and bedding partings, and to a still less extent of the openings of fissility. It is recognized that many of the fissures are exceedingly complex. They are, indeed, in many instances, a series of parallel or intersecting fractures, forming a zone of brecciation. However, for such a zone, as a whole, the statement still holds that the openings have great length and depth as compared with their width. In position, the joint-, fault-, and fissilility-openings ordinarily have an important vertical element, or at least traverse the beds. Frequently they are nearly vertical, or traverse layers of formations at right angles. In consequence of this, they are very important factors

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* "Metamorphism of Rocks and Rock Flowage," by C. R. Van Hise, *Bull. G. S. A.*, vol. ix., 1898, pp. 310-311, 313-318.

in the flowage of underground water. Relatively pervious formations separated by impervious formations may be thus connected. Pervious formations overlain by impervious formations may be connected with the surface. Bedding-partings are parallel to the layers. Since underground waters very frequently follow formations, the bedding-partings, which extend long distances, become very important factors in the promotion of flowage parallel to the formations. This is especially true of the contact of formations of different character. These contacts are places of maximum differential movements, of consequent complex fracturing, and therefore of important openings and large circulation.

(2) The spaces of the second class are those of the mechanical sediments, including conglomerates, sandstones, soils, tuffs, etc. The openings of mechanical sediments have a strong tendency to a definite form, and are continuous. The forms of these openings have been fully discussed by Slichter.* The openings alternately narrow and widen. At their wider parts their sections are roughly polygonal, the polygons having more than three sides, and these are curved. At their narrowest places, the cross-sections of the openings approximate to triangles, and where the grains are of equal size, the triangles are equilateral. The form of the tubes at their minimum cross-section is due to the contact of three grains in a plane, the space between which is nearly triangular.

(3) Irregular openings are those of the vesicular lavas and the irregular fractures of the rocks. They are in part continuous and in part discontinuous. In rocks where the openings are exceedingly irregular in form, the flowage of water is limited to the continuous openings, however small they may be.

Openings of any of the above classes, whether a result of deformation or produced by original sedimentation or formed in connection with volcanic action, may be enlarged by solution. Indeed, this will be the case wherever the processes of solution more than counterbalance the processes of precipitation. It is later explained that this is the more likely to occur with downward moving water than with upward moving water. Since

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* "Theoretical Investigation of the Motion of Ground Water," by C. S. Slichter, 19*th Ann. Rept. U. S. Geol. Surv.*, for 1897–98, pt. ii., pp. 305–323.

downward moving waters are dominant above the level of groundwater and prominent in the upper part of the belt of saturation, it is in this area that openings are most frequently enlarged by solution. (See pp. 46–48, 132.) It has been argued by Posepny* that openings serving as channels for underground water may be wholly produced by solution. That openings may be somewhat prolonged and different openings connected by solution, thus helping underground circulation, is more than probable, but that important passages are produced wholly by solution is an assumption which I think has not been verified by the facts of observation.

Size and Number of Openings.—Large openings are favorable to rapid flowage. Small openings are unfavorable to rapid flowage. This results from the fact that the friction between the walls and the moving column steadily becomes greater for a given volume of water as the openings become smaller. Large openings are favorable to a somewhat direct course. Small openings are favorable to a circuitous route. The direct course of water in large openings is illustrated by limestone regions, where there are numerous large joints and caves within which the water is quickly concentrated. This being the case, the flowage of water is very largely in the upper part of the zone of fracture. Where the openings are small, a circuitous route must be taken, for to pass a given volume of water from one point to another it is necessary that a wide range of openings must be used. This is more fully explained, pp. 28–36.

Fault, joint, bedding, and fissility openings may be so numerous that the pore-space is very large. Upon the average fault openings are farther apart, but larger than the joint openings, and joint openings are wider spaced and larger than the openings of fissility. It cannot be said which kind of openings upon the average gives the larger pore-space. Since, however, large openings are favorable to rapid flowage, for a given pore-space the fault openings are likely to give a greater flowage than joint openings, and joint openings a greater flowage than those of fissility. This follows from the greater size of the fewer openings. To this is to be added the element of greater

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* "The Genesis of the Ore-Deposits," by F. Posepny, *Trans. Am. Inst. Min. Engineers*, vol. xxiii., 1894, pp. 207–212.

continuity of the larger openings. Therefore, with a given pore-space, the flowage may be vastly greater in the case of faults than in the case of joints, and much greater in the case of joints than in the case of fissility. It will later be explained that the larger openings are occupied by the trunk streams, and that in these openings ores are most likely to be concentrated; hence, ore-deposits most frequently form in fault-fissures, less frequently in joints, and still less frequently in the smaller and more discontinuous openings.

If the principle that large openings are favorable to rapid flowage be applied to mechanical sediments, it follows that with a given pore-space the coarse conglomerates furnish a much larger flow than fine conglomerates, the fine conglomerates a larger flow than the sandstones, and these a vastly larger flow than the fine-grained shales.

Upon the basis of size, openings in rocks may be divided into (a) openings which are larger than those of capillary size, or supercapillary openings, (b) capillary openings, and (c) subcapillary openings.

For water, openings larger than capillary openings, according to Daniell,* may be circular tubes which exceed .508 mm. in diameter, or may be sheet-openings, such as those furnished by faults, joints, etc., the width of which are one-half of this or exceed .254 mm. To movement of water in such openings the ordinary laws of hydrostatics apply. Capillary openings for water solutions include those which, if circular tubes, are smaller than .508 mm. in diameter, or, if sheet spaces, are narrower than .254 mm., and which in either case are larger than the openings in which the molecular attractions of the solid material extend across the space. Such openings in the case of circular tubes are those smaller than .0002 mm. in diameter, or, if sheet passages, are below .0001 mm. in width. Capillary openings therefore include circular tubes from .508 mm. in diameter to .0002 mm. in diameter, and sheet passages from .254 mm. in width to those .0001 mm. in width. Capillary openings of other forms have a range limited between .508 mm. and .0001 mm., but no one form has so wide a range as this. To movement of water in openings such as these the laws of cap-

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* *Text-Book of Physics*, by Alfred Daniell, 3d ed., 1894, pp. 277, 316.

illary flow apply. By subcapillary openings are meant those in which the attraction of the solid molecules extends from wall to wall. These include all tubes smaller than .0002 mm. in diameter, and sheet openings smaller than .0001 mm. in width. For intermediate forms the subcapillary openings have as their maximum limit a range from .0002 mm. to .0001 mm.

Within this paper I cannot fully discuss the laws of flowage for each of these classes of openings and their application. This is fully done in a treatise on "Metamorphism," from which this paper is abstracted. It is, however, necessary to summarize the laws of flowage of water in each of the three classes of openings.

The flowage of water through supercapillary tubes nearly follows the ordinary laws of hydrostatics, *i.e.*, the flowage of water is as the square root of the pressure due to head. If $V =$ velocity, $H =$ pressure due to head, and $G =$ force of gravity, then $V = \sqrt{2GH}$. For instance, the velocity resulting from a head of 10 cm. would be the square root of 2 x 981 x 10 cm.

This formula is only approximately correct, for the internal friction in supercapillary tubes is dependent upon the viscosity of the solutions (a factor considered on p. 30), upon the regularity of the tubes, and upon the velocity of flowage. If the tubes are not straight, eddies will form which will increase the internal friction and decrease the speed of movement. In the long, rough, irregular underground passages not of determinable size, eddies may so increase the internal friction as to render the formula of hydrostatic flow inapplicable. Further, as a result of the viscosity, the resistance increases with increase of velocity, so that where the velocity of movement is considerable, even if the tubes are open and continuous, the formula gives too high results.

The flowage of water with a given head in supercapillary openings is very rapid indeed, as compared with the smaller openings. The supercapillary openings include the greater number of the fault openings, joint openings, bedding partings, many openings of fissility, and the openings in the coarser mechanical sediments, such as very coarse sandstones, and conglomerates.

According to Poiseuille's law, the flowage of water in capillary openings is proportional not to the square, as in supercapillary openings, but to the fourth power of the radius; is proportional not to the square root of the pressure, as in supercapillary openings, but to the pressure; is inversely proportional to the length of the tube; and is indirectly proportional to the viscosity of the liquid.*

From the foregoing it follows that the flow in a tube with a radius of .2 mm. in diameter would be sixteen times as great as in a tube .1 mm. in diameter. Furthermore, in a tube of a definite length, if the pressure be doubled the flow would be doubled, if trebled the flow be trebled. With a given pressure, if the length be doubled the flow would be diminished to one-half, if trebled to one-third. The viscosity of underground waters decreases rapidly with the temperature, being only one-fifth as much at 90° C. as at 0° C. Therefore, with capillary tubes of a given size the flowage would be five times as fast at 90° C. as at 0° C.

How important the laws of capillary flow are in the movement of underground water and the production of ore-deposits will be understood when it is known that the openings of all ordinary sandstones and mechanical sediments are capillary openings. Furthermore, it is to be remembered that at a depth of 2700 meters, supposing the increment to be 1° C. for 30 meters, the temperature is 90° C. Therefore this fact, because of decreased viscosity, is very favorable to the flowage through the openings at considerable depth.

Notwithstanding the increased mobility of water, the circulation in small capillary tubes is very slow indeed; so slow that layers of rocks in which the openings are of small capillary size, such as those of dense clays and shales, are spoken of as impervious. Although this is not exactly true, the movements of water through such materials is slow as compared with the movement in larger capillary openings.

Openings of the third class are subcapillary. In these the

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* According to Poiseuille, the general formula for the flow through a tube of circular section is $f = \frac{\pi a^4 p}{8 \mu l}$, in which f is the discharge in cubic centimeters per second, a is the radius of the tube, l its length, p is the difference in pressure at its ends in dynes per square centimeter, and μ is the coefficient of viscosity of the liquid. (See "Theoretical Investigation of the Motion of Ground Water," by C. S. Slichter, 19*th Ann. Rep. U. S. Geol. Surv.*, pt. ii., p. 317.)

attraction of the solid molecules extends from wall to wall. The water is held as a film glued to the walls by the adhesion between the water and rock. There is no free water. In such openings as these the flowage must be exceedingly slow or nil. Subcapillary openings as here used include also intermolecular spaces.

It is evident, from the reasoning given on the preceding pages, that the openings in the zone of rock-flowage are those of subcapillary size. Furthermore, it is evident that the subcapillary openings are discontinuous. It has been seen that at a depth greater than about 11,000 meters the water probably has a temperature greater than the critical temperature of water; but in the opinion of some physicists the liquid state may persist even after the critical temperature be passed.* Whether the H_2O below this depth is a liquid or is water-gas cannot certainly be determined; but it may be supposed that the viscosity is comparatively small. Furthermore, the water is under enormous pressures. Under circumstances of temperature exceeding the critical temperature of water and very great pressure, one would be rash to assert that water does not pass through the exceedingly small subcapillary spaces of rocks in the zone of flowage, or possibly also through the intermolecular spaces. Some movement of water might also occur in connection with the processes of solution and deposition, or recrystallization, which, as I have explained, is characteristic of this zone. That is to say, the mobility within the solid material implies at least an equal mobility in the liquid material which is also present.

In reaching a probable conclusion it is, however, to be remembered that it must be assumed that the rocks of the lower part of the lithosphere are also probably saturated with water, and that the pressure above is resisted by equal pressure from below. Doubtless, under the changing conditions caused by rock deformation, metamorphism and denudation, and by other vicissitudes to which the lower part of the lithosphere is subjected, the water-pressures become unequal at various times and places, and at such times and places there would be an undoubted tendency for water to move from places of great pressure to places of less pressure.

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* Preston, "Theory of Heat," p. 378.

Whatever conclusion may be reached as to the possibility of the circulation of water in the zone of rock-flowage, it will probably be agreed by all that the circulation, if it occurs at all, must be exceedingly slow. Indeed, upon this point we are not confined to deduction. We have an almost certain inference from the character of the alterations which occur in the zone of rock-flowage. In my treatise on Metamorphism I show that within the zone of fracture, immigration and emigration of rock-material is very great, and that the composition of a rock may within this zone be materially modified as a consequence. However, while a rock in the zone of flowage may be transformed from a massive form to a schist or a gneiss, the composition of the resultant schist or gneiss is almost identical with that of the original rock. Had there been rapid and extensive circulation of water within this belt, it would have been inevitable that the composition of the resultant metamorphosed rocks would have been different.

Ore-Deposits Derived from Zone of Fracture.

We conclude from the foregoing that while underground circulation of water upward, downward, and lateral, is a possibility within the zone of rock-flowage, it is very slow, and that it cannot be appealed to to explain metalliferous deposits. If any one asserts that the metalliferous materials of mineral veins are derived by water circulation from the centrosphere,* or are derived from the lithosphere* below the zone of rock-fracture, I hold this to be a pure unverified assumption for which there has not as yet been adduced one particle of evidence, and opposed to which stand well-known principles of physics concerning the movement of water in minute openings, and all observations which have been made as to the actual changes which have taken place in the rocks once within the zone of rock-flowage.

The original source of much of the material for the metalliferous deposits may, indeed, be largely the centrosphere or the lower part of the lithosphere; for from these sources vast masses

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* The term lithosphere is here applied to the outer shell of earth, which is known to be solid. The term centrosphere, following Powell, is applied to the central mass within the lithosphere comprising the greater part of the world, as to the character of which we have no definite knowledge.

of volcanic rock are injected into the zone of fracture or brought to the surface. This is especially true during great periods of vulcanism. Furthermore, it is well known that in regions of volcanic rocks many ore-deposits are found. Also it is believed that all the rocks of the lithosphere were originally igneous, and that from these igneous rocks the sedimentary rocks have been derived by the epigene forces, *i.e.*, the forces working through the agencies of atmosphere and hydrosphere. It follows, therefore, that the metals of ore-deposits, either directly or indirectly, are derived from igneous rocks. However, the ores are directly derived from rocks in the zone of fracture by circulating underground waters. The rocks which furnish the metallic compounds may be intruded igneous rocks; they may be extruded igneous rocks; they may be the original rocks of the earth's crust; they may be sedimentary rocks derived by any of the processes of erosion from primary rocks; they may be the altered equivalents of any of these classes.

That there is a sufficient amount of metalliferous material within the rocks of the zone of fracture to account for all metallic deposits will be admitted by all. It is well known that the amount of material which it is necessary to suppose to be originally present in the country-rock within the reach of the underground water circulation in the zone of fracture, in order to fully account for the ore-deposits, is an exceedingly small fraction of 1 per cent.; such small fractions in the case of the rarer metals that the numbers have little significance to us. Even in the case of the common metals, such as iron, lead, zinc and copper, the fraction of a per cent. which it is necessary to suppose to be present is exceedingly small. This is well illustrated by the lead- and zinc-district of southwestern Wisconsin. Here, according to Prof. Chamberlin, Mr. Buell has calculated that if the source of the metal in the Potosi district, the richest in the region, be restricted to a layer 100 feet deep and limited on the outside of the area of paying crevices by half the average distance between the crevices, to account for all the lead which had been taken out, it would only be necessary to suppose that the rock contained "one-fourteen-hundredth of one per cent., or a little more than one-seven-millionth of the rock."*

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* "Ore-Deposits in Southwestern Wisconsin," by T. C. Chamberlin, *Geol. of Wis.*, vol. iv., 1882, pt. iv., p. 538.

The second fundamental premise of this paper is, that the material for ore-deposits is derived from rocks within the zone of fracture.

The Source of Underground Water.

Since it has been shown it cannot be assumed that there is any considerable circulation of underground water in the zone of rock-flowage, it follows that we cannot suppose that the water of the zone of fracture passes into or is derived from the zone of rock-flowage on any large scale. Doubtless this transfer does take place to some small extent. Also, through the agency of vulcanism water occluded in magma is transferred from the zone of rock-flowage, or even possibly from the centrosphere, to the zone of rock-fracture. Furthermore, hydration and dehydration of the rocks are constantly taking place, and these processes may not balance. However, the amount of underground water coming from the deep-seated zone of rock-flowage in these ways at any one time is relatively small, and therefore the meteoric water entering the crust substantially balances that issuing from it. Hence, so far as the main work of ore-deposition is concerned, the water is that of the zone of rock-fracture, and this water is water of meteoric origin, which makes its way from the surface into the ground, and there performs its work and issues to the surface again.

The third premise of this paper is that by far the major part of the water depositing ores is meteoric.

The Cause of the Flowage of Underground Water.

The fourth premise of this paper is, that the flowage of underground water is caused chiefly by gravitative stress.

Gravity is effective in the movement of underground water in proportion to the head. Head is due to the fact that the water entering the ground at a certain level, after a short or long underground journey, issues at a lower level.

The efficiency of gravity is also dependent upon temperature. In so far as water is warmer at its point of issuance than it was when it joined the sea of underground water, this is favorable to circulation, and gives an effect in the same direction as head. This is due to the fact that the density of water varies inversely with the temperature.

Taking the volume of water at 4° C. as 1, its volume at 50°

C. would be 1.0120; at 75° C. would be 1.0258, and at 100° C. would be 1.0432.* Therefore the increase in the temperature of underground water may lessen its density as much as 4 per cent. without exceeding its boiling-point at normal pressure, and a diminution of density of 1 per cent. or more is probably not uncommon. It is therefore evident that in columns of water of equal length the stress of gravity is considerably greater upon the column having the lower temperature. That the difference in gravitative stress, due to difference in temperature, may be sufficient to produce rapid circulation in pipes which are supercapillary, is shown by the use of the principle in the hot-water system of heating buildings. Underground, as in the hot-water system of heating, heat is the energy which causes the water to expand, and gives a difference in density. When heat has produced a difference in density of the two columns, gravity is the force which inaugurates and maintains the circulation.

It is believed that underground circulation may be promoted in an important degree by difference in temperature of the descending and ascending columns of water, resulting from heat abstracted from the rocks, due wholly to their normal increment of temperature with depth. Later it will be shown that the downward moving water is ordinarily dispersed in many small openings and moves relatively slow. Therefore it may be supposed at any given place to have approximately the temperature of the rocks. The upward movement of water, upon the contrary, is shown to be usually in the larger openings and relatively rapid. Therefore at any given place its temperature is probably higher than is normal for the rocks at that depth. The result is to give the descending and ascending columns a difference in temperature, the ascending column being hotter. As already noted, the expansion of water with increase of temperature is considerable, amounting to over 4 per cent. between 0° C. and 100° C., that is, a given mass of water would occupy a volume 4 per cent. greater. In other words, if there is an average difference of 100° C. in the ascending and descending columns, 100 feet of the downward moving

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* "Exercises in Physical Measurements," by L. W. Austin and C. B. Thwing, 1896, p. 151.

water would balance 104 feet of the upward moving water. If we suppose the descending and ascending columns to be connected, of equal height, and having an average difference of 100° C. in temperature, this would be equivalent to a head of 4 feet per 100 feet all along the length of the column. Probably the difference in temperature between the columns is not often so great as 100° C., but the illustration shows that the difference in temperature between ascending and descending columns of the same length may give a sufficient stress to overcome friction and viscosity, and give a somewhat rapid movement to underground water.

As an illustration of the principle may be mentioned the water-power of the sea-mills of Cephalonia, which, according to the Crosbys, is wholly due to the difference in the temperature of the descending and ascending waters.* In regions where vulcanism or dynamic action have recently occurred, the difference in density resulting from difference in temperature in the descending and ascending columns may be an even more important influence in the circulation of the underground waters than in regions where the high temperature is due to the normal heat of the rocks. Such a region is the Yellowstone Park.

In some cases the issuing water throughout a great region is very clearly at a higher temperature than the entering water, and in such regions this difference in temperature must be a very important factor in its underground circulation. In such cases the difference in temperature of the descending and ascending waters generally results from the normal increase of temperature due to depth, from regional vulcanism, and from the rocks having a higher temperature than normal because of recent orogenic movements.

An excellent illustration of such a region is the Cordilleran region of the western United States, in which there are many valuable ore-deposits. Gilbert† and others have shown that scattered throughout this vast region, occupying nearly one-

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* "The Sea-Mills of Cephalonia," by W. F. Crosby and W. O. Crosby, *Tech. Quar.*, vol. ix., 1896, pp. 6–23.

† "The Geology of Portions of Nevada, Utah, California and Oregon, Examined in years 1871 and 1872," by G. K. Gilbert, *Rept. Geog. and Geol. Surveys* west of 100th Meridian, vol. iii., 1873, pt. 1, pp. 148–149.

third of the United States, are many hot springs, the temperatures of which vary from 37° C. to 100° C. More numerous than these are the warm springs, the temperatures of which are below blood heat. The warm springs may be considered as including those between 18° C. and 37° C. According to Gilbert, the water of all the foregoing springs exceeds the mean annual temperature of the region by 8.3° C.

Although we have no data by which to verify the statement, I have no doubt whatever that the springs, the temperature of which is above the mean annual temperature, but less than 8.3° C. above, exceed by many times the total of all springs the temperatures of which are 8.3° C. or more above the normal temperature of the region. And it is to be remembered that a slightly increased temperature of issuing water over that of the falling water through the vast number of springs and through seepage is of far greater quantitative importance than the marked increase of temperature in the comparatively few warm and hot springs. This illustrates the old principle that the widespread, moderate forces are incomparably more important than the more conspicuous, but more circumscribed forces.

While gravity is the only important force to which appeal can be made to account for the circulation of waters producing ore-deposits, circulation in some small degree does result from other immediate causes. For instance, earth movements may deform the rocks, and in this process squeeze out the water, as in the production of the crystalline schists from the sedimentary rocks. If the deformation of the rocks be referred to their ultimate cause, gravity, even the circulation of the water resulting from deformation is indirectly due to the stress of gravity. However, the important immediate causes of movements of underground water below water level are two—gravity and deformation.

But whatever the cause of the flow of underground water, the direction of movement is from places of greater pressure to places of less pressure. A current going in any direction is evidence of an excess of pressure in the rear of the current. Thus, water which enters by seepage or through capillary tubes into a larger opening, such as a fissure, must be under greater pressure than the column of water into which it makes its way. Whether the motive force in the movement of the water is difference in gravitative stress or deformation, or any other cause, the excess of pressure resulting in movement is behind the current.

In the foregoing statement as to the cause of the movement of underground water, only the vertical component of the columns has been considered. The horizontal component of the column has no effect. So far as there is horizontal movement, the energy required for this movement to overcome friction and internal viscosity is derived from the forces already mentioned,—that is, gravitative stress or deformation.

Belts of Underground Circulation.

The circulation of underground water is divided into two parts: that of an upper belt above the level of groundwater, and a lower belt below the level of groundwater.

Upper Belt of Underground Circulation.—The upper belt of underground water circulation extends from the surface to the level of groundwater. The thickness of this outer belt of water circulation varies greatly. At or near streams, lakes, or ocean, and in areas where the surface is not much higher than the adjacent bodies of water, the level of groundwater may reach near or to the surface, and thus there may be, for these areas, either a very thin upper belt of circulation, or none. In regions of moderate elevation and moderate irregularities of topography the level of groundwater is usually from 10 feet to 100 feet below the surface. It is especially likely to be near the surface in regions where there is a thick layer of drift or a thick layer of disintegrated rocks. In elevated and irregular regions, and especially those in which the precipitation is rather small, the level of groundwater may be from 100 to 300 feet below the surface. In high, desert regions, and especially limestone regions, the level of groundwater may be from a thousand to several thousand feet below the surface.

The position of the level of groundwater is more fully considered further on, in connection with the belt below that level.

A large amount of the water which enters the upper belt is, without entering the lower belt, again brought to the surface through capillarity, or through the influence of vegetation. The circulation of this water in the upper belt alone has little influence upon the ore-deposits, and is here ignored. Another portion of the groundwater moves downward through the upper belt and joins the sea of underground water. This water is associated with oxygen, carbon-dioxide, and other gases. These substances perform various classes of work, which are considered on pp. 48–53.

Lower Belt of Underground Circulation.—The lower belt of circulation has as its upper limit the level of groundwater. This level is not horizontal, but is undulating, the undulations following the topography. A topographic map of a region is to a certain extent a topographic map of the level of groundwater; but the latter is less accentuated. The elevation of the contour of the groundwater at a given place is less than the elevation of the surface contour by the depth of the level of groundwater.

That the level of groundwater roughly follows the topography is shown by the fact that upon many hills and mountains, wells reach water at the very moderate depths of a few score, or at most 100 or 200 feet. The relation is further illustrated by the fact that where a shore begins to rise from a body of water, as from a lake, the level of groundwater also rises, but not so rapidly. As an example of this may be mentioned the case of a well at Madison, Wisconsin, about 1200 feet from Lake Mendota and 88 feet above its surface, in which the water is on an average about 52 feet above the surface of the lake.*

In general, the more accentuated the topographic features, the greater is the difference between the surface topography and that of the level of groundwater. However, this difference also depends upon the character of the rocks. Where the openings in the rocks are numerous and large, there is a greater difference in the topography of the surface and of the level of the groundwater than where the rocks are less open. In fractured limestone regions containing caves, the level of the groundwater may follow approximately that of the drainage of the district, and thus there be a great difference between the topography of the surface and that of the groundwater. Where a region is covered with a thick mantle of fine material, as drift,

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* "Principles and Conditions of Movements of Groundwater," by F. H. King, 19*th Annual Rept. U. S. Geol. Surv.*, for 1897–98, pt. ii., p. 99, 1899.

the topography of the groundwater may very closely follow that of the surface. Finally, the less the precipitation the greater the difference between the contours of the surface and the level of groundwater. In the Grand Cañon region of Colorado we have a district in which the topography is much accentuated with sudden and great changes in elevation, in which the rocks are largely limestone and the precipitation small. Therefore in this region there is a very great difference between the topography of the surface and that of the level of groundwater.

Capacity of Water for Work in the Lower Belt of Underground Circulation.—The temperature of water in the lower belt of underground circulation increases with depth. The average increment is about 1° C. for 30 meters. Supposing the water at the surface to be 0° C., it would be 100° C. at a depth of 3000 meters. At a depth of 10,000 meters it would be 333° C. It has been shown, pp. 10–12, that the pressure increases with depth with sufficient rapidity to hold the water in the form of a liquid. Therefore the work of the water in the zone of fracture below 3000 meters is that of superheated water. It is well known that pure water at ordinary temperatures is capable of dissolving all compounds to some extent, but the amount of the more refractory compounds dissolved is exceedingly small. But pure water at a high temperature is a potent solvent. Barus has shown that water at temperatures above 185° C. attacks the silicates composing soft glass with astonishing rapidity.*

At 180° C. various zeolites can be dissolved in pure water, the material crystallizing out on cooling. Lemberg shows that water at 210° C. slowly dissolved anhydrous powdered silicates. It is therefore apparent that water in the lower part of the zone of fracture is a most potent chemical agent.

Furthermore, it is well known that one salt in solution may assist water in dissolving another salt. For instance, the presence of alkaline sulphides is very favorable to solution of sulphides of the heavy metals, such as copper, silver and gold. On the other hand, the presence of one compound in solution

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* "Hot Water and Soft Glass in their Thermo-dynamic Relations, by C. Barus, *Am. Jour. Sci.*, IV., vol. ix., 1900, pp. 161–175.

may be unfavorable to the solution of another compound. Thus in the underground waters the material in solution continually affects the capacity of the water to dissolve and precipitate other materials. This subject will be further discussed, pp. 43–45.

Movements of Water in the Lower Belt of Underground Circulation.—The complex movements of underground water may be resolved into two components, horizontal or lateral movements and vertical movements.

The vertical component of the journey of underground waters in the zone below the level of groundwater may be considered as confined to the zone of fracture, and is probably measured at a maximum by 10,000 meters, or at most by 12,000 meters. The lateral component, on the other hand, may vary from a few meters to hundreds or even a thousand or more kilometers. Upon the average, the horizontal component is probably far greater than the vertical component.

In order to understand the work done by underground water in its journey, it is first necessary to know the path which it follows. Upon this point the recent analytical work of Prof. C. S. Slichter* gives the desired information. He has ascertained that the spaces in soils and in mechanical sediments, so far as the flowage of underground water is concerned, may be considered as a series of triangular tubes. By Prof. Slichter's analysis the flowage of water from one place to another, say from A to B (see Fig. 1), is not by a direct path, but by a large number of diverging paths from A during the first part of the journey, and by a large number of converging paths to B during the latter part of the journey. This may be illustrated by supposing the water to be poured into a well, A, and to flow to a well, B. The horizontal course of the water is represented by Fig. 1, and the vertical course by Fig. 2. These conclusions apply equally well to any porous rock other than a soil or sandstone in which the spaces are distributed in a somewhat uniform manner.

It is apparent that these conclusions have far-reaching consequences as to the flowage of underground water. In the

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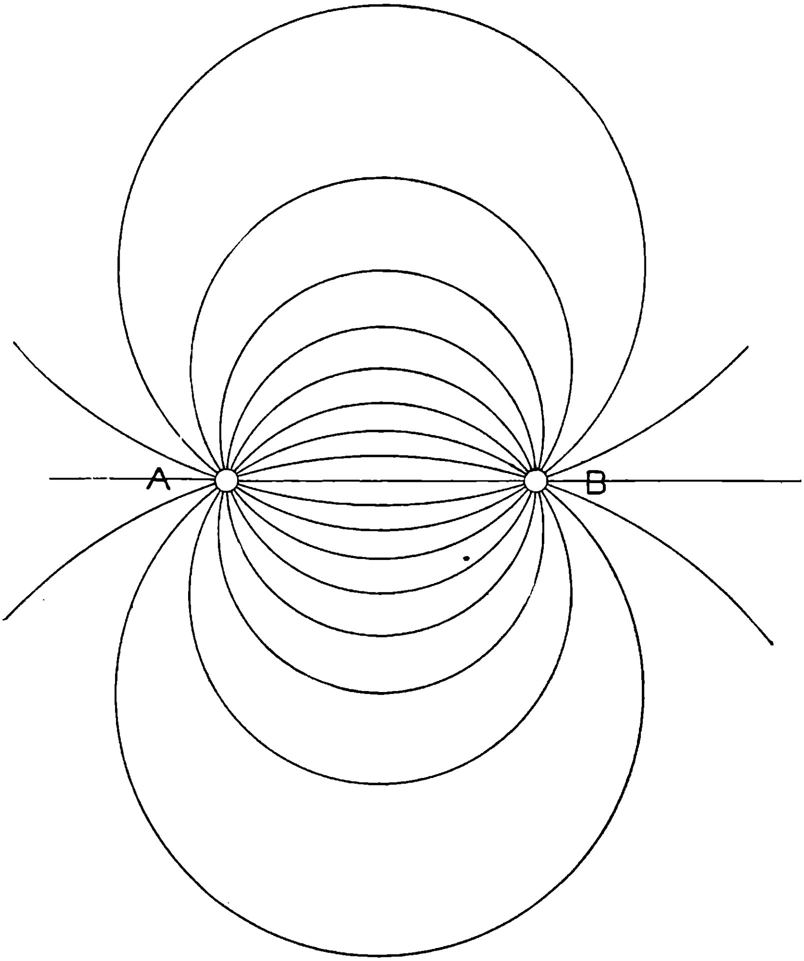
* "Theoretical Investigation of the Motion of Ground-Waters," by C. S. Slichter, 19*th Ann. Rept. U. S. Geol. Surv.*, for 1897–98, p. 312.

passage of the water from the top or slope of a hill to a point of issue at the foot of the hill, supposing these to be the only points of entrance or issuance of the water, and

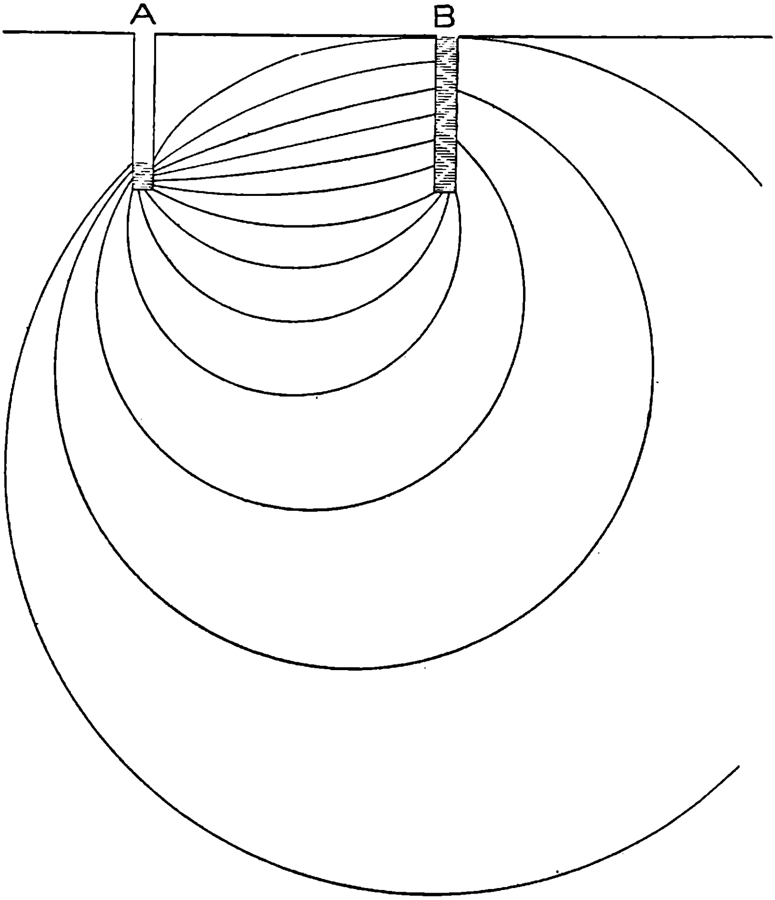
FIG. 1.



Ideal Horizontal Section of the Flow of Underground Water through a Homogeneous Medium, from One Well to Another.

supposing the spaces to be uniform, the vertical course would be represented by the lines of Fig. 3, and the horizonal course would be represented by the lines of Fig. 1. We see at once that for the larger topographic features the vertical component of flow may pass quite to the lower limit of the zone of fracture. This would probably be true even if water throughout its underground journey remained at a constant temperature. But it is to be remembered that the deeper water penetrates, the higher its temperature; also that the movement of water in the lower part of the zone of fracture is largely through capillary openings; further, that the flowage in capillary openings is inversely as the viscosity; and, finally, that the viscosity decreases rapidly with increase of temperature. Therefore, the increase of temperature with depth is a potent factor favorable to a deep course for underground water. It therefore seems probable

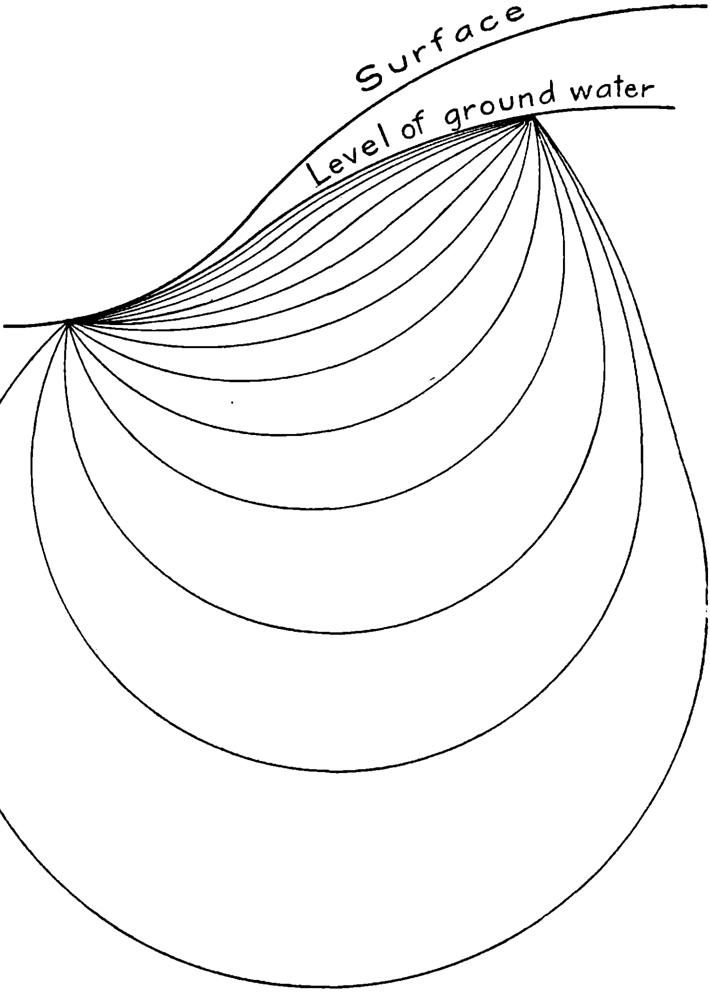
FIG. 2.



Ideal Vertical Section of the Flow of Underground Water through a Homogeneous Medium, from One Well to Another.

that as a result of head due to topographic irregularities and temperature differences, the entire zone of fracture is being regularly traversed by underground waters. Of course, the amount of flowage is far greater in the upper part of the zone than in the lower part, but even in the lower half or third of the zone of fracture the amount of flowage cannot be considered small.

FIG. 3.



Ideal Vertical Section of the Flow, through a Homogeneous Medium, of Underground Water Entering at One Point on a Stope and Issuing at a Lower Point.

The principle of the distribution of the flowage of water over the entire available area is well illustrated by the case of water flowing horizontally into a beaker from one side and overflowing the beaker on the other side. The movement of the water will not be confined to the liquid near the surface of the beaker, but all portions of the water in the beaker from the top to the very bottom will take part in the flowage, although, of course, the rate of movement will be much more rapid at the top than at the bottom.* The well-known hydrodynamical principle thus illustrated, that the entire available cross-section will always be utilized by flowing currents, is directly applicable to lateral moving waters in the zone of fracture. It is conclusive evidence that this zone will be searched to its base by moving waters, although the waters joining and departing from the underground sea appear and disappear at the surface.

In an actual case of underground flowage the water does not enter the ground at a single point, but enters at every point of a slope. As a sample case, we may suppose that the water entering on a slope reaches the surface again at the level of a stream in an adjacent valley. To get an idea of the complexity of the flow in this ideal case, we may arbitrarily select a number of points where the water enters, and trace out its course. We may plat by different kinds of lines, continuous and broken, the vertical components of the flowage of the water which enters at each place independently of the water that enters at other places. (Fig. 4.) We have a series of intersecting lines in the figure representing the vertical components of movement.

It is not supposed that water actually follows paths similar to those represented by the figure, for there is mutual interference of the water entering at the various points. As a result of this, the water entering the opening nearest the exit would take a more direct course than the average of that platted; but, as a consequence of this, the water from the next openings up the slope would take a more indirect course, on the average, than that platted, and so on. The total result would be to give

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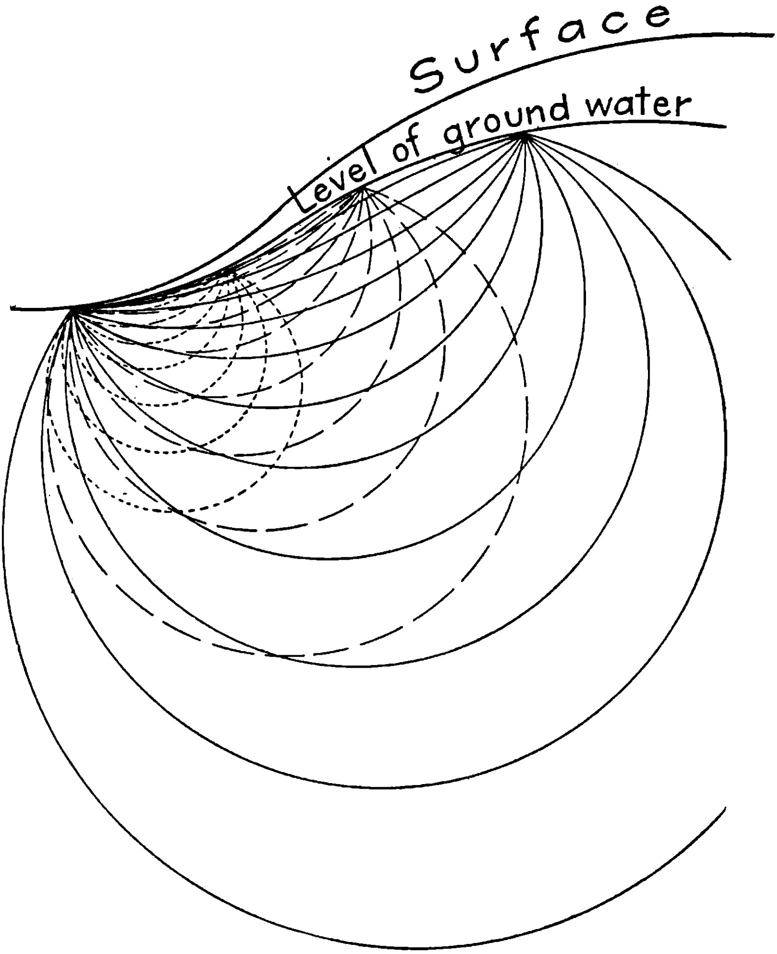
* Slichter, *cit.*, p. 331, sect. 5. Compare Posepny, *cit.*, *Trans. Am. Inst. Min. Engineers*, vol. xxiii., 1894, p. 220.

an average course for the water which can be represented by combining the independent curves. (Fig. 5.) The effect, so far as the geological action of the underground water is concerned, would be approximately the same, whether the course of the water were that represented by Fig. 4 or that represented by Fig. 5. This statement, applicable to a few points of entrance and one of exit, is equally applicable to a great number of points of entrance. The statement can be further ex-

FIG. 4.

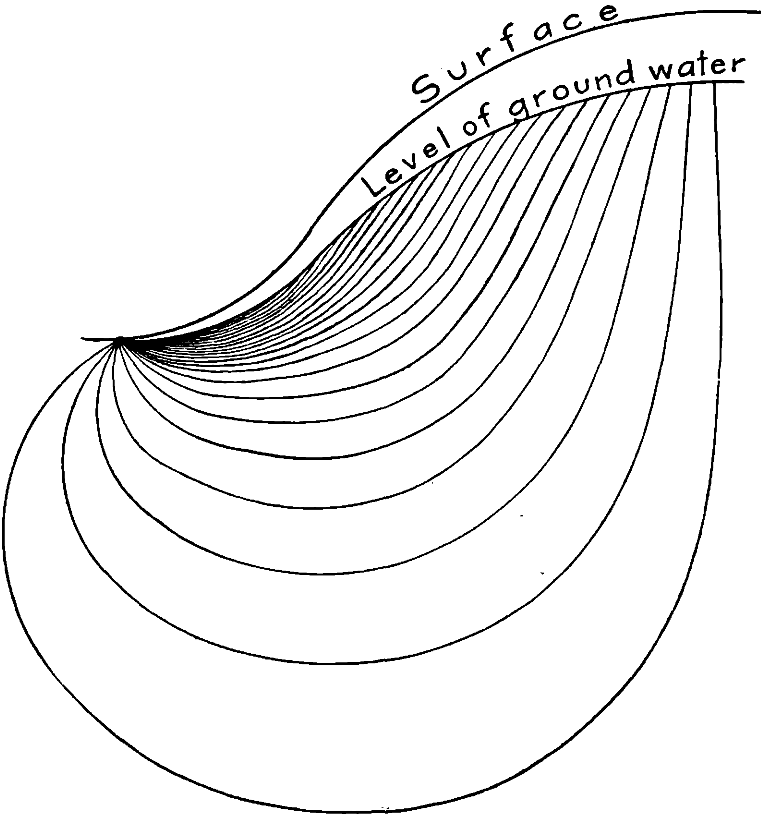


Ideal Vertical Section of the Flow, through a Homogeneous Medium, of Underground Water Entering at Three Points and Issuing at a Single Point, Each System of Flow Being Independent of the Others.

tended to an indefinite number of points of entrance distributed along the contours of the slope as well as up the slope, and to many points of exit at or near the level of the valley.

The Preferential Use by Water of Large Channels.—In nature the points of entrance for groundwater are indefinitely numerous, and the places of exit comparatively few. The water falls upon the ground everywhere and enters the innumerable pores between the grains. After a longer or shorter underground course, perhaps passing under many subordinate hills and valleys, it escapes to the surface as a spring or by seepage, nearer the drainage-level than where it entered the ground. The

FIG. 5.



Ideal Vertical Section of the Flow, through a Homogeneous Medium, of Underground Water Entering at Many Points along a Slope and Issuing at a Single Point of Lower Elevation.

water began its journey through an almost infinite number of openings. It issues at many openings, but these are few compared with the vast number of those at which it entered.

This conclusion is based on the following facts: Openings in rocks are never of uniform size. It has been seen that the resistance to flowage in capillary openings is far greater than in supercapillary openings. In supercapillary openings of moderate size the resistance is greater per unit of flowage than in larger ones. Thus there is a strong tendency for the water starting through innumerable small openings to converge into larger and larger openings, which are the lines of least resistance. Of course, it may go long distances underground, as in some sandstones, without finding larger openings than those near the surface; but if large openings exist, they will be fully utilized. Finally, when a single opening or a group of openings larger than the average reach the surface at a lower altitude than the average level of entrance of the water, there is a spring.

It has been seen that during the first part of the underground journey of water the vertical component is downward, and during the latter part of its journey the vertical component of much of it is upward. It follows that, on the average, the downward movements of water are through the smaller, and the upward movements through the larger, openings in the rocks. Of course, where large openings are available for the downward-moving water they will be utilized; and doubtless the larger openings are utilized to a great extent by the downward moving waters. However, even if this be the case, the statement would still be true that *upon the average* the larger openings are more extensively used by the upward moving water than by the downward moving water. From the foregoing it appears that the system of circulation of underground water has a very close analogy to that of a tree of a peculiar character.

The points of entrance are the ends of the indefinite number of twigs; these twigs unite into a branch; the branches unite to produce a larger branch; the larger branches unite into a trunk; and at the end of a trunk is a spring. The analogy of an underground drainage system to a tree is even closer than that of a surface system, for in a system of underground water circulation three dimensions are concerned to an important extent, while in a surface system of drainage the movement of the water is approximately confined to a plane. However, from what has gone before, it is clear that the tree of underground water has a peculiar shape. The twigs and branches have an important downward component; the larger branches of the tree may be considered as approximately horizontal; and the trunk usually has an important upward component. Thus twigs, branches and trunks together ordinarily make a great U. The sides of the U may be rather close together in the case of marked topography, where the water issues near the places of entrance. The sides of the U may be very far apart in the case of gentle topography, where there is great lateral movement of the water. Such a system of underground movement is somewhat similar to that of a surface system of drainage.

The analogy of a tree has been utilized in order to get definitely in mind the general character of the circulation of underground water. However, the analogy must not be pushed too far. A tree commonly has but a single, continuous, solid trunk, although willows and other trees have many trunks. Very frequently, indeed commonly, the trunk-channels of underground water circulation are very complex. While a main water course may exceptionally occupy a single open passage, ordinarily it is composed of a number of interlocking passages. These may be the parallel openings of a complex fault, they may be the smaller numerous openings of a zone of fissility, or they may be the more open spaces of sandstones or conglomerates. In short, a trunk-channel of underground water differs only from other channels in that they are places where there is more circulation.

PHYSICO-CHEMICAL PRINCIPLES CONTROLLING THE WORK OF UNDERGROUND WATERS.

Before considering the actual geological work of underground water in the alteration of the rocks and in the production of ore-deposits, it is necessary to consider briefly the physico-chemical principles which control that work.*

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* In my treatise on "Metamorphism" (*Monograph U. S. Geol. Survey*) I consider this subject in detail. In the present paper, only that portion of this part of the Monograph is summarized which is absolutely necessary in order to understand the deposition of ore-deposits.

Chemical Action.

The fundamental principle of chemical dynamics is that chemical action is proportional to the active mass. This is the law of mass action.*

Chemical action may take place between gases and gases, between gases and liquids, between gases and solids, between different liquids, between liquids and solids, between different solids. So far as the depositions of ores are concerned, the reactions in connection with underground liquid solutions are by far the more important.

The water of rocks, whether at ordinary temperatures or pressures or at higher temperatures and pressures, may take any of the substances with which it comes in contact into solution; may deposit substances from solution; may combine with substances forming hydrates, as in the case of many of the zeolites or of limonite from hematite; may part with its hydrogen in exchange for bases, and especially the alkalies and alkaline earths, thus at the same time changing the composition of the rock and taking the bases replaced into solution, as in the change of enstatite to talc. There may be reactions as a result of different substances being taken into solution at different times; there may be reactions as a result of different solutions coming together, and thus mingling; there may be reactions between substances in solution and the solid material with which the water is in contact; there may be reactions as a result of changing temperature and pressure. All of these changes are of the nature of chemical action. Therefore, by chemical action of underground water is meant the taking of material into solution, the deposition of material from solution, the interchange between materials in solutions, the interchange between materials in solutions and adjacent solids, and, finally, the interchange of the adjacent solid particles. But this last reaction is probably accomplished through the medium of a separating film of water, in which case the apparently simple reaction is really accomplished by transfers between the solutions and solids.

In all these interchanges the materials therefore pass through a state of aqueous solution, and, according to modern ideas of physical chemistry, the salts in aqueous solution are at least

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* "Outlines of General Chemistry," by W. Ostwald: Translation by Walker, 1895, p. 292.

partly separated into their ions. Their properties in this condition are therefore the sum of the properties of their separated ions. Indeed, the potency of water as an agent through which metamorphism may take place is due, according to these ideas, to its capacity to separate substances which it holds in solutions into their free ions. In this power of ionization water exceeds all other solvents. And it is by the migration of these free ions that the interchanges are accomplished. As the greater portion of underground liquid solutions are rather dilute, at least where somewhat free circulation is the rule, we may suppose that the salts held in solution are largely separated into their ions, and therefore these free ions are ever ready for chemical reactions.

Also water reacts upon the salts it holds in solution by hydrolitic dissociation, producing free acids and hydrates of the bases. This process is especially important with the salts of the weak acids.* The dominant acids of nature are the very weak acids silicic and carbonic; and, therefore, hydrolitic dissociation is very important. The silicates of the alkalies in dilute solutions are practically completely decomposed, the result being the liberation of free silicic acid and hydrates of the alkalies, as shown by Kahlenberg and Lincoln.† The carbonates of the alkalies are also, to a considerable extent, similarly dissociated.

Underground Aqueous Solutions.—The quantity of a solid which can be dissolved in liquid depends upon the number and nature of the compounds present, upon the pressure, and upon the temperature.

When a solid salt is placed in liquid, it forms a homogeneous mixture of salt and liquid. This statement applies to all natural compounds,—that is, the minerals of nature are salts which are soluble in water. No substance is wholly insoluble in the underground waters, even at ordinary temperatures and pressures. This statement applies alike to quartz and the most refractory silicates. Under surface conditions, the etching of quartz grains is evidence of the first statement,‡ and the uni-

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* "Theoretical Chemistry," by W. Nernst, 1895, p. 660.

† "Solutions of Silicates of the Alkalies," by Louis Kahlenberg and A. T. Lincoln, *Journ. Phys. Chem.*, vol. ii., 1898, p. 89.

‡ "Solution of Silica Under Atmospheric Conditions," by C. W. Hayes, *Bull. Geol. Soc. Am.*, vol. viii, 1897, pp. 213–220.

versal decomposition and partial solution of the silicates is evidence of the second; and in the lower zone of water circulation the solution of quartz and the refractory silicates may be completely accomplished, as in the case of the Calumet and Hecla conglomerates, many of the bowlders of which have been completely dissolved and their spaces taken by copper.

The quantity of material which may be dissolved in any case under definite conditions has a limit. When this limit is reached the solution is saturated. This limit depends upon pressure and upon temperature.

The Relations of Solution and Temperature.—The relations of temperature and solution have two phases; (1) the speed of the reaction, and (2) the quantity of material which may be held in solution.

(1) The speed of solution is greatly increased by rise of temperature.* A slight increase in temperature may increase the rate of solution out of all proportion to the absolute change in temperature. At temperatures above 100° C., and especially above 185° C., the activity of water may increase to an amazing degree. The rapid solution of glass by Barus† at temperatures above 185° C. illustrates this. At any temperature solution will continue until the point of saturation is reached. However, it is clear that this state will be attained at high temperatures in but a small fraction of the time required at low temperatures. For instance, to saturate an underground solution with the refractory silicates or sulphides at ordinary temperatures might require months or even years, while to saturate them at temperatures above 185° C. might require only an equal number of minutes, or at most hours. The capacity of water for action at high temperatures combined with pressure, considered below, is adequate to explain the complete recrystallization of great volumes of natural glass and crystallized rocks.

(2) The effect of temperature upon quantity of material which may be held in solution does not admit of a simple gen-

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* "Theoretical Chemistry," by W. Nernst. Translated by C. S. Palmer, London, 1895, p. 568.

† "Hot Water and Soft Glass in their Thermo-dynamic Relations," by C. Barus. *Am. Journ. Sci.*, 4th series, vol. ix., No. 51, 1900, pp. 167–168.

eral statement.* For most substances moderate increase of temperature gives greater capacity for solutions; but for many substances there exists a temperature at which there is the maximum capacity for solution, and the amount of material which may be held in solution at higher and lower temperatures is less than this maximum. For various substances this maximum capacity for solution lies between 60° C. and 140° C., and for many substances it is probably below 200° C. It therefore follows in underground solutions that a general statement cannot be made as to how change of temperature may affect solubility. However, it is highly probable that up to temperatures of 100° C., and, therefore, to depths of 3300 meters, increase of temperature increases the average capacity of underground water to hold material in solution. It may be probable that the average capacity of underground water may increase to temperatures considerably above 100° C., and, therefore, to depths greater than 3300 meters. But when water passes downward to the deeper parts of the zone of fracture the increase in temperature may lessen the average capacity for holding material in solution, provided the joint effect of pressure be barred.

The Relations of Solution and Pressure.—In general, the volume of the solvent plus that of the salt is greater than that of the solution. For a given quantity of the solution the contraction is greater the more of the solvent is used.† In some cases, however, the volume of the salt and solvent is less than that of the solution, or expansion results from dissolving the solid. Sal ammoniac in water is an illustration of this case. From the foregoing relations we obtain a rule as to the relations of pressure to solubility.‡ In the common case in which the volume of the solution is less than that of solvent and salt, pressure increases solubility; for in that case solution tends to bring the molecules nearer together and works in conjunction with the pressure. In the reverse case, that in which the volume of the solution is greater than that of solvent and salt, pressure decreases the solubility, the reason being the reverse of that of the previous case.

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* "Solutions," by W. Ostwald. Translated by M. M. P. Muir, London, 1891, pp. 55–77.

† "Solutions," *cit.*, p. 82.

‡ "Theoretical Chemistry," by W. Nernst, 1895, p. 567.

It is well known that the solubility of calcium carbonate and some other carbonates is increased by pressure.* It is a fair inference from Barus' work that the solubility of the silicates is also increased by pressure. Barus† found that when soft glass is dissolved in water at temperatures above 210° C., the volume is 20 to 30 per cent. less than the two separately. This glass was one which contains alkalies, alkaline earth and lead, and, therefore, is somewhat similar in composition to many natural silicates. The solubility of many other salts, besides the carbonates and silicates, occurring underground is increased by pressure. While, therefore, pressure may lessen the solubility of some natural salts, in the majority of the complex underground solutions the volume of the solution is less than that of the salts and solvent separately; and, therefore, the total of the salts in solution is generally increased by pressure.

It has been pointed out that in the lower part of the zone of fracture increase in temperature with depth may exceptionally lessen the average amount which may be held in solution, but increasing pressure with increasing depth promotes solubility. The quantitative values of these two elements are, however, unknown, and no positive statement can be made as to whether the increasing temperature and pressure combined in passing to the lower part of the zone of fracture increases or decreases the capacity of underground water for solution. However, it is clear that to very considerable depths, that is, to 3000 meters or more, the joint effect of the temperature and pressure factors is to increase the average capacity for solution.

Precipitation—After a number of chemical substances are brought together, and especially when they are united by a solvent, interactions between them may occur which, after a time, appear to cease. When the conditions have become such that there is no increase or decrease in the amount of any one of the chemical compounds, the system is in a condition of chemical equilibrium.‡ The interaction may result in the precipitation of compounds.

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* "Gold-quartz Veins of Nevada City and Grass Valley, California," by W. Lindgren. *17th Ann. Report U. S. Geol. Survey*, 1895–96, pt. ii.; 1896, pp. 176-178.

† "Hot Water and Soft Glass in their Thermo-dynamic Relations," by C. Barus. *Am. Journ. Sci.*, 4th series, vol. ix., 1900, p. 173.

‡ Nernst, *cit.*, pp. 355–356.

Since the separation of material from solution in underground waters is of the utmost importance, it is necessary to consider the conditions under which precipitation takes place. It is clear that the necessary condition for precipitation is supersaturation; for if a solution be sufficiently supersaturated some of the material must be thrown down, or be precipitated.

Supersaturation and consequently precipitation may result in various ways, of which the following are the more important: (1) By change in temperature, (2) by change in pressure, (3) by reactions between aqueous solutions, (4) by reactions between liquid solutions and solids, and (5) by reactions between gases and solutions or solids, or both.

1. Precipitation by Change in Temperature.—Change in temperature is the rule for underground circulating waters. The waters which are passing to lower levels are upon the average becoming warmer. Waters which are rising to higher levels are upon the average becoming colder. Also, there are changes of temperature both positive and negative due to varying local conditions.

If the temperature of a saturated solution changes in a direction adverse to solution, it tends to become supersaturated. If crystals of the solid solution are present, and this is usually the case with underground solutions, considerable supersaturation does not occur; for the excess of salt separates, so that at any given temperature equilibrium is nearly retained by continuous adjustment.

It has already been seen that increase of temperature to 100° C. or more promotes solution, and decrease of temperature from 100° C. or more causes supersaturation, and therefore precipitation. One would, therefore, expect that descending waters which are increasing in temperature are, upon the whole, constantly taking additional material into solution, at least to a depth of 3300 meters, and that waters ascending above this level which are becoming cooler are upon the whole precipitating material. However, this statement needs various qualifications. As a consequence of the action of igneous rocks and dynamic action temperatures higher than the normal for a given depth may be obtained. While these temperatures may be so high as to be unfavorable to the quantity of material held in solution, they are very favorable to rapid solution. Since the temperature is variable which causes the maximum solution of a given salt, it follows that as water passes down through the middle part or lower parts of the zone of fracture, or as it becomes somewhat highly heated because of the presence of igneous rocks or of heat produced by orogenic movement, that the increase of temperature may induce the precipitation of some compounds, and favor the solution of additional quantities of other compounds. Therefore, because of changing temperature in the middle and lower parts of the zone of fracture, and where igneous rocks are present or earth movements have occurred, there is selective solution and precipitation. However, in the normal case within the belt of which we have most exact information, that is, the upper 3000 meters of the crust of the earth, the upward course of water is likely to be favorable to precipitation. (See pp. 58–65.)

2. Precipitation by Change in Pressure.—It has been seen that where waters are descending the pressure is constantly becoming greater, and they are capable of taking additional material in solution. Where waters are ascending the pressure is constantly becoming less, and they are, therefore, not capable of holding so much material in solution. Hence, the pressure effect in ascending waters is to promote precipitation. All of these statements apply to the average complex underground solutions. Exceptional cases may exist where the reverse effect occurs.

3. Precipitation by Reactions between Aqueous Solutions.—Physical chemistry holds that when solutions containing various salts are mixed, the resultant solution will contain all the salts and ions which can be made by the various combinations of their positive and negative factors. In any given case there is a constant relation between the amount of a salt which can be held in solution and the number of free ions of that salt which balance each other, and upon this fact are based the laws of precipitation from solutions.

The laws of chemical precipitation from aqueous solutions are somewhat complex, and cannot be here fully summarized. So far as present purposes are concerned, the old statement of chemistry will suffice. When solutions of two or more kinds are mingled, if a compound or compounds can form which are insoluble in the liquids present, this will take place and precipitation will follow.*

The most important case of precipitation in nature is that resulting from the mingling of aqueous solutions of solids.

Another case of precipitation occurring in nature results from mixing solutions, one of which contains a gas. Perhaps the most important case of this kind is the mixing of a solution containing oxygen with one containing salts of iron protoxide. As a result of this, the salts will be changed from ferrous to ferric iron, and the latter precipitated either as a sesquioxide or hydrosesquioxide. In the latter case hydration occurs simultaneously with the oxidation.

4. Precipitation by Reactions between Liquid Solutions and Solids.—A very important underground reaction is that between the solutions and the adjacent solid materials. Ordinarily in this case a portion of the solid material is taken into solution and a portion of the material before held in solution is deposited. This principle may be illustrated by the laboratory experiment in which metallic iron is placed in a solution of a copper salt, for instance copper sulphate. The iron goes into solution as sulphate and metallic copper is precipitated. An excellent case illustrating precipitation from solution in nature, one of the most fundamental importance, is the almost immediate partial substitution of magnesium for the calcium of shells and corals by the sea-waters.

In order that crystals in a solvent shall grow, it is necessary that the solutions shall be saturated or supersaturated at the immediate place of crystal growth. Since underground, there is always a superabundance of solid material present as compared with the amount of water, we may suppose that at a moderate depth below the surface, and especially in the smaller spaces where movement is slow, the solutions are often saturated. It is a well-known fact that under conditions of saturation, with a superabundance of solid material, the larger crystals grow at the expense of the smaller ones, and that this process goes on more rapidly in proportion as the temperature is high and the pressure is great. This principle is taken advantage of in the

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* For a more exact statement of the principles of precipitation see the various treatises on physical chemistry. A simple statement of the laws of precipitation is given by C. Tolman, *Journ. of Geol.*, vol. vii., 1899, pp. 587–591.

chemical laboratory in the production of a coarse precipitate before filtration by boiling or other means, the finer particles of the precipitate being dissolved and the coarser ones being enlarged at their cost.

5. Precipitation by Reactions between Gases and Solutions, and Solids.—The reactions between gases and liquid solutions and solids involve matter in all its three forms. The laws of their mutual interactions are very complex, and they cannot here be taken up. But for the present purpose it may be said that the result of the mixture of gases,' liquid solutions and solids, may result in the precipitation of a substance from solution. The most common active gases present underground are carbon dioxide, hydric sulphide, and oxygen. The action of hydric sulphide upon a solution may throw down a sulphide of a metal; the oxidizing action of oxygen may result in precipitation, as in the case of peroxidation of iron. Furthermore, the action of the gases and liquid solutions may together result in the abstraction of substances from the solid compounds and the precipitation of them, or parts of them, elsewhere. The combined action of gases, liquids and solids is more common in the belt of weathering than elsewhere, see pp. 46–48.

THE GENERAL GEOLOGICAL WORK OF UNDERGROUND WATERS.

It has been seen that the geological work of underground waters is dependent on many factors. Some of these are the limitation in depth by the zone of fracture, the nature of the openings in the rocks, the rapidity of the flowage, the character of the materials through which the waters flow, the character of the substances it may carry in solution, the pressure, and the temperature. Of these many factors, two are ever working together according to very definite laws. These are pressure and temperature. Both increase with depth, and therefore greatly promote the activity of deep underground waters. However, of all of these varying factors, varying temperature is the one which is of incomparably the greatest importance. High temperature ordinarily results from depth of penetration; but it has been pointed out that it may result from various other causes, of which chemical action, mechanical action and the presence of intrusive igneous rocks are the more important. The capacity which water has for taking and holding various relatively insoluble compounds in solution increases as the temperature increases, to a 100° C. or more. The velocity of chemical reactions increase enormously with increase of temperature. Not only is high temperature favorable to geological work because of the chemical activity of the water, but high temperature greatly decreases its viscosity, and this, as already explained, is favorable to depth of penetration and flowage through minute openings. Since the temperature changes of underground water are commonly dependent upon depth, the vertical component of the movement of underground water is ordinarily far more important in geological work than the longer horizontal component.

Division of the Zone of Fracture into a Belt of Weathering and a Belt of Cementation.

So far as the work of underground water in the production of ore-deposits is concerned, the zone of fracture may be divided into two belts: (1) an upper belt of weathering, and (2) a lower belt of cementation. The belt of weathering extends from the surface to the level of groundwater, and for a variable distance into the sea of underground water. The belt of cementation extends from the bottom of the belt of weathering to the bottom of the zone of fracture.

In the belt of weathering various gases are present, of which carbon dioxide and oxygen are the more important. With these are a great variety of solutions and the greatest possible variety of solids. The reactions in the belt of weathering, therefore, involve gases, liquids and solids. Furthermore, in this belt we have the complicated action of organic bodies upon inorganic bodies. These organic compounds vary in magnitude from the smallest bacteria to large trees, which act both while alive and dead. It is, therefore, clear that the chemical reactions in the belt of weathering are of an extraordinarily complex character. Only the more important of them will be considered. The dominant ones are carbonation, hydration, oxidation and solution.

The process of carbonation takes place upon a most extensive scale in the belt of weathering, producing abundantly carbonates of the alkalies, alkaline earths and iron, and less abundantly carbonates of other metals. Where vegetation is absent the air in the soil contains only a small amount of carbon dioxide, but where vegetation is abundant and is decaying upon a large scale, the carbon dioxide in the soil is from 15 to 100 times more abundant than in air; hence, in the process of carbonation the presence of vegetation is of fundamental importance. The dominant compounds upon which the process of carbonation acts are the silicates. In the carbonation of the silicates the silica separates as silicic acid.* Since the quantity of silicates decomposed by carbonation is very great, the amount of silicic acid liberated is enormous. This passes into solution, and, as explained below, is transferred to the belt of cementation.

Next in importance to carbonation is hydration. While hydration is usual in the belt of weathering, under some conditions, and especially those of great aridity and high temperature, dehydration may occur.

Oxidation is also very general in the belt of weathering, but deoxidation may occur in regions of very luxuriant vegetation, where there is an unusually large amount of reducing material.

If the compounds formed in the belt of weathering all remained *in situ*, the volume of the rocks would be greatly increased by the above changes; but simultaneously with these reactions, solution, the fourth important reaction of the belt of weathering, is taking place upon a great scale. The quantity of material dissolved is more than sufficient to counterbalance the increase in volume due to the chemical changes, and consequently the volume of the rocks continually decreases. In consequence of this preponderance of solution the openings of the belt of weathering tend to increase in size. However, this is not apparent with the unconsolidated materials at the surface, for gravity brings the particles together as fast as material is dissolved; but in the rocks below the soils, which have sufficient strength to support themselves, the openings are widened. The best illustrations of rocks with enlarged openings are the limestones.

In connection with the chemical changes above summarized, mechanical action is continually subdividing the material.

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* "Solutions of Silicates of the Alkalies," by L. Kahlenberg and A. T. Lincoln. *Journ. Phys. Chem.*, vol. ii., 1898, pp. 88–90.

In general, then, in the belt of weathering, disintegration, decomposition and solution are the rules. The minerals which remain are usually few and simple; the volume of the rocks is diminished; they soften and degenerate; and they are finally destroyed as coherent solids.

In the belt of cementation, hydration, carbonation, oxidation, and deposition occur. Hydration and deposition are the characteristic reactions. Carbonation and oxidation are subordinate. The reactions take place by metasomatic change within many of the original minerals and by deposition of material within the openings. Many of the minerals produced are strongly hydrated. Because of hydration and deposition the volume of the rocks is increased. Cracks and crevices produced by mechanical action, such as those of faults, joints, bedding partings and fissility; and the openings originally present in the rocks, such as pore-spaces in the mechanical sediments and the vacuoles in volcanic rocks, are slowly but certainly filled by the action of the groundwater, and the rocks are thus cemented and indurated. This process may be called construction.

The belts of weathering and cementation, therefore, contrast strongly. In the former solution continually takes place; in the latter, deposition; in the former we have disintegration, decomposition and softening; in the latter we have cementation and induration; in the former the volume of material is lessened; in the latter it is increased; in the former the characteristic chemical reaction is carbonation; in the latter it is hydrogen. Therefore, the belt of weathering is characterized by disintegration and decomposition, carbonation, hydration and oxidation, by solution and decrease of volume. The belt of cementation is characterized by cementation and induration, by hydration, by deposition, and by increase of volume.

Migration of Material from the Belt of Weathering to the Belt of Cementation.

It is believed that the material dissolved in the belt of weathering is largely deposited in the belt of cementation. Thus may be explained the steady diminution of a given mass of material in the belt of weathering, and the increase in mass of the material in the belt of cementation. Since this migration of material is one of great importance, it will be necessary to consider it in some detail.

As a result of the horizontal component of the movement of underground water, there is a tendency for material to be taken into solution and to be abstracted by the water. The longer the horizontal underground course, the nearer will the water approach to saturation with the compounds with which it is in contact, because of the time factor. If the journey be long, the state of saturation may be attained at an early stage, after which the additions and subtractions of material upon the average neutralize each other. Throughout the journey there are various chemical interactions. There may be solution of material at a certain place and later deposition of it elsewhere; there may be interactions between the solutions and solids; there may be interactions between the mingled solutions from different sources. However, these reactions do not change the end-result—that is, the longer the horizontal journey the richer the solutions become, and material is abstracted until the point of saturation is reached.

Since it is clear that, so far as the horizontal movement of underground water is concerned, the effect is to abstract material, and since deposition, with consequent cementation and consolidation rather than solution is a general fact in the belt of saturation, we conclude that this result must be due to the vertical movement of the water. In the downward journey of the water from the surface to the level of groundwater, it is continuously taking material into solution, and therefore steadily contributes an increment of material to the sea of underground water.

After the water reaches the level of groundwater, movement does not cease. Disregarding the lateral movement, the sea of underground water at a given place might be considered as a column moving downward as rapidly as the increment of groundwater is added from above. However, superimposed upon this vertical movement is lateral movement which carries it to some point where upward movement is taking place. Therefore the amount which continues downward is an ever-decreasing fraction of the entire amount of precipitation which joins the sea of groundwater. But for this part the pressure and temperature steadily increase, and the capacity of the water to take material into solution steadily changes. One might conclude that during at least the first part of the downward course of the water solution was occurring. During the upward course of the water, pressure and temperature steadily become less, and one might conclude that for at least the latter part of the upward course deposition was occurring. However, these simple statements do not fully cover the facts; for, as already pointed out, the relations of temperature and pressure are exceedingly complex, and also deposition, cementation and consolidation seem to be general facts for the belt of cementation.

It has already been pointed out that the conditions for solution are very favorable in the downward passage of water through the belt of weathering, and that each unit of water which joins the belt of cementation carries with it in solution a certain increment of material. During the long-continued erosion of a region the belt of weathering at any given time represents the residual disintegrated and partly decomposed material then above the level of groundwater. Thus the belt of weathering is steadily progressing downward. The forces of weathering are continually finding new material at the bottom of the belt upon which to work. Therefore, as denudation goes on there is ever a belt of a certain thickness which contributes material to the belt of cementation below. Hence we have an adequate source for an increment continuously added to the belt of cementation. If this increment thus added to the sea of underground water could be deposited throughout its course in the belt of cementation, there would be a sufficient cause for the induration of this belt.

However, according to one of our fundamental premises, the quantity of water which emerges by seepage or through springs to the surface and joins the run-off must be equal to the amount added to the sea of groundwater by percolation. The question must therefore be asked as to the relative amounts of materials carried to the sea of groundwater by percolation and that abstracted from it by the ascending waters. To this question no answer based upon comparative analyses can be given. However, the general deposition and consolidation in the zone of cementation already emphasized seems to be conclusive evidence that the amount of material contained in issuing water is not so great as that which joins it through percolation.

Of the substances deposited in the belt of cementation, quartz is undoubtedly the one which dominates over all others. The one great process in the belt of cementation is silication. Next in abundance to the quartz, the various silicates are deposited, and especially the zeolites and chlorites. Of less importance are the carbonates of the alkaline earths. Still less abundant are the various metalliferous ores and associated gangue minerals not of the classes already mentioned. While these subordinate products are of great economic importance, their quantity is insignificant as compared with the non-metalliferous deposits.

If it is certain that the one great process of the belt of cementation is silication; it is equally certain that the one great process in the belt of weathering is the carbonation of the silicates, thus forming carbonates and liberating soluble silicic acid. Hence it is highly probable that silicic acid is the dominant constituent contained in solution in downward percolating waters. Therefore we have a source both for the deposited quartz and for the process of silication which forms the silicates. In another place* I have shown that one of the deep-seated dominating reactions is the process of silication of the carbonates or the substitution of silica for carbon-dioxide with the simultaneous liberation of carbon-dioxide. This process takes place at moderate depth, especially under dynamic conditions, although it is especially important in the zone of rock-flowage. The carbon-dioxide liberated in part joins the underground waters. Such carbonated waters are very capable of taking into solution the salts of the metals, and particularly the salts of the alkalies, alkaline earths and iron. The solutions which reach the surface bear as their more abundant compounds the carbonates of the alkalies, alkaline earths and iron. With these are also other salts, including the salts of the valuable metals. Also issuing waters contain other acids besides carbonic acid, such as chlorhydric, sulphidric, sulphuric and others.

From the foregoing it appears that during the circulation of

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* "Metamorphism of Rocks and Rock Flowage," by C. R. Van Hise, *Bull. G. S. A.*, vol. ix., 1898, p. 282.

water in the belt of cementation the processes of precipitation and solution are selective. Quartz and silicates are the dominant precipitates. Carbonates of the alkalies and alkaline earths are the dominant salts which join the run-off. The above precipitations and solutions are precisely what should be anticipated from the laws of chemical action already given. The compounds which upon the average are thrown down to the greatest extent, are those which are least soluble and most abundant. The compounds which are retained in solution to the greatest extent are those which are most soluble and least abundant. However, of the more soluble and less abundant compounds a portion is precipitated. The conditions under which we would expect partial precipitation of these compounds, at least for the upper 3000 meters, are those of lessening temperature and pressure. These are the conditions of the ascending columns of water. It has already been seen that the ascending columns are likely to be the main water channels. Hence is explained the frequent precipitation of soluble carbonates of the alkaline earths and rare metalliferous ores in these trunk channels.

It is not supposed that the above furnishes a full explanation of the cementation of the entire zone of fracture. It has been pointed out, p. 48, that hydration is perhaps the most characteristic reaction of this belt and that hydration results in expansion of volume. So far as this reaction takes place, and it undoubtedly occurs on a most extensive scale, this would tend to fill the openings and thus cement and consolidate the rocks without reference to material from the belt of weathering. Thus for instance metasomatic change including hydration in a vesicular basic igneous rock may so increase the volume of the material as to completely fill the vesicles by zeolites, quartz, and other minerals without the additions of any material from an extraneous source. Which of the two factors, material from the belt of weathering, or expansion by the processes of metasomatism including hydration, is the more important in filling openings in the belt of cementation, I am wholly unable to state.

Other factors also, doubtless, enter into the cementation of openings. Some of these have already been mentioned. These are selective solution and precipitation, depending upon varying temperature and pressure, and the reaction of the different solutions upon one another. Another factor which is probably important is diffusion, but its action is too complex to be taken up in this general paper.

By the various processes of cementation the larger openings are filled with deposits. However, where one of these contains metalliferous ores in sufficient quantity to be of service to man, many thousands are filled with quartz, calcite, dolomite, and other gangue minerals. I repeat again that the deposition of the ores is but a special phase of a general geological process of great consequence.

PART II.—APPLICATION OF PRINCIPLES TO ORE-DEPOSITS.

The general discussion in Part I. is believed to contain in large measure the philosophy of the formation of ore-deposits by underground waters. It is now clearer than when first stated that the deposition of the greatest group of metalliferous ores is a special case of the work of underground water.

There have been endless discussions as to whether ore-deposits are produced by descending, lateral-secreting, or ascending waters. It is a corollary from Part I. that the first concentration of many ore-deposits is the result of descending, lateral-moving, and ascending waters. I say first concentration; for it will subsequently appear that many, if not the majority, of the workable ore-deposits have undergone a second concentration.

The larger, more nearly complete idea of the genesis of ore-deposits comprises all of the old ideas, shows that instead of being contradictory, as supposed by many, they are mutually supporting; combined, they furnish a much more satisfactory theory than any one of them alone. How true these statements are will later more clearly appear.

In the first stage of the concentration of many deposits the waters are descending. During the descent they are widely dispersed in small passages, have an exceedingly large surface of contact with the rocks, come under conditions of increasing temperature and increasing pressure, and are moving slowly downward. All of these conditions favor solution to the point of saturation. The various metalliferous elements present in exceedingly small quantities in the rocks, as well as many other compounds, are picked up. (See pp. 38–41.) This follows from the law of physical chemistry, that a solution will hold some part of all of the elements with which it is in contact. While deposition as a whole may be occurring in the belt of cementation, solution of the ores certainly takes place.

The waters which perform the first work in the genesis of ore-deposits are descending waters.

Superimposed upon the downward component of the moving waters is a lateral component. This lateral component, combined with the vertical component, carries water sooner or later to the trunk channels. The amount of water taking part in the lateral movement is greatest near the surface of ground-water, and from that surface steadily decreases to the bottom of the zone of fracture. It has been explained that all fissures and other openings gradually die out below as the zone of rock-flowage is neared. (See pp. 7–10.) Therefore, for a given fissure, the waters which enter it do so from the side or top, not from the bottom. Furthermore, the water does not enter, the fissure at a single place, but may enter at numberless points all the way along its course, from the deepest parts of the fissure to the surface. Somewhere, however, the water which enters a fissure must flow from it. This place may be at the surface of the ground or at a considerable depth below the level of groundwater (see Fig. 6). The streams entering the fissure at high levels may have a downward component, and contribute water abundantly. Below the level at which water escapes laterally from a channel of given size, the water contributed to it decreases on the average with increase of depth, until in the deeper part of the zone of fracture the contributions are very small. Posepny* calls attention to the generally observed fact of the decreasing amount of laterally contributed waters as depth increases. As a specific instance of this, he mentioned the Przibram district, in which the water which enters the fissures below a depth of 300 meters is so small as to be insignificant.

While the amount of water laterally entering a fissure steadily decreases from near its top to the bottom, the amount

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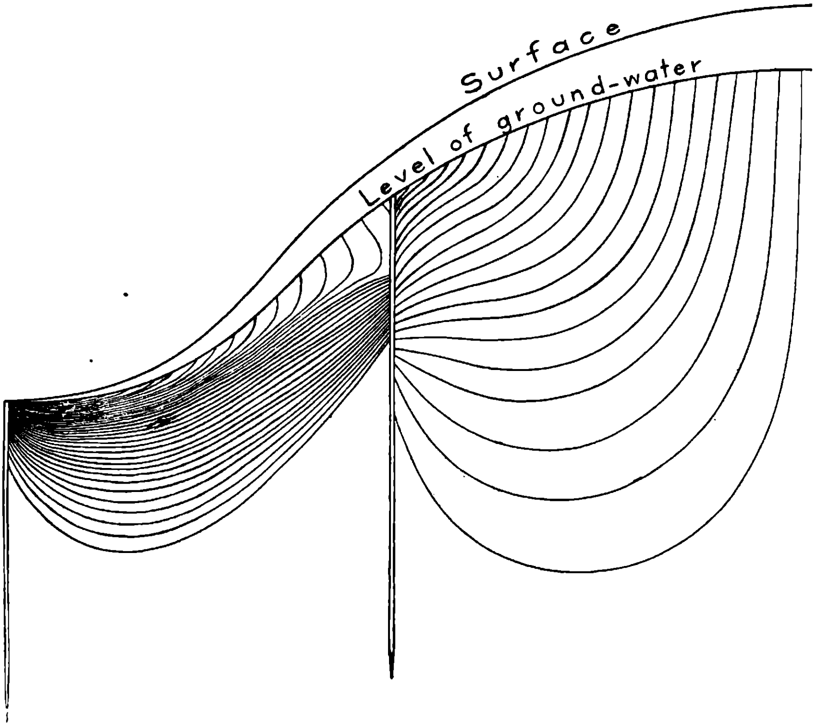
* "Genesis of Ore Deposits," by F. Posepny (Discussion, 1894), *Trans.*, xxiv., 971.

of mineral material per unit volume in all probability steadily increases; for the waters entering at a low level take a longer journey through smaller openings and at higher temperatures and pressures than the waters entering at a high level. Therefore it is clear, if the rocks with which the deeper water comes in contact can furnish metalliferous materials, that such water

FIG. 6.



Ideal Vertical Section of the Flow of Water Entering at a Number of Points on a Slope, and Passing to a Valley Below, through a Homogeneous Medium, Interrupted by Two Open Vertical Channels, on the Slope and in the Valley Respectively.

will be heavily loaded. It follows from this, even if the amount of water which is furnished in a given brief time to a fissure be small, that such water may furnish from the country-rock much more mineral material in solution than sufficient to entirely fill a fissure during its long life. This is evident from the following: Water issuing at the surface from mineral springs generally contains more than 1 part of silica in

100,000.* If it be premised that only as much silica be deposited as issues at the surface, in order completely to fill a fissure it would be necessary only to suppose that the amount of water which enters a unit length of a fissure is 100,000 times as great as the volume of a unit length of the opening.

We now understand that the amount of water entering a fissure decreases from the level of groundwater to its bottom, but that the amount of mineral matter brought into the fissure by the water (but not necessarily deposited) increases per unit volume from top to bottom. It is, therefore, impossible to make a general statement as to whether more mineral material is contributed to a trunk channel in its upper portion or in its lower portion. Doubtless this varies in different cases. Other conditions than amount of water or depth may be controlling factors in this respect. For instance, if igneous rocks be intruded at high or low levels only, the presence of the igneous rocks may furnish conditions which determine the amount of metalliferous material contributed by the waters.

While the foregoing paragraphs imply that the lateral moving waters are also downward moving, this is meant only as a general rule. The lateral movement may be accompanied by no downward movement. Not only this, but lateral movement may be accompanied by an upward component. Indeed, this is believed to be very frequently the case, especially so far as the main branch streams in the deeper parts of the zone of fracture are concerned. In so far as there is an upward component in these branch streams, the reactions which obtain are the same as those of the trunk channels to be considered below.

From the foregoing, *it appears that ores are carried to trunk channels by laterally moving waters. Lateral secretion is therefore an essential step in the first concentration of ore-deposits*, although I use the term lateral secretion in a broader sense than did Sandberger.

We have now reached the place where the ore-deposits themselves are found. As already noted, these mainly occur in the more continuous larger openings. These openings are

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* "Lists and Analyses of the Mineral Springs of the United States," by A. C. Peale, *Bull. U. S. Geol. Surv.*, No. 32, 1886, p. 363.

occupied by the trunk streams of circulating waters, and therefore the journey of the water is in the latter part of its course. Hence these trunk streams, as has already been shown (p. 35), have in general an upward rather than a downward vertical component. The waters reaching the trunk channel at any point immediately begin their ascent. At any given cross-section of a channel there must pass all of the water contributed below. This amount at great depth has already been seen to be small. From a small amount, the waters steadily increase in volume to the point where they begin to escape laterally from a trunk channel (see Fig. 6). Hence from a trunk channel of a definite size the circulation is slow below and increases in speed above. Near the bases of the channels from which the Mammoth Hot Springs and geysers of the Yellowstone Park issue the amount of water contributed may be small, and the movement of the water may be exceedingly slow. Even if true, as held by some, that rapid movement of water is unfavorable to deposition of ores, it is wholly possible at moderate depth and especially in the deeper parts of a channel from which the flow at the surface is rapid that the conditions are those of slow movement and rapid precipitation of ore-deposits.

As the water passes upward, the variety of solutions as well as the amount increases; for each stream differs in its salts from any other, since no two streams can possibly have had exactly similar histories. Moreover, the character of the wall-rock may vary from place to place. The pressure and the temperature are also lessening. These conditions are favorable to precipitation. *Therefore, many ores in their first concentration are precipitated by ascending waters.*

It is now clear that a satisfactory account of the genesis of ores includes ascending waters. By the ascending waters many ores in their first concentration are actually precipitated, and thus the emphasis which has been placed upon this part of the work of circulating waters.

The broader statement of the genesis of a great class of ore-deposits is that the water after penetrating the earth is widely scattered in contact with rocks in innumerable minor openings. These waters travel downward with steadily increasing pressure and temperature. They take up the constituents of the ore-deposits. The downward movement of the waters has superimposed upon it a lateral component, as a result of which the waters are carried to the larger openings. During this process, also, the waters continue to take material into solution. In the larger openings where the waters are congregated they are upon the average at first ascending with decreasing temperature and pressure, and there the ores are precipitated.

Of course, from this statement it is not meant to imply that materials are not deposited by descending and lateral moving waters, nor that materials are not dissolved by ascending waters. Indeed, it is certain that solution and precipitation are taking place at all times throughout the entire course of all the branches of the underground circulation. This is a necessary consequence of the laws of physical chemistry. It is only meant to imply that in the first concentration of one class of ore-deposits, solution so far as the ores are concerned is the rule for the descent and deposition for the ascent, although there is no doubt that there are many local exceptions to this.

It is of course understood that the underground circulation in any actual instance will be much more complex than that given in the simple ideal case which has been considered. This part of the subject will be developed. For instance, it is certain that, in the same mineral-bearing area, immediately adjacent trunk-channels may have had very different histories. This is especially well shown by the deposits of Butte, Montana, where there are two parallel main zones of mineralization, only a short distance apart, the mineral wealth of one of which is mainly copper, while that of the other is mainly silver.* Many of the other special factors which modify the simple general statement above given are discussed on pp. 112–140.

THE PRECIPITATION OF ORES BY ASCENDING WATERS.

The precipitation of ores in the trunk-channels by ascending waters is of so much importance in the concentration of ores that this process needs further consideration. The precipitation results from the various principles given pp. 41–45.

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* "Notes on the Geology of Butte, Montana," by S. F. Emmons. *Trans.*, xvi., 54, 1888.

Precipitation by Decrease of Temperature and Pressure.

The general relations of solution and precipitation as a consequence of varying temperature and pressure have been considered pp. 42–44. Where the increment of temperature is normal, it has been seen that decreasing temperature and pressure resulting from the ascension of waters from at least a depth of 3000 meters are favorable to precipitation. Furthermore, the same statement holds even if the increment of temperature is greater than normal, provided the temperature does not greatly exceed 100° C., and cases in which water issues at the surface at such temperatures are very rare. Moreover, probably decreasing pressure and temperature with rising solutions at depths greater than 3000 meters are favorable to precipitation. Since it has just been shown that ascending waters are likely to be in trunk-channels, these are the places where lessening temperature and pressure are most likely to produce precipitates. Therefore the openings of faults, joints and bedding partings and the more open places in porous sandstones, conglomerates and amygdaloids, are likely to have material precipitated in them as a consequence of lessening temperature and pressure.

When one attempts to apply these general statements to specific salts, we find experimental data lacking. It is undoubtedly the case that decreasing temperature and pressure are much more influential in the precipitation of some salts than of others; and that with a few salts decreasing temperature and pressure are favorable to solution. Until experimental work has determined how the various salts commonly found underground respond to changing temperature and pressure, it is impracticable to specify the ores the precipitation of which are strongly favored by decrease of temperature and pressure. One would expect that precipitation as a consequence of changing temperature and pressure would tend to give a somewhat orderly vertical distribution of the various metalliferous ores.

Precipitation by Mingling of Solutions.

Precipitation in the trunk-channels is produced by reactions caused by the mingling of various solutions. The solutions may be those of solids in the water, or of gases in the water, or of both. According to the modern theory of solutions, a solid dissolved in water is in the form of a gas; and therefore, so far as the precipitation is concerned, it makes no difference whether the substance in the water, if separated, would be a solid or a gas.

It is evident that solutions from different sources are entering a given trunk-channel at many places. Each of the incoming streams will have a solution different from that entering by any other stream, although in many cases the differences may be slight. As a case of certain considerable differences may be mentioned the ascending and descending streams. (See pp. 96–97.) Thus a multitude of streams of different composition enter and mingle in a trunk-channel. If in a chemical laboratory a multitude of solutions taken at random are thrown together, it is certain that various precipitates will be formed. It is just as certain when the various solutions in an underground channel come together that precipitates will frequently form. This mingling of solutions is one of the most important of all the factors which results in the deposition of the ores. I have little question that in this fact of the wide variety of solutions which enters a given channel we have in a large measure the explanation of the variable richness in ore-deposits in a given fissure. It is well known that an ore-deposit varies in richness in an exceedingly irregular manner. At a place in a fissure where a metal is abundantly found, the explanation in many cases is certainly that at or near that place there entered a stream which either carried the precipitated metal or carried an agent capable of precipitating the metal which was already in the trunk-channel. For instance, it is believed that where the great bonanza of the Comstock lode was found, there or near there entered either solutions rich in gold and silver which met other solutions capable of precipitating this gold and silver, or else at that place there entered a solution having a compound which was capable of precipitating the gold and silver already traveling upward within the lode. Perhaps the former hypothesis is the more probable.

Ore-chutes, or chimneys of ore of exceptional richness, are very frequent phenomena in veins. These are sometimes parallel with the dip, at other times pitch to the right or left of it. The explanation of these ore-chutes in many instances I believe to be a cross-fracture or joint through which waters entered, either carrying metalliferous material itself or solutions capable of precipitating the metalliferous mineral in the trunk-channel at the place where the lateral streams of water entered.

The lead and zinc deposits of the Mississippi valley, according to Jenney, are larger at the crossings of two sets of fissures than elsewhere. This may be partly explained by the greater abundance of the solutions furnished by two sets of fissures, but are probably at least partly explained, as suggested by Jenney,* by the mingling of two different kinds of waters, thus giving conditions favorable for precipitation.

In the Enterprise mine, at Rico, Col., described by Rickard,† the ore-bodies are in vertical veins and in flats under shales. While a set of cross-veins is barren, "the rich ore-bodies overlie them in the contact zone." Below the shale it is common to find ores of more than average grade in the pay veins where they are broken by the cross-veins. It is believed the explanation of these relations is the reactions resulting from the mingling of the solutions of the "verticals" with the inclined cross-veins.

The silver-lead deposits of the Aspen district of Colorado, described by Spurr,‡ furnish an instance of very probable precipitation of rich ore-chutes by the mingling of solutions. Spurr states that generally an ore-body is "found at the intersection of two faults, one of these faults usually dipping steeply, while the other is much flatter." For this "the explanation is offered that by the mingling of solutions which had previously flowed along different channels the precipitation of metallic sulphides was brought about."

Probably the rich ore-chutes of gold ore in the Sierra Nevada, which, according to Lindgren, pitch to the left as one looks down the veins, further illustrate the principle of precipitation by mingled solutions. For the most part, Lindgren makes no statement as to the relations of ore-chutes and lateral seams. However, on the Canada Hill vein there are "occasional rich bunches at the intersections" of the two systems of veins.§

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* "The Lead and Zinc Deposits of the Mississippi Valley," by W. P. Jenney, *Trans.*, xxii., 1894, pp. 189-190, 224.

† "The Enterprise Mine, Rico, Col.," by T. A. Rickard, *Trans.*, vol. xxvi., 1897, pp. 977-978.

‡ "Geology of the Aspen Mining District, Colorado," by J. E. Spurr, *Mon. U. S. Geol. Survey*, No. xxxi., 1898, pp. 230, 234-235.

§ "The Gold-quartz Veins of Nevada City and Grass Valley, California," by Waldemar Lindgren, *17th Ann. Rept. U. S. Geol. Surv.*, pt. ii., 1896, p. 197.

It is believed that the Cripple Creek deposits likewise illustrate this principle. Penrose* notes that many of the rich ore-chutes occur at cross-fissures. The formation of these ore-chutes at such places is doubtless partly explained by the greater amount of solutions furnished at an intersection of two trunk-lines of underground circulation; but it is thought probable that the main cause for the formation of ore-chutes at such places is the reaction of solutions furnished by one set of fissures upon those furnished by the other set. However, it is but fair to say that Penrose makes the explanation the "mechanical one, in deflecting the course of the ore-bearing solutions."

While apparent irregularities in the kinds and percentages of metals are doubtless in many cases explained as above, the distribution of the metals in a definite order from the surface downward, and the general law that many valuable metalliferous ores grow poorer in depth if the measure be 1000 meters or more are to be explained by other principles. Of these, varying temperature and pressure are important; but more important in many instances, as will be shown subsequently, is a second concentration produced by descending waters.

Reactions Due to Wall-Rocks.

Precipitation of metalliferous ores from the solutions in the trunk-channels due to the influence of the wall-rocks are frequently produced in the following ways: (1) It has already been explained that a solid when placed in contact with a liquid may precipitate some compound previously held in solution, some part of the solid going into solution at the same time. Thus, the wall-rock may precipitate ores. (2) The wall-rock produces an effect upon the trunk-solutions by furnishing precipitating solutions to it, and this may result in precipitation of metals already in solution within the trunk-channels. (3) The wall-rock itself may furnish metalliferous material for the ore-deposit which may be precipitated when it reaches the trunk-channel by the solutions there contained. This has been greatly emphasized, probably over-emphasized, by Sandberger. Where the wall-rock is easily soluble, ready enlargements of the openings occur,

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* "Mining Geology of Cripple Creek, Colorado," by R. A. F. Penrose, Jr., *16th Ann. Rept. U. S. Geol. Surv.*, 1894–95, pt. ii., pp. 164–165, 1895.

furnishing places for the deposition of the metalliferous material. (See pp. 132–135.)

It is believed that the effect of the wall-rock in these various ways in the production of many ore-deposits is of great importance. As an illustration, may be cited the very general association of lead-ores with limestone. Probably by far the larger portion of the lead-ores mined in the past have come from within limestone. I believe it to be highly probable that the position of the ores in limestone is due to the character of this rock. Any one of the factors above mentioned might be more important in a given case, but doubtless in many instances two or more work together. Thus, the position of the lead in a limestone may be partly explained by reactions between the solutions of the trunk-channel entering the limestone and the limestone itself. Or, the precipitation of the lead may be partly the result of the reactions between the solutions furnished by the trunk-channel and the solutions furnished by the limestone. In a given case the waters of a trunk-channel entering the limestone may be acid. The solutions from the limestone would immediately react upon this solution, tending to neutralize it, and the precipitation of lead sulphide might be a consequence. Or, the wall-rock might furnish the lead, as in the Mississippi valley. The ready solubility of the limestone would furnish the openings and caves, giving a receptacle for the lead, as in southwestern Wisconsin.

A still clearer case of precipitation resulting from the influence of the wall-rock is the well-known occurrence of metallic copper about grains of magnetite, and in the openings of sandstones, conglomerates and amygdaloid of Keweenaw Point.* Where the copper is about the magnetite it seems perfectly clear that the protoxide of iron in the magnetite was the reducing agent which precipitated the metallic copper.† The metallic copper between the particles was doubtless precipitated by ferrous solutions furnished by the wall-rocks, which in many cases are basic volcanics.

The reactions due to the country-rock are more likely to be effective in proportion as it is porous, and therefore allows solu-

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* "The Copper-Bearing Rocks of Lake Superior," by R. D. Irving, *Mon. U. S. Geol. Surv.*, No. 5, 1883, p. 420.

† Irving, *cit.*, Pl. xvi., Fig. 1.

tions to permeate it. The country-rock is especially effective in its reactions where the trunk-channel is a complex one, and gives a large surface of action. This is illustrated by the Calumet and Hecla conglomerate, by the Cripple Creek ore-deposits,* and by many other districts (see p. 114).

A particularly clear illustration of the effect of the wall-rock is furnished by ores in which the sulphides are confined to strata containing organic matter, as in some copper-deposits† and some of the gold-reefs of Australia. In the case of the copper-deposits, the organic matter has in all probability reduced sulphites or sulphates to sulphides. The function of the organic material in the case of the gold may have been to reduce it to metallic gold, or to reduce it through the production of *ous* salts, for instance, ferrous sulphate (see pp. 92–94).

General.

In conclusion, it may be said that the precipitation of metallic ores by the mingling of various solutions is probably the most important single factor which results in the first concentration of ores. Probably next in importance to this are the reactions upon the trunk-streams due to the wall-rocks. Inasmuch as the waters of lateral streams from beyond the wall-rocks must pass through the latter, many of the streams contributed through the wall-rocks to the trunk-channels produce an effect partly due to materials more remote than the wall-rocks and partly to the wall-rocks. Thus in many cases the effect of solutions beyond the wall-rocks and that of solutions furnished by the wall-rocks cannot be discriminated. However, since the effect of the wall-rocks has been so much discussed, it seemed to me best to treat the two separately as far as practicable.

Diminishing temperature and diminishing pressure, while probably subordinate in their effect to the mingling of streams and reactions due to the wall-rocks, are in many instances undoubtedly important, and in some instances may be the dominant factors. In general, the tendency of writers has been to

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* "Mining Geology of Cripple Creek, Colorado," by R. A. F. Penrose, Jr., *16th Ann. Rept. U. S. Geol Surv.*, 1894–95, pt. ii., p. 163, 1895.

† "The Genesis of Ore-Deposits," by F. Posepny, and Discussion of same, by F. M. F. Cazin, *Trans. Am. Inst. Min. Eng.*, vol. xxiii., 1894, pp. 316, 606–607.

emphasize the effect of diminishing temperature and pressure, and to minimize or even disregard altogether the effects of mingling solutions or the wall-rocks, or both.

The Compounds Deposited by Ascending Waters.

Of the metalliferous ores, those of iron, copper, lead, zinc, silver and gold are the more important. Where these are deposited by ascending waters they occur mainly as sulphides. In many cases the sulphides are simple binary salts. However, sulpharsenites and sulpharsenates, sulphantimonites and sulphantimonates are common; but these also are sulphides, and all will be thus referred to without qualification. Besides sulphides, metallic products sometimes occur, as in the case of copper and silver; also tellurides, carbonates and silicates are formed.

Why average compounds deposited by ascending waters are, for the most part, not oxidized compounds, but sulphides, tellurides, or metallic compounds, is easily explained. The widely disseminated, downward-moving water, bearing oxygen, is robbed of this constituent early in its course. Ferrous compounds are abundantly present in the rocks in the forms of magnetite and silicates. Iron is a strong base; and where ferrous compounds are present they continue to abstract the oxygen of the downward moving waters until it has practically disappeared. Moreover, buried organic matter takes oxygen from underground waters. In believing that the sulphides are commonly precipitated by ascending waters in the openings below the level at which oxidizing solutions are active, I follow Le Conte and Posepny.*

Source of the Metals.—The nature of the rocks which contribute the metallic salts has been much discussed. With Sandberger,† I have little doubt that the metallic constituents of ores are in large part derived from the igneous rocks which have been intruded or extruded into the lithosphere; and especially is this true of the basic rocks. Le Conte‡ points out that the undoubted frequent occurrence of workable ore-deposits in regions of vulcanism may be explained by the heat furnished by the

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* "On the Genesis of Metalliferous Veins," by Joseph Le Conte. *Am. Journ. Sci.*, third series, vol. xxvi., 1883, p. 4. "The Genesis of Ore-Deposits," by F. Posepny, *Trans.*, xxiii., 1894, p. 236.

† "Untersuchungen über Erzgänge," by F. Sandberger, 1882.

‡ *Op. cit.*, p. 10.

igneous rocks, this promoting the work of underground solutions. That the heat furnished the igneous rocks is a very important factor in the production of the ore-deposits, I have no doubt. Since it is very difficult to prove that the metallic content of an igneous rock is original, it is impossible to make any general statement as to whether the metallic content or the heat furnished by the igneous rocks is the more important in the production of ore-deposits. It seems to me clear that both are important; and equally clear, in many cases, that both work together. That is to say, an igneous rock may furnish all or a part of the metal which appears in an ore-deposit, and the heat of the same igneous rock may greatly assist its concentration by the underground waters.

While the massive igneous rocks are the undoubted source of a large portion of metallic deposits, it is also equally certain that another large part is derived from the sedimentary rocks and the metamorphosed, or partly metamorphosed, igneous and sedimentary rocks. Lastly, it is also certain that many ore-deposits derive their metalliferous content in part from igneous rocks and in part from sedimentary rocks. Probably this is the most frequent of all cases. To give any estimate of the relative amounts of metalliferous materials derived from the original igneous rocks and from the secondary rocks is quite impossible.

This statement will, of course, be very unsatisfactory when applied to an individual district. However, it is not the purpose of this general paper to consider individual districts, except as they illustrate principles. It is properly the part of the geologist or mining engineer who studies an individual district to find the source of the metal. In many cases, careful investigations can undoubtedly determine this point, as, for instance, that of the iron-ores of the Lake Superior region. In other districts, however, the most exhaustive study may not enable the investigator to determine the source of the metalliferous material. This is especially likely to be true of ore-deposits produced by ascending waters from a somewhat deep circulation. The underground waters may have their sources of supply in rocks which do not reach the surface, and have not been penetrated by the mine workings.

In concluding this part of the subject, it may be suggested that in many instances mistakes have been made in assuming that some one formation, sedimentary or igneous, is the sole source of the valuable metals. Such an assumption is particularly prevalent in papers descriptive of gold deposits and silver deposits. In many districts where there are various sedimentary and igneous rocks, I have no doubt that the silver and gold are partly derived from two or several formations.

Source of the Sulphur of Sulphides.—According to modern research, the metallic sulphides are original constituents of igneous rocks. This is a direct observation; but even if the observation had not been made, the large amount of sulphur compounds issuing from the interior of the earth in connection with vulcanism would lead to the conclusion that sulphides must exist in the igneous rocks. It is therefore probable that sulphur, as sulphide, is or was present in sufficient quantity in the original rocks to fully account for all of the sulphur compounds in the ore-deposits.

It is, of course, well known that sulphides in the belt of weathering are largely oxidized to sulphites and to sulphates, and taken into solution by descending waters. These compounds join the sea of underground water. There the sulphites and sulphates, either just below the level of groundwater or at a greater depth, may come in contact with buried organic material. Under these conditions it is well known that the sulphites and sulphates are reduced to *ous* salts, or to sulphides.

Occasionally the metals may be carried to the trunk-channels as sulphites and sulphates, and there be reduced to sulphides. This would be especially likely to happen where the ores are disseminated through beds bearing carbonaceous material. Cazin mentions the Vermont copper-mine as a case where the ores are mingled with organic material.* Rickard mentions a number of cases where the deposition of the ores is confined to material containing organic matter, the more important being those gold-bearing sulphide reefs of Australasia, California and Colorado, where the ore is associated with strata bearing organic matter.†

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* "Discussion of the Genesis of Ore-Deposits," by F. M. F. Cazin, *Trans.*, xxiii., 1894, 606–607.

† "The Origin of the Gold-Bearing Quartz of Bendigo Reefs," T. A. Rickard, *Trans.*, xxii., 1893, 314–315. "The Enterprise Mine, Rico, Colo.," T. A. Rickard, *Trans.*, xxvi., 1897, 977–979.

In one case of the gold-quartz veins of California, in carbonaceous argyllite, pyrite occurs in the argyllite but not in the quartz. This is very strongly suggestive that the carbonaceous matter of the argyllite has reduced the sulphates to sulphides. This occurrence in the California gold-belt is especially suggestive, since the analyses of two springs of ascending waters at the 400-foot levels in two separate mines show the presence of considerable quantities of sulphates.*

Probably also sulphites and sulphates may be reduced to sulphide by ferrous iron in the rocks. If this reaction takes place, it should be especially characteristic of the more basic rocks. The frequent occurrence of sulphides in the altered basic rocks, and especially the scoriaceous basic rocks, is very strongly suggestive that this reduction has taken place. So far as I know, this reaction has not been before suggested. It is probably an important one in the reduction of the sulphites and sulphates to sulphides in the lower part of the zone of fracture, and may explain the deposition of sulphides in rocks where organic material is not available for the reduction.

The sulphides, whether as original constituents of the igneous rocks or produced by the above reactions, are taken into solution and deposited in the main channels of water-circulation. Of the fact of the solution and deposition of the sulphides there can be no doubt. However, the solvents in different cases are doubtless different, and moreover, in a single case, the solvents are probably complex. It is well known that the sulphides of the valuable metals are somewhat freely soluble in alkaline solutions, and especially solutions of the alkaline sulphides.† Furthermore, from observation in the field it is known that certain of the sulphides have been thus transported, as for instance at Steamboat Springs and Sulphur Bank,‡ and doubtless this manner of transportation is very common. However, as shown in another place, the bicarbonates with an excess of carbon-dioxide are the most abundant compounds in underground solutions. These bicarbonates are largely those

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* "The Gold-Quartz Veins of Nevada City and Grass Valley, California," by Waldemar Lindgren, *17th Ann. Rept. U. S. Geol. Surv.*, pt. ii., 1895-96, p. 81; also Plate VIII., p. 140, and pp. 121-123, 172-173.

† Lindgren, *op. cit.*, pp. 177-178.

‡ Le Conte, *cit.*, *Am. Jour. Sci.*, vol. xxvi., p. 3.

of the alkalies and alkaline earths. Such carbonated waters also favor the solution of sulphides. Furthermore, sulphides are doubtless rendered more soluble by the presence of various other compounds in the underground solutions. However, the transportation of sulphides is not limited to solutions which bear other compounds; for the sulphides themselves are soluble in pure water to some extent, as has been shown by Doelter.*

But in whatever form the sulphides are transported, they are largely precipitated in due time in the trunk-channels. By denudation these sulphides may again reach the belt of weathering when the cycle is complete. The sulphide may be again oxidized to sulphate, and so on. It is therefore clear that sulphur, as sulphide and sulphate, may again and again take part in the deposition of ores;† but the first source of the sulphur must be the sulphides of the original rocks.

In this connection Chamberlin has noted that in Wisconsin waters comparatively near the surface bear oxygen and oxidized compounds, while deep artesian waters are "marked by slightly sulphuretted waters."‡ Thus analyses of waters in a region of comparatively undisturbed sedimentary rocks confirm the statements of the previous paragraphs. That is to say, waters which are deep-seated, and therefore must take an upward journey to reach the surface, are likely to bear sulphides.

While it is believed that sulphides are generally deposited by upward-moving waters, this is not supposed to be the universal case. Nature's processes are always too complex to be covered by a single general statement. As a result of mingling solutions at various places, and of reactions between solutions and walls, many lateral moving and downward moving streams doubtless do deposit rather than dissolve sulphides. Indeed, in the frequent case already noted, where in downward moving waters, sulphites or sulphates are reduced by organic matter to sulphides, precipitation of a portion of the sulphide is usual. But still the statement would hold true that upon the average more sulphides are dissolved by descending waters than deposited, and more sulphides are deposited by ascending waters than dissolved.

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* Lindgren, *op. cit.*, pp. 179–180.

† Le Conte, *op. cit.*, p. 13. Compare Posepny, *Trans.*, xxiii., 1894, 263.

‡ "The Ore-Deposits of Southwestern Wisconsin," by T. C. Chamberlin, *Geol. Wis.*, vol. iv., 1882, p. 547.

We conclude, therefore, that, *whatever the source of the sulphides as first concentrates, these ores are generally deposited by ascending waters in the trunk-channels.*

Source of the Carbonic Acid of Carbonates.—Aside from sulphhydric acid, the other acid of great importance in the deposition of ore-deposits is carbonic acid. This as is well known is, indeed, the dominant acid contained in issuing underground waters. This point both Le Conte and Posepny strongly emphasize.* I have already pointed out two sources for the excess of carbon-dioxide held in the underground waters. Where vegetation is abundant, carbon-dioxide is concentrated in the soil. A large part of this is retained in the belt of weathering by the process of carbonation of the silicates, but another part joins the sea of underground waters. Another source for the carbon-dioxide is that liberated from cavities within rocks. It is well known that in many rocks a large amount of carbon-dioxide is included in innumerable microscopic cavities. When such rocks are complexly deformed in the zone of fracture, the fractures must intersect many of these cavities, and thus liberate the carbon-dioxide. Where there are zones of crushing, that is, where there are trunk-channels for percolating waters, the amount of carbon-dioxide which may thus be liberated may be considerable. Another source for the carbon-dioxide is a process of silication, explained p. 51, as a result of which the carbonates are decomposed by the silicic acid at depth, liberating the carbon-dioxide. Therefore, deep-seated waters are ever receiving contributions of carbon-dioxide, and thus are continually more capable of taking metals in solution, until the waters reach conditions where silication does not occur.

In this process of silication alone is believed to be an adequate source of carbon-dioxide; so that metals may be carried as bicarbonates and the water also hold a further excess of carbon-dioxide.

A very interesting confirmation of the liberation of silica by the process of carbonation near the surface and the liberation of carbon-dioxide, probably by the process of silication at depth, as above explained, is furnished by the Geyser mine of Custer county, Colorado, described by Emmons.† Here waters were

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* Le Conte, *op. cit.*, p. 11. Posepny, *Trans.*, xxiii., 237.

† "The Mines of Custer County, Colorado," by S. F. Emmons, *17th Ann. Rept. U. S. Geol. Surv.*, pt. ii., 1895–96, pp. 460–464.

analyzed from the 154 meter and the 615 meter levels. The superficial waters contained ten times as much silica as the deep-seated waters. In the deep waters the carbonic acid is greatly in excess of that contained in the vadose circulation.

General.

The foregoing statement explains to some extent the source of the compounds deposited by ascending waters. But it is not the intention here to discuss its application to each individual metal. This I do not attempt, because I lack the necessary accurate observations upon which such a discussion should be based. To tell in what manner each of the individual metals is carried will require very detailed investigation. For instance, the questions as to the condition in which gold occurs in the original rocks, the manner in which it is carried in solution, and the form in which it is deposited have been much discussed. However, the difficulties in this and other cases, since the modern theories of physical chemistry have been developed, do not seem to be so great as when it was supposed that we must regard each metal in solution as combined with some one acid. It has already been stated that all substances are soluble in water, and somewhat readily soluble in various underground solutions. It is believed that in the very dilute underground solutions, metallic salts are largely in the form of free ions. Therefore, in one sense, gold and other metals in solution are not combined with acid ions, although they are balanced by them. Where precipitated, a metal might be thrown down in the metallic state, as, for instance, copper, silver or gold, by the ions which once balanced it being balanced by other metals.

While it is not the purpose here to take up the solution and deposition of the compounds which occur in ore-deposits in detail, it is necessary to refer to the law of mass-action in this connection. Other things being equal, those compounds which are abundant will be dissolved in larger degree during the downward course of the waters, and the same compounds will be most abundantly precipitated in the trunk-channels. It is well known that iron is the most abundant of all the metallic compounds in the crust of the earth. In this fact, combined with the law of mass-action, we have the dominating abundance of iron sulphide as compared with all sulphides of other metals. It is well known in many cases that the deeper a mine goes below the level of groundwater, the greater the proportion of iron sulphide and the lessening proportions of the other metals, as a result of which, combined with increased cost of working, it frequently does not pay to work a deposit beyond a certain depth. The law of mass-action explains the abundance of the iron sulphide; it does not explain the frequent relative increase in the iron sulphide and the decrease of more valuable sulphides as one passes from the level of groundwater into deep workings. To explain this we must take into account the effect of the downward-moving waters, discussed under the succeeding heading.

We have now seen that the zone of fracture is searched by the percolating waters; that metalliferous materials taken into solution by the downward and lateral moving waters are carried to the trunk channels of underground circulation; that in these trunk channels the metalliferous materials are precipitated in various ways. Thus a first concentration, by ascending waters giving sulphurets and metals of some of the elements, is fully accounted for.

In some cases the deposits thus produced are sufficiently rich, so that they are of economic importance. In these cases, which undoubtedly exist, but which perhaps are less numerous than one might at first think, a concentration by ascending waters has been sufficient.

A conspicuous illustration of ore-deposits of this class which may be mentioned are the metallic copper deposits of the Lake Superior region. The copper was in all probability reduced and precipitated directly as metallic copper from upward moving cupriferous solutions. The reducing agents were the ferrous compounds in the solid form, in part as magnetite and as solutions derived from the iron-bearing silicates. When the copper was precipitated, the iron was changed into the ferric condition.* It is well known that metallic copper once formed is but slowly affected by the oxidizing action. Oxidation has, in fact, occurred in the Lake Superior region, but from the

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* "Paragenesis and Derivation of Copper and its Associates on Lake Superior," by R. Pumpelly, *Am. Jour. Sci.*, vol. ii., 1891, p. 33.

facts now to be observed not to an important extent. An oxidized belt may have formed in pre-glacial times, but if so it was swept away by glacial erosion, and sufficient time has not since elapsed to form another. The ore-deposits now worked have apparently remained practically unchanged since the time of their first concentration. In this fact we have the explanation of the great richness of these deposits to extraordinary depths.

As a case of sulphide deposits which continue to great depth without diminution in richness, may be mentioned the gold-quartz veins of Nevada City and Grass Valley, California. According to Lindgren, "it can be confidently stated that there is no gradual diminution of the tenor of the ore in the pay-chutes below the zone of surface decomposition,"* although within the same chute there are many and great variations in richness. This statement is applicable to deposits which reach a vertical depth of 500 or 600 meters. If Lindgren is correct in thinking the gold-quartz veins of the Sierra Nevada do not diminish in depth below an extremely superficial upper zone, this would be a case in which sulphuret ores were sufficiently concentrated by ascending waters alone to afford workable ore-deposits.

The Precipitation of Ore-Deposits by Ascending and Descending Waters Combined.

Thus far we have considered ores precipitated by ascending waters alone. However, many of the ores thus produced have been profoundly modified by the action of descending waters.

Where the point of exit of the ascending waters of the trunk channels is in a valley or near the level of surface drainage, the waters may continue to ascend quite to the surface. However, where the openings are below slopes the waters ordinarily do not continue to ascend to the surface, but make their way laterally from the trunk-channel at and below the level of groundwater (see Fig. 6). Above the level of groundwater, and frequently for a certain distance below the level of groundwater, the movement is downward in the openings. The water

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* "The Gold-Quartz Veins of Nevada City and Grass Valley, California," by Waldemar Lindgren, *17th Ann. Rept. U. S. Geol. Surv.*, pt. ii., 1895-96, p. 163.

thus moving downward includes not only that which directly passes into the trunk openings at the surface, but a much larger quantity which converges into these openings from the smaller openings on all sides.

In regions in which mining is going on, denudation has ordinarily truncated the veins for considerable depths, in many cases to hundreds or even thousands of meters. It is therefore clear, in a majority of cases, that portions of the fissures in which the waters are now descending were, in the past, in all probability much deeper below the surface, and therefore the waters at that time in the larger fissures were probably ascending. During the time the water was ascending, the first concentration of sulphurets and other products took place. But as a result of the downward migration of the belt of weathering and the downward movement of water in that belt, alteration and secondary concentration of ore-deposits have taken place. This second concentration of ore-deposits is of the very greatest importance, and I believe largely explains the frequent greater richness of the upper 50 or 100 or 500 meters, and in some cases 1000 meters, as compared with lower levels.

It has already been pointed out that the descending waters bear oxygen and carbon dioxide; and furthermore, that solution is taking place. Moreover, the belt of weathering is migrating downward because of erosion. The result of all these changes is to produce an upper belt of second concentrates from the first concentrates formed by ascending waters. This material may be divided into three parts: (1) above the level of groundwater is a belt largely composed of oxides, carbonates, chlorides and associated products, which, however, may contain enriched sulphides. (2) Above and below the level of groundwater is a transition belt composed of sulphides rich in the valuable metals, such as gold, silver, copper, lead and zinc, which, however, contain subordinate amounts of oxidized products. (3) Deeper down is a belt of lean sulphides bearing small amounts of the more valuable sulphurets, and which commonly passes into iron sulphide. Between the three classes of material there are gradations. The oxidized belt gradually passes into the rich sulphide belt; the rich sulphide belt gradually passes into the poor sulphide belt.

The above results are due to a complicated set of reactions which cannot here be given in full. It is, however, clear that if the sulphides are equally abundant the sulphide which is the most easily oxidized will be the first to disappear. The order of disappearance will therefore be iron, copper, zinc, lead, silver. It is, however, understood that the oxidation of an easily destroyed sulphide is not complete before the oxidation of a refractory sulphide has begun. All of the sulphides are oxidized all the time, but the more readily a sulphide is oxidized, the more rapidly it is destroyed. During oxidation the sulphides are largely altered to soluble sulphates, which are taken into solution and carried downward.

The evidence of the extensive formation of sulphates in veins by descending water is found in the presence of sulphates in mine waters and in the frequent formation and precipitation of basic ferric sulphate in the veins, as, for instance, at Cripple Creek,* and in the Mercur district, Utah.† The formation of gypsum and magnesium sulphate in veins is scarcely less positive evidence of the oxidation of the sulphides to sulphates. Further evidence of the formation of sulphates by oxidation of the sulphides is furnished by the hydrous sulphate of aluminum which occurs in the gold-veins of California.‡

The sulphides, however, are not all oxidized to sulphates; a portion of them, by oxidation, break up into sulphurous oxide and oxides of the metals. A part of the oxides unite with the carbonic acid to produce carbonates. Finally the oxides and oxidized salts, both formed in place and transported, react upon the unaltered sulphides, producing richer sulphurets. The reactions may be between an oxide or a salt of a metal and its sulphide, as, for instance, the oxide or sulphate of copper upon the sulphide of copper, as given by the following equations:

$$6CuS + 2Cu_2O = 5Cu_2S + SO_2,$$

and

$$6CuS + 2Cu_2SO_4 + 3H_2O = 5Cu_2S + 2H_2SO_4 + H_2SO_3.$$

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* "Mining Geology of the Cripple Creek District," by R. A. F. Penrose, Jr., *16th Ann. Rept. U. S. Geol. Surv.*, pt. ii., 1894–95, p. 130.

† "Economic Geology of the Mercur Mining District, Utah," by J. Edw. Spurr, *16th Ann. Rept. U. S. Geol. Surv.*, pt. ii., 1894–95, p. 435.

‡ "The Gold-Quartz Veins of Nevada City and Grass Valley, California," by Waldemar Lindgren, *17th Ann. Rept. U. S. Geol. Surv.*, pt. ii., 1895–96, p. 120.

Or the reaction may be between the oxide or salt of one metal and the sulphide of another metal, as, for instance, copper oxide or copper sulphate upon iron sulphide, thus precipitating copper sulphide. The particular reactions in an individual case will depend upon the relative solubilities of the compounds present, and the law of mass-action. This will more clearly appear upon subsequent pages.

The concentrations by ascending and descending waters have been considered as if they were successive. In some instances this may be the case; but frequently it is much more probable that ascending and descending waters are 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 Fig. 6, a first concentration by ascending waters is taking place in the lower part of the fissure, and a second concentration 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 for this class of ore-deposits, therefore, is 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.

The above general statement may perhaps be better understood if supplemented by a consideration of specific associations of the metals. The associations which are chosen for illustrative purposes are as follows: (1) associations of lead, zinc and iron, (2) associations of copper and iron, (3) associations of silver and gold with the base metals.

THE ASSOCIATION OF LEAD, ZINC AND IRON COMPOUNDS.

In order to understand the relations of the lead, zinc and iron compounds where they occur together in ore-deposits, it seems advisable to take an individual district rather than to make a general statement. An excellent illustration of the association of these metals is furnished by the Upper Mississippi Valley, and this district will therefore be considered.

Facts of Occurrence.

Here, as is well known, in openings in limestones, lead and zinc minerals are associated with marcasite, and some pyrite and chalcopyrite.* Calcite is an abundant gangue mineral, as would be expected, but it and the other gangue minerals will here not be taken into account. Since the pyrite and chalcopyrite are very subordinate, they will not again be alluded to. All of the sulphide of iron will be referred to as marcasite.

The order of occurrence in the district is commonly as follows: Above the level of groundwater in the belt of weathering the dominant valuable minerals are galena and smithsonite. Frequently encrusting the galena, or in crystals upon it, there are some cerussite and less anglesite; with the smithsonite there is some sphalerite. The smithsonite may extend 5 or 10 meters below the level of groundwater; but deeper the oxidized products almost wholly disappear. The smithsonite below the level of groundwater is explained in some cases by the material being along a main channel of downward percolating waters; in other cases by the fact that the level of groundwater is probably now higher than it once was, as a result of depression and valley-filling at the close of the glacial epoch; thirdly, by the well-known general downward movement of oxidizing water somewhat below the level of groundwater; and, fourthly, by reactions between oxidized lead salts and the sphalerite. (See p. 80.) Below the galena and smithsonite is sphalerite, with a large amount of marcasite.† For much of the district the workings have not extended far below the level of groundwater, but in certain parts of the district working has extended for a considerable depth.

While the above general statement is correct for much of the district, it must be understood that a single sulphide does

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* "The Ore-Deposits of Southwestern Wisconsin," by T. C. Chamberlin, *Geol. of Wis.*, vol. iv., 1882, pp. 380–393.

† Chamberlin emphasizes the inferior position of the zinc as compared with the lead and the association of the zinc and iron, but he does not consider the positions of these compounds with reference to the level of groundwater. *Loc. cit.*, pp. 488–491.

not occur at a given level to the exclusion of the others. Indeed, in many cases all of the sulphides are found at the same level. In many of the smaller veins the sulphides occur in a definite order. The full succession at various openings, from the wall to the druse, is (1) marcasite, (2) ferriferous sphalerite, (3) galena, in cubic crystals, (4) ferriferous sphalerite (subordinate in quantity), (5) marcasite, (6) galena, in octahedral crystals (very subordinate in quantity).* Of this succession at various veins some of these elements are lacking. A very common order is (1) sphalerite, (2) galena, and (3) marcasite.

First Concentration.

No clearer possible illustration could be found of the general principles of ore deposition by the underground waters, and the phenomenon of crustification emphasized by Posepny, than that furnished by this district. The first concentration is believed to be the work of ascending waters, the materials being precipitated in the form of sulphides. It is probable that there was a tendency at the time of the original crystallization for the sulphides to be thrown down in a definite order across the openings, as shown by the phenomena of crustification. Furthermore, it appears that there may have been two main cycles of precipitation, so far at least as the sphalerite and galena are concerned, but the first cycle was by far the more important. It is also possible that there was a tendency for the sulphides to be precipitated in a definite order vertically, as a consequence of which the marcasite was the predominate precipitate at the lowest level, sphalerite at the intermediate levels, and galena at higher levels. Such an order might be explained as a result of the lessening pressure and temperature as the depositing solutions rose in the openings.

Second Concentration.

While it is possible that the vertical order of the minerals is due to a first concentration, it is probable that this is not the most important factor in the regular vertical distribution of the sphalerite and galena. It is believed that the present general order of these materials is mainly controlled by the downward-moving waters combined with denudation.

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* Chamberlin, *loc. cit.*, pp. 491–497.

It is not necessary to show that the smithsonite above and a short distance below the level of groundwater was largely derived from sphalerite, and that the cerussite and anglesite were largely derived from galena. The details of the relations of the various oxidized and sulphuretted minerals above the level of groundwater are exceedingly complex, and no description of them will here be attempted. Nor in this paper is it necessary to write reactions for the transformation of the sulphides into the oxidized products, since the general characters of such reactions are so well known.* It is, however, necessary to explain how downward-percolating waters may concentrate galena at a high level and sphalerite at a lower level.

Galena.—If it be premised that the ascending waters evenly distributed the sulphides, at least so far as the vertical element is concerned, it is certain that downward-moving waters, combined with denudation, may concentrate the galena at high levels and the sphalerite at lower levels.

The galena is the most difficultly oxidizable of the three sulphides. It is, therefore, the most stable of them. By the oxidation and solution of the sphalerite and marcasite above the level of groundwater the galena would be concentrated. That this process has taken place on an extensive scale is shown by the occurrence of many detached fallen crystals and masses of galena in the openings above the level of groundwater, and also at the bottoms of the wider openings and caves a short distance below the level of groundwater. Indeed, a considerable portion of the lead of the district which has been taken above or within a few feet below the level of groundwater strongly corroborates the idea of concentration as result of solution of the other sulphides which held the galena to the walls, thus permitting the material to drop to lower positions in the crevices.†

While the concentration of the galena is partly explained as above, it may be explained also in part by chemical reactions between the various compounds. In the belt of weathering part of the galena as already noted is being oxidized, as is shown by the incrustations and superimposed crystals of cerussite and anglesite. During the formation of the sulphates and

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* Chamberlin, *loc. cit.*, pp. 498-509.

† Chamberlin, *loc. cit.*, pp. 453 to 498.

carbonates, a certain amount of these salts is taken into solution and carried downward. These sulphates and carbonates would react upon the other sulphides present and reprecipitate the lead as galena. These reactions might take place to some extent above, but would be especially likely to occur below, the level of groundwater. As a result of the downward migration of the belt of weathering, there would be in the downward-moving waters a continual supply of the sulphates and carbonates of lead. The chief reaction would be that between the lead salts and the dominant iron sulphide. Supposing the iron were in the form of FeS, the reactions may be written as follows:

$$PbSO_4 + FeS = PbS + FeSO_4,$$
$$PbCO_3 + FeS = PbS + FeCO_3.$$

If the iron be supposed to be in the form of FeS_2, as is most likely, oxygen also would be necessary for the reactions. The equations would then be as follows:

$$PbSO_4 + FeS_2 + O_2 = PbS + FeSO_4 + SO_2,$$
$$PbCO_3 + FeS_2 + O_2 = PbS + FeCO_3 + SO_2.$$

However, it has been premised that with the original sulphides zinc sulphide is present, and this may also react upon the lead salts, according to the following reactions:

$$PbSO_4 + ZnS = PbS + ZnSO_4,$$
$$PbCO_3 + ZnS = PbS + ZnCO_3.$$

In the case of the latter reaction, smithsonite would be formed. In this connection it is notable that frequently associated with the galena for some distance below the level of groundwater, smithsonite occurs, as already noted. While a part of the smithsonite below the level of groundwater is of this origin, doubtless the larger portions of it are differently explained. (See p. 77.)

To the foregoing reactions, partly explaining the concentration of galena, objection may be made upon account of the small solubility of lead sulphate and lead carbonate. It is true that these substances are very sparingly soluble in pure water; however, they are sufficiently soluble in waters bearing carbon-dioxide to account for the phenomenon. If this be not the case, the lead may have been carried downward as chloride.

Independent, however, of chemical theory, we know in many districts, and particularly in the lead and zinc district of southwestern Wisconsin, that the galena has been changed to some soluble form upon an extensive scale. As evidence for this inference, galena crystals above the level of groundwater are much corroded, and the amount of cerussite and anglesite associated with them is so small as not to account for the corrosion, and therefore the lead has been transformed to a soluble salt, which has been transported below in important amounts.* So far as my argument is concerned, it is of no consequence whether the lead is as a sulphate, carbonate, chloride or other salt. However, it is believed that these are the forms in which the lead was transferred on the most extensive scale. I regard the cerussite and anglesite as evidence of the partial transfer of the lead as sulphate and carbonate. A large amount of sulphate and carbonate probably formed, but the compounds are so insoluble that a part of the salts produced were not carried downward, but precipitated near the places of formation.

Sphalerite.—Zinc holds sulphur less strongly than lead, but much more strongly than iron. Therefore, the sphalerite would be concentrated in the zone below the galena, the reactions being similar to those producing the galena. They may be written as follows:

$$ZnSO_4 + FeS = ZnS + FeSO_4,$$
$$ZnCO_3 + FeS = ZnS + FeCO_3,$$

or

$$ZnSO_4 + FeS_2 + O_2 = ZnS + FeSO_4 + SO_2,$$
$$ZnCO_3 + FeS_2 + O_2 = ZnS + FeCO_3 + SO_2.$$

Marcasite.—At a certain depth in the openings below the level of groundwater, nearly all of the salts of lead and zinc descending from the belt of weathering would be precipitated by reactions between them and the iron sulphide, as above explained. The remainder of this paragraph cannot be said to apply to the deposits of the upper Mississippi Valley; for the vertical extent of the veins is probably very limited, many of them apparently being cut off by impervious strata within short distances from the surface. However, in veins in which the

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* Chamberlin, *op. cit.*, pp. 498-499, 500.

first concentration extends to a depth greater than that to which downward-moving waters are effective, only the sulphurets of the first concentration would be found below this level. These sulphurets would consist mainly of marcasite, with subordinate amounts of sphalerite and galena. However, even in this belt, concentration of galena and sphalerite may occur to some extent, although it receives no contribution from the lead and zinc salts from above; for even after the salts of lead and zinc traveling downward from the belt of weathering are all precipitated, the waters may still hold oxygen. This oxygen would, to the largest extent, act upon the marcasite, producing to some extent soluble salts which would be abstracted, and thus reduce the quantity of this material, and relatively enrich the deposits in lead and zinc, although not increasing the absolute amount of lead and zinc present in a given vertical distance. So far as the zinc and lead salts were oxidized by the oxygen-bearing water, these would react upon the iron sulphide again, and they would be precipitated according to the reactions above given.

General.

It is believed that the concentration by descending waters explains, through the reactions given on pp. 80–81, the orderly distribution of the ores in a vertical direction,* although original deposition by ascending waters may have produced its effect. Furthermore, it is believed that this concentration was the final determinative factor in making the ores so rich as to warrant exploitation. This statement in reference to the rich deposits applies both to the oxidized products and to the sulphurets, both above and below the level of groundwater. This process of concentration is primarily chemical, but also to some extent is mechanical, the latter being especially true of the galena loosened by solution from the walls which have fallen to the lower positions in the crevices and caves.

While the reactions of the downward moving oxidized products upon low grade sulphurets, thus producing rich sulphides, have been dwelt upon, it is not supposed that these are the only reactions which have resulted in enrichment. As pointed out by Chamberlin,† organic matter has made its way into the

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* Compare Chamberlin, *op. cit.*, pp. 551–553.

† Chamberlin, *op. cit.*, p. 544.

opening of the limestone, and as further indicated by Chamberlin,[*] and emphasized by Blake,[†] organic matter is abundant in certain of the shaly layers. As argued by Chamberlin and Blake, organic material in the rocks from both of these sources was probably an important factor in the reduction and precipitation of the downward moving sulphates. As pointed out by Blake, the evidence of the effect of this organic matter is especially clear in the cases of the large sphalerite deposits which rest upon the oil-rock at the top of the Trenton as a floor.

My own views in reference to the concentration of the ores in the upper Mississippi valley differ somewhat from those of Chamberlin,[‡] Whitney,[§] and others, who have held that these ores are products of descending and lateral-secreting waters alone; but still more from those of Percival[||] and Jenny,[¶] who have held that the ores were derived from a deep-seated source. This first supposed the transportation to have taken place through igneous, the second through aqueous agencies. Since the discussion of this difference of view involves the influence of some of the special factors considered later, it is deferred to pp. 116–124.

Therefore, so far as practicable, the above statement concerning concentrations by ascending and descending waters and the reactions of the sulphates upon the sulphides is made without reference to the special features of the upper Mississippi valley district. This procedure has been followed because it is believed that in many of the lead and zinc districts of the world the above statement is applicable in its main features.

THE ASSOCIATION OF COPPER AND IRON COMPOUNDS.

Another very general association of metals is that of copper and iron. It is well known, where this association occurs, that

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[*] Chamberlin, *op. cit.*, p. 546.

[†] "Lead and Zinc Deposits of the Mississippi Valley," by Wm. P. Blake, *Trans. A. I. M. E.*, xxii., pp. 630–631. "Wisconsin Lead and Zinc Deposits," by Wm. P. Blake, *Bull. G. S. A.*, vol. v., 1894, pp. 28–29.

[‡] Chamberlin, *op. cit.*, pp. 544–549.

[§] Whitney, "Geol. of Wis.," vol. i., 1862, pp. 398, *et seq.*

[||] Percival, "First Ann. Rept. Geol. Surv. of Wis.," 1854, pp. 30–33; "Ann. Rept. Geol. Surv. of Wis.," 1856, p. 63.

[¶] Jenny, "Lead and Zinc Deposits of the Mississippi Valley," *Trans. Am. Inst. Min. Eng.*, vol. xxii., 1894, pp. 219–223.

above the level of groundwater, cuprite (Cu_2O), tenorite (CuO), azurite ($CuCO_3Cu(OH)_2$) and malachite ($CuCO_3$, $Cu(OH)_2$) are very frequently found. It is further very well known that below the level of groundwater these oxidized and carbonated products occur in greatly diminished quantity, and that rich sulphurets frequently occur, such as chalcocite (Cu_2S), bornite (Cu_3FeS_3) and chalcopyrite ($CuFeS_2$), and sometimes covellite (CuS). Somewhat deeper below the level of groundwater the oxides and carbonates are not found. Furthermore, the chalcocite, covellite and bornite are very generally restricted to the upper part of the belt of groundwater; deeper, the places of these minerals are largely occupied by chalcopyrite. Not only this, but still deeper the chalcopyrite is less prominent in many instances, and the iron sulphides more prominent. In the lower workings of many of the deeper mines the only metalliferous product found is cupriferous iron sulphides, the chalcopyrite having wholly disappeared.

Whether or not this general statement is correct for a particular area, each mining engineer can judge from his own knowledge. There may be exceptions to it, due to various causes, one of which has been alluded to in explaining bonanzas. Thus below cupriferous pyrites there may again be found richer copper sulphides. Indeed, as before stated, ore-deposits vary greatly in their richness both horizontally and vertically,* and the above statement can only be considered as a general average.

The above order is believed to be explained by the work of downward-moving waters. The combinations of lead, zinc and iron were followed from above downward. The reactions which occur in the case of the copper-iron deposits we may perhaps follow, to vary the order, from the base upward. At greater or less depths below the level of groundwater the ores are frequently cupriferous pyrites, the direct deposit of the ascending waters. At a little higher level oxygen from above may have oxidized a portion of the iron and transported it elsewhere, thus relatively enriching the deposit in copper. At a still higher level there will be a contribution of soluble copper salts from above. Since copper sulphate would certainly be the

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* *Trans.*, xxiv., 991–992.

most common salt, for convenience all the soluble salts will be regarded as sulphates. Reactions similar to those given below may easily be written for other salts.

At the level where salts of copper appear from above, by the reaction of the copper salt upon iron sulphide, chalcopyrite may be produced, the reactions following from the fact that copper-iron sulphides are less soluble than iron sulphides, and from the law of mass action. The reactions may be written as follows:

$$CuSO_4 + 2FeS = CuFeS_2 + FeSO_4,$$

or

$$CuSO_4 + 2FeS_2 + O_4 = CuFeS_2 + FeSO_4 + 2SO_2.$$

Where the iron sulphide is pyrrhotite, intermediate between FeS and FeS_2, the reactions may be written by combining the above equations in proper proportions.

In passing upward from the lowest level at which the chalcopyrite appears, this mineral may steadily increase in quantity until it becomes an important constituent, and finally the iron sulphide may become subordinate. Under these circumstances bornite is likely also to appear. The production of bornite by the direct reactions of the copper salts upon iron sulphide may be supposed to be as follows:

$$Cu_2SO_4 + CuSO_4 + 3FeS = Cu_3FeS_3 + 2FeSO_4,$$

or

$$Cu_2SO_4 + CuSO_4 + 3FeS_2 + 6O = Cu_3FeS_3 + \\ 2FeSO_4 + 3SO_2.$$

However, the bornite may also be produced by the reaction of the copper salt upon the chalcopyrite itself. For instance:

$$2CuFeS_2 + CuSO_4 + O_2 = Cu_3FeS_3 + FeSO_4 + SO_2.$$

Reactions might also be written for the production of the bornite from the chalcopyrite by the reaction of cuprous sulphate and oxygen. Further reactions might be written as result of which the bornite is derived from chalcopyrite and iron sulphide together; but it is hardly worth while to do this, since no new principle is illustrated.

Passing to still higher levels, with the chalcopyrite and bornite chalcocite may appear. The chalcocite may be produced directly by the reaction of cuprous salt upon iron sulphide, as follows:

$$Cu_2SO_4 + FeS = Cu_2S + FeSO_4,$$

or

$$Cu_2SO_4 + FeS_2 + O_2 = Cu_2S + FeSO_4 + SO_2.$$

Furthermore, the chalcocite may be produced by reactions of the sulphates either upon the chalcopyrite or upon the bornite. In the first case the reaction may be written as follows:

$$CuFeS_2 + CuSO_4 + O_2 = Cu_2S + FeSO_4 + SO_2,$$

or from the bornite by the following reaction:

$$Cu_3FeS_3 + CuSO_4 + O_2 = 2Cu_2S + FeSO_4 + SO_2.$$

Of course, it is understood that these sulphides overlap one another. Before the iron sulphide has wholly been replaced by chalcopyrite, bornite may appear. At the place where bornite has become reasonably abundant, chalcocite may be found. However, certain general statements may be made. If the dominating material is iron sulphide, the copper mineral which is present is likely to be chalcopyrite rather than the richer sulphurets. Chalcopyrite, on the one hand, is likely to be associated with the pyrites, and on the other hand with bornite, or even chalcocite. Bornite and chalcocite are likely to be associated with each other and with chalcopyrite, but with the first two compounds iron sulphide is likely to be subordinate or absent.

At still higher levels in a mine, a moderate distance below the level of groundwater, oxidized and carbonated products may appear with the sulphurets. These mixed products, sometimes called oxysulphurets, are well illustrated in the Appalachian, Arizona and Montana deposits.* Still higher, and especially above the level of groundwater, the oxidized products may become dominant, for there the rich sulphurets which have emerged from the level of groundwater have been directly acted upon by the oxygen and carbon-dioxide. A

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* "The Copper Resources of the United States," by James Douglas, *Trans.*, xix., 1891, 690, *et seq.*

series of transformations now take place which may result in metallic copper, cuprite, tenorite, azurite and malachite. As in the case of the lead and iron, the nature of these reactions is so well known that they will not here be written out. The oxidation of the sulphur and copper may be simultaneous, or the sulphur may be oxidized first, forming metallic copper, which may later be oxidized in whole or in part. The oxidized products may be first the oxide, cuprite. This may be altered to tenorite, and this, later, may unite with carbon-dioxide and water to form the hydro-carbonates, azurite, and finally, by further hydration, malachite. Illustrating this process, Prof. Penrose has shown me, in a single hand-specimen from the oxidized belt of the Arizona mines, concentrically arranged metallic copper, cuprite, tenorite, and carbonate of copper, the copper being in the core and the carbonate of copper on the outside. The oxidized products may largely remain in place, furnishing rich ores, or they may be almost wholly dissolved and carried to lower levels, to react upon the sulphides, as already explained.

Therefore, largely by processes of oxidation and reaction upon sulphurets, first forming rich sulphurets and later rich oxidized products, there may be concentrated in the upper few, or few score, or few hundred meters of a vein, a large part of the copper produced by a first concentration through a much greater distance. Since the reactions already considered are not the only ones which enter into the second concentration of rich deposits, individual illustrative cases are deferred until after the other factors are considered. (See pp. 102–108.)

By the foregoing it is not meant to imply that each copper sulphide deposit has gone through the entire history above detailed. Indeed, there is no doubt that the general story outlined will need much modification when applied to an individual case. However, it is held that some process of secondary concentration similar to that outlined has been a very important factor in the production of rich copper deposits at many localities.

THE ASSOCIATION OF SILVER AND GOLD WITH THE BASE METALS.

The two common cases of the association of lead, zinc and iron, and that of the association of copper and iron, have now been considered. A similar set of transformations can be traced out in either of these classes of deposits which contain associated silver and gold.

Silver.

In the case of silver, it is well known that the original forms are generally sulphides, sulphantimonites, sulphantiminates, sulpharsenites, and sulpharsenates. Silver is one of the compounds which holds strenuously to its sulphur. Ordinarily it is not sufficiently abundant to constitute the main mass of an ore-deposit. However, since it holds so strongly to its sulphur, the silver salts are likely to be found, in the case of lead-zinc-iron compounds, most abundantly with the lead, less abundantly with the zinc, and least abundantly with the iron; and in the case of the copper-iron compounds, most abundantly with the copper and less abundantly with the iron. The rich silver compounds, viz., native silver, cerargyrite ($AgCl$), argentite (Ag_2S), proustite (Ag_3AsS_3), pyrargyrite (Ag_3SbS_3), stephanite (Ag_5SbS_3), may be abundantly found in the upper parts of mines, but frequently decrease in amounts in passing from the surface deep into the zone of sulphides, and at sufficient depth in this zone these silver minerals may entirely disappear, the products being wholly argentiferous lead, zinc, copper, and iron minerals. In many cases independent silver minerals do not occur at all, all of the silver being in the lead, zinc, copper, and iron compounds. In the case of the lead, zinc, and iron deposits, as the ores become poorer in lead and zinc, they are also likely to become poorer in silver. Also, in case the copper-iron deposits become poorer in copper with depth, the silver will also ordinarily decrease in amount. Therefore the plumbiferous and zinciferous pyrites and cupriferous pyrites deep down are ordinarily lower in silver than the deposits above, which are richer in the base metals.

In this general paper it is hardly worth while to write the reactions for the production of the rich silver sulphurets. Since silver holds to its sulphur more strenuously than any of the base metals with which it is associated, the first of these baser metals which is met in mass will be reacted upon by the silver salts. Suppose, for instance, that in the belt of weathering the silver sulphide is oxidized to silver sulphate or changed to silver chloride. The first of the salts and the second to some extent are taken into solution and pass down where they may come in contact with chalcocite. Argentite would then be precipitated according to the following reactions:

$$Cu_2S + Ag_2SO_4 = Ag_2S + Cu_2SO_4.$$
$$Cu_2S + 2AgCl = Ag_2S + 2CuCl.$$

In a manner similar to the treatment of the other salts, various other reactions could be written between salts of silver and the other sulphides of copper, lead, zinc and iron. For the present purposes, it is only necessary to understand that the silver will be concentrated either as an independent silver sulphuret or as a silver sulphide associated with the rich sulphides of the base metals.

As a case in which silver is concentrated in a sulphide rather than in the carbonate, may be mentioned the Leadville ores. Here, according to Emmons, the galena is much richer in silver than the cerussite. Not only is this so in general, but there are some very interesting special cases. For instance, in the case of five assays of galena nodules which had carbonate crusts, "there are six times as much silver in the galena as in the cerussite."* This discrepancy may be partly explained by the abstraction of the silver as sulphate from the lead carbonate, but I suspect it to be mainly explained by the reaction of the oxidized silver salts upon the galena, producing a galena richer in silver than originally existed.

Above the level of groundwater the silver occurs to some extent in the native form, but more largely as cerargyrite. Silver does not readily unite with oxygen, hence the explanation of the metallic form. However, it does have a strong affinity for chlorine, and where that element is present cerargyrite is likely to be found.

Where the silver is largely changed to the sulphate and chloride, and is not largely precipitated as cerargyrite, the upper part of the silver veins in the belt of weathering may be greatly depleted in silver as a result of this leaching process. That the silver is not thrown down as cerargyrite may be due to a

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* "Geology and Mining Industry of Leadville," by S. F. Emmons, Mon. xii., *U. S. Geol. Surv.*, 1886, pp. 553–554.

deficiency of chlorine in the descending solutions, or to the fact that the solutions are of such a character or so abundant that they are capable of dissolving the silver chloride. Probably illustrating this process of depletion is the Cripple Creek district, where the upper parts of the veins which carry free gold are deficient in silver, while the original telluride contains a certain amount of silver, showing that the silver has probably been leached out.*

Gold.

Gold occurs extensively (1) in the native form, (2) associated with the sulphides, and (3) as a telluride.

In the belt of weathering, gold is very largely found in the metallic form associated with the oxidized products of the base metals, and especially with oxide of iron. Much of such gold has plainly been associated with sulphides or has been united with tellurium.

Below the level of groundwater the most common associations of gold are the sulphides of the base metals. Where base metals other than iron do not occur, gold occurs associated on a great scale with pyrite. In such associations, where the sulphides are abundant, the gold is likely to be plentiful; where the sulphides are deficient, the gold is also likely to be deficient.† This relation is illustrated both by California and Australasia. The relation suggests that the original solution and deposition of native gold is frequently connected with that of the sulphides, and therefore it is reasonable to infer that the same conditions which produced sulphides also resulted in the solution and precipitation of gold.

In various districts in the Cordilleran region, and especially in Colorado, and more particularly in the Cripple Creek district, the original form in which much of the gold was deposited is a telluride.‡

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* "Mining Geology of the Cripple Creek District," by R. A. F. Penrose, Jr., 16*th Ann. Rept. U. S. Geol. Surv.*, pt. ii., 1894–95, pp. 131–132.

† "The Gold-Quartz Veins of Nevada City and Grass Valley, California," by Waldemar Lindgren, 17*th Ann. Rept. U. S. Geol. Surv.*, pt. ii., 1895–96, pp. 124–126. "The Genesis of Certain Auriferous Lodes," by J. R. Don, *Trans.*, xxvii., 1898, 567.

‡ "Mining Geology of the Cripple Creek District," by R. A. F. Penrose, Jr., 16*th Ann. Rept. U. S. Geol. Surv.*, pt. ii., 1894–95, pp. 119–121.

The original form of the gold of the Judith mountains* is also a telluride. Telluride of gold further occurs in the gold-belt of California,† in the mines of Custer county, Colorado,‡ and in western Australia, associated with sulphides. Pearce§ suggests|| that the free gold which occurs in various regions may have been originally deposited as a telluride which was later oxidized in the belt of weathering. The Cripple Creek district, in which the gold in the weathered zone is in the metallic form,¶ furnishes an excellent illustration of the formation of free gold from a telluride.

From the foregoing it is plain that gold may be originally precipitated by ascending solutions in a vein as metallic gold, as a telluride, or partly in both forms. Moreover, either one or both of these forms may be associated with the sulphides of the base metals.

Nothing has thus far been said as to the form in which the gold is transported. However, it is certain that gold is soluble in the various underground solutions, and especially in the alkaline sulphides. Moreover, gold readily makes combinations with iodine and chlorine, and as an iodide and chloride is easily soluble. Also alkaline iodides are capable of dissolving gold.** Furthermore, gold is soluble in ferric sulphate. That gold and the salts of gold—one of which we know to exist in nature as a solid, the telluride—are soluble in underground solutions is the main point. Since the modern ideas of physical chemistry have been developed, the form in which the gold is carried is put in a new light. It was supposed that it must be regarded as united with one or more of the other ions present. Since underground solutions of gold are exceedingly dilute, it is highly probable that the gold is ionized or is

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* "Geology and Mineral Resources of the Judith Mountains of Montana," by W. H. Weed and L. V. Pirsson, *18th Ann. Rept. U. S. Geol. Surv.*, pt. iii., 1896–97, pp. 589, 591, 597.

† Lindgren, *op. cit.*, p. 117.

‡ "The Mines of Custer County, Colorado," by S. F. Emmons, *17th Ann. Rept. U. S. Geol. Surv.*, pt. ii., 1895–96, p. 433.

§ "The Superficial Alteration of Western Australian Ore-Deposits," by H. C. Hoover, *Trans.*, xxviii., 1899, 762.

|| *Proc. Colo. Sci. Soc.*, vol. ii., 1885, pp. 1–6.

¶ Penrose, *op. cit.*, p. 119–120.

** "The Origin of the Gold-bearing Quartz of Bendigo Reefs, Australia," by T. A. Rickard, *Trans.*, xxii., 1893, pp. 308–309.

in the free state. Thus regarded, it would be kept in the ionic state not by any one of the associated acid ions present, but partly by all of them. While the above is true, it is also doubtless true that certain solutions are much more capable of dissolving gold and gold salts than others, and upon this point further investigation is needed.

In whatever form gold is carried, it is known to be precipitated in the first concentration as a telluride, or as metallic gold associated with tellurides or sulphides, or both. Whether it is also precipitated as a sulphide is uncertain. Too little is known about the tellurium salts or the origin of the tellurides to enable one to make any statement concerning the precipitation of gold in this form. However, it is comparatively easy to suggest agencies which may have resulted in the precipitation of gold in the metallic form. When it is remembered that copper is extensively precipitated in the metallic form in the Lake Superior region, and that gold is even more readily reducible, the frequent precipitation of gold in the metallic form need occasion no surprise. Gold would be precipitated in the metallic form by organic matter or by any *ous* salt.

Rickard[*] calls attention to the frequent association of metallic gold with sedimentary rocks bearing organic matter in Colorado, California, New Zealand, Australia and Tasmania.[†] The most remarkable case is the concentration of gold in veins where they cross strata of carbonaceous shale, called indicators. Says Don,[‡] "Away from the indicator, the greater part of the vein quartz is absolutely barren; but at the intersection with the indicator larger masses of gold (often more than 100 ounces in one piece) have been obtained, and the greater part of the gold extracted from this belt has come from those parts of the quartz veins near some one of the indicators." Furthermore, Rickard[§] describes experiments in which the black carbonaceous shale of Rico was placed in silver solutions and in solutions containing Cripple Creek gold-ore.

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[*] *Trans.*, xxii., 314–315.

[†] "The Indicator Veins of Ballarat, Australia," by T. A. Rickard, *Eng. and Min. Journ.*, vol. lx., 1895, pp. 561–562.

[‡] "The Genesis of Certain Auriferous Lodes," by J. R. Don, *Trans.*, xxvii., 1898, p. 569.

[§] "The Enterprise Mine, Col.," by T. A. Rickard, *Trans.*, xxvi., 1897, pp. 978–979.

Both metallic silver and gold were abundantly precipitated upon the shale in a short time. In the instances above mentioned it can hardly be doubted that the organic material was an important or controlling factor in the reduction and precipitation of the gold.

Gold would also be precipitated from solutions which came in contact with ferrous oxide, such as magnetite, or by solutions bearing ferrous or cuprous sulphate, or any other ferrous or cuprous salts. When it is remembered that *ous* salts are extensively produced underground (see pp. 67–68), it becomes highly probable that such solutions are frequently the cause of the precipitation of gold with sulphurets. Since iron is the most abundant of all the metals carried in underground solutions, such sulphates would be more likely to be sulphates of iron than any other. If the salts formed in the belt of weathering were ferric sulphates, they would be likely to be reduced to the ferrous condition at depth by the ferrous iron, which is especially abundant in the basic rocks. Indeed, analyses of mineral waters which bear sulphates also ordinarily show ferrous iron.* Therefore ascending waters bearing ferrous sulphate or other *ous* salt might be brought into a lode by side-streams and there precipitate the gold. Such side-channels entering through lateral cracks may, in many cases, explain the extreme irregularity of the distribution of the gold.

Although Lindgren argues to the contrary in the Sierra Nevada,† the suggestion that a part of the gold there has been reduced by ferrous sulphate has extreme plausibility. The gold associated with the pyrites is native. In that district two analyses of the waters of feeding-streams (the only analyses reported) entering the lodes at a depth of 400 feet are given. Both of these analyses show that sulphates and iron are present.‡ According to the analyses the iron is reported as ferric; but apparently no precautions were taken, when the waters were collected, to prevent the oxidation of ferrous to ferric iron. Indeed, the description of the deposits made by the underground springs renders it highly probable that ferrous salts were there contained,

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* "Mineral Waters of the United States," by A. C. Peale, *Bull. U. S. Geol. Surv.*, No. 32.

† Lindgren, *op. cit.*, p. 181, and pl. v., p. 134.

‡ Lindgren, *op. cit.*, pp. 121–123.

as shown by the precipitates of yellow material, which is partly ferric oxide. Moreover, if these analyses are not sufficient evidence of the presence of sulphates, the clean vein quartz itself, which contains a large number of fluid inclusions, contains sulphates,* showing that sulphate-bearing waters are not exceptional, but must have been present at the time the lodes themselves were formed. Finally, the ore-shoots have great irregularities in richness, for which Lindgren offers no explanation. The suggestion above made that the gold is precipitated in the metallic form by the reducing action of ferrous sulphate explains all of these facts. The deposits are rich where the side-springs issued from cross-fissures and furnished ferrous sulphate to the ascending waters. The gold is in the metallic form because reduced by the ferrous sulphate.

The argyllite with which many of the gold-ores of the Sierra Nevada are associated is carbonaceous,† and this carbonaceous material may have assisted in the production of the *ous* salts which ultimately reached the trunk-channels. Indeed, in some places, as, for instance, where the pyrite occurs in a carbonaceous argyllite but not in quartz,‡ the gold may have been directly precipitated by the carbonaceous material. But since the gold in the Sierra Nevada is mainly deposited in open fissures,§ the suggestion of reduction of the major portion of the gold by *ous* salts, and especially ferrous sulphate, is thought to be the more plausible, although, as already explained, the formation of the ferrous sulphate may be due in part to carbonaceous material in the country-rock.

It can hardly be doubted that after a first concentration of gold has taken place, that as consequence of descending waters a second concentration may take place. But definite equations cannot be written until it is determined in what form the gold is transported. However, if in the solutions we do not know the acids against which the gold is balanced when transported downward, we may feel sure that when such solutions reach the sulphide zone that there will be reactions between the acid

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* Lindgren, *op. cit.*, pp. 130–131, 260, 261.

† "The Gold-Quartz Veins of Nevada City and Grass Valley, California," by Waldemar Lindgren, *17th Ann. Rept. U. S. Geol. Surv.*, 1895–96, pt. ii., p. 81, 1896.

‡ Lindgren, *op. cit.*, p. 140, pl. viii.

§ Lindgren, *op. cit.*, p. 259.

ions balancing the gold and the bases in the tellurides and sulphides. As a consequence of these reactions metallic gold, and possibly tellurides and sulphides, will be precipitated in a manner similar to that of the precipitation of copper. Individual cases of second concentrations will be considered after other factors influencing concentration have also been dealt with. (See pp. 102–108.)

CONCENTRATION BY REACTION UPON SULPHIDES COMPARED WITH METALLURGICAL CONCENTRATION.

One of the more common processes of metallurgy for the separation of gold, silver, copper and lead from iron is based upon the principle explaining the second concentration given on preceding pages, viz., that iron holds sulphur less strongly than the other elements named. The sulphuretted ores are imperfectly roasted, thus partly oxidizing them to oxides and sulphates. The ores are then smelted in a furnace with a flux. The oxides of the valuable metals and the sulphates react upon the remaining sulphides of all the metals, producing a matte containing the sulphides of the valuable metals. The iron gets all or nearly all of the oxygen; and the iron oxide unites with the fluxes and passes into the slag.

OTHER REACTIONS OF DESCENDING WATERS.

In the foregoing pages the second concentration of metals by solution, downward transportation and precipitation by reactions upon the sulphides of the first concentration has been emphasized. However, it is not supposed that this is the only process which may result in enrichment in the upper parts of vein 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 descending waters carrying metallic material dissolved in the upper part of the veins may be precipitated by material contained in the rocks below. This material may be organic matter, ferrous salts, etc. So far as precipitating materials are reducing agents, they are likely to change the sul-

phates to sulphides and precipitate the metals in that form. While sulphides may thus be precipitated either above or below the level of groundwater, they are more likely to be thrown down below the level of groundwater. Other compounds than reducing agents 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 current 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 variations in ascending currents result 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. The waters from above in the neutral zone of circulation 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 an accelerated 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, but the dilution would work in the reverse direction.

The metals precipitated by the mingling of 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.

The above methods of 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 second concentration resulting from an actual downward transportation of the material of the first concentration. *It is believed that the downward transportation of metals is the most important of the causes explaining the character of the upper portions of lodes* (see pp. 74–76)*; but whether this be so or not, their peculiar characters are certainly due to the effect of descending waters.*

SECOND CONCENTRATION FAVORED BY LARGE OPENINGS OF THE BELT OF WEATHERING.

The concentration of large ore-bodies in the belt of weathering is greatly favored by the abundance and size of the openings as compared with the openings existing at greater depths.

The openness of the rocks above the level of groundwater and the comparative lack of openings below the level of groundwater have already been alluded to as general phenomena, and

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* Compare Le Conte, *Am. Journ. Sci.*, iii., vol. xxvi., p. 9.

† Le Conte, *op. cit.*, p. 12.

an explanation offered for their existence, viz., that in the belt of weathering, solution is the law, and in the belt of cementation, deposition is the law. (See pp. 46–48.) Of course, it is understood that there is usually not a sudden change in the amount of opening space, but that the extremely open upper ground grades into the much less open lower ground at and below the level of groundwater. In some instances the gradation requires some distance. This openness of the belt of weathering and the comparative closeness of the belt of cementation is well illustrated by many limestone regions; for instance, the lead and zinc district of southwestern Wisconsin, already described, pp. 77–83, 116–124. It is also well illustrated by the Leadville district of Colorado, where, Emmons says, "There is a noticeable absence in the region of greatest ore-development of channels extending downward."* Thus, so far as the openings are concerned, the conditions for the formation of large ore-deposit are more favorable above the level of groundwater, and as far below the level of groundwater as openings are numerous, than at deeper levels.

The existence of numerous and large openings below the level of groundwater may be explained in individual cases in a number of ways. Of course, the more recent the earth-movements, the more numerous and larger are the openings. In some places the descending waters are not saturated when they reach the level of groundwater, and solution continues for some distance below that level. Furthermore, the level of groundwater varies under different circumstances. Where a region is being uplifted, the level of groundwater, other things being equal, will be descending. Where a region is subsiding, the level of groundwater will be rising. As a result of physiographic changes, there may be alternate valley filling and valley erosion. These changes affect the level of groundwater. In Pleistocene time there was an extensive period of valley filling instead of erosion. Consequent on this, the level of drainage, and therefore the level of groundwater, rose. Also there may be very considerable variations of the level of groundwater, as a consequence of long-con-

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* "The Geology and Mining Industry of Leadville," by S. F. Emmons, *Mon. U. S. Geol. Surv.*, No. 12, 1886, p. 573.

tinued climatic changes; such, for instance, as the alternating periods of humidity and aridity in the Cordilleras of the West in connection with the Pleistocene.* The annual variations in rainfall cause a less-marked change in the position of the level of groundwater. All these changes favor alternate solution and deposition; solution when the water falls, precipitation when it rises. Where the underground water has been at a low level, this will be favorable to the production of large openings. Where, later, for some reason, the level of groundwater rises, these openings are in a very favorable condition to be filled with ore, as a result of the reactions of the descending solutions on the ores below and of the mingling of ascending and descending waters.

It might be argued that the existence of ore-deposits in the large openings near the surface is evidence that the ores were not first deposited by ascending waters. However, as has been already explained, in the large openings there may be concentrated mineral material originally distributed by ascending waters through a much greater vertical distance. Thus, a very rich ore-deposit, formed by the reaction of descending waters upon a first concentration produced by ascending waters, might be bounded below by a horizon in which the ground is very close, the comparatively small openings which once existed having been cemented by the material deposited during the first concentration by the ascending water.

DEPTH OF THE EFFECT OF DESCENDING WATERS.

For the depth to which downward-percolating waters produce an effect there can be no doubt of their importance in the production of ore-deposits. The only question which remains open is the depth to which this process is effective. This varies greatly in different districts, and in different mines of the same district. In general, the effect is likely to be deep-seated in proportion as the lode worked is on high ground (see pp. 135–136). Also, in arid regions the level of groundwater is deeper below the surface than in humid regions. Moreover, the process of denudation is slower, so that the downward-moving wa-

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* "Lake Bonneville," by G. K. Gilbert, *Mon. U. S. Geol. Surv.*, No. 1, 1890. "Geological History of the Lake Lahontan, a Quaternary Lake of Southwestern Nevada," by I. S. Russell, *Mon. U. S. Geol. Surv.*, No. 11, 1885.

ters have both a wider zone in which to work above the level of groundwater and a longer time in which to work upon a given horizon, and thus in such regions the oxides and carbonates are likely to occupy a considerable zone. This is very well illustrated by the copper-mines of Arizona and New Mexico, and by the colorados of the silver-gold deposits in various arid regions. In humid regions, upon the other hand, the level of groundwater is likely to be near the surface. If this be combined with marked relief so that denudation is rapid, the processes of oxidation and carbonation may not be nearly so complete above the level of groundwater. Indeed, in many cases erosion may be so rapid that the sulphurets do not have time for oxidation, and they may extend nearly or quite to the surface, although in such cases they are likely to be enriched, as explained (pp. 73–76), and it is very uncommon to find a deposit in which no effect of descending waters can be discovered.

It has already been seen that the level of groundwater may vary from the surface to 300 meters or more below the surface. Hence it is certain that, from the surface to 300 meters below the surface, the underground waters may be a potent factor in the production of the rich ore-deposits. The deposits in this belt are particularly profitable, not only because of the accessibility of the material, but because of the fact that there is no expense for pumping; and furthermore, the products are in forms which in most cases are easily reducible. This may be illustrated by the gold and silver deposits. In the former, the native gold is free from its entanglement of sulphurets and tellurides; in the latter the silver is largely in the form of the readily extracted chloride, or in some instances as native silver.

Up to this point there will be no disagreement on the part of any one. But the question now arises as to the depths below the level of groundwater to which descending waters produce their effects. This is a question to be answered not by deduction, but by observation. Even Posepny, who emphasizes the effect of ascending waters, agrees that oxidized products are the evidence of the work of vadose circulation, or the circulation of lateral and downward-moving waters. Furthermore, Posepny*

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* "Genesis of Ore-Deposits," by F. Posepny (Discussion), *Trans.*, xxiv., 1894, p. 967.

agrees that the iron-mines of the Lake Superior region, which are oxidized products, have been produced by downward-moving waters. A number of these mines have been worked to a depth of 500 or more meters below the level of groundwater. It is, therefore, perfectly clear in these cases that the downward-percolating waters produce an oxidizing effect to a depth of at least 500 meters below the level of groundwater. And this is so in a region in which the level of groundwater is relatively near the land surface, and which is not mountainous. In various other regions oxidized products are also found to a very considerable depth below the level of the groundwater.

In the San Juan district of Colorado, in the Gold King mine, at a vertical depth of more than 300 meters, "the ore taken out is characterized by decomposition, being stained by iron oxide, and showing almost no metallic sulphides."* The author does not state how far this is below the level of groundwater, but merely says that the water-level is deep. Many other veins contain sulphurets, which extend nearly to the surface. In the Cripple Creek district of Colorado and the Judith mountains of Montana—humid areas—oxidized products are found to a depth of 125 meters. The workings at the time when Penrose, Weed and Pirsson† examined the districts had not extended beyond this depth; and therefore we have no knowledge as to the depth at which the last of the oxidized products will be found, or as to the depth to which the sulphides and tellurides have been reacted upon and enriched by the downward-moving solutions from above. This belt of enriched material may be of even greater depth than that of the oxidized products.

As has already been shown (pp. 75–90), where the ores are predominantly lean sulphides in the lower workings of the mines, these react upon the downward-moving oxidized salts of the valuable metals, and thus produce rich sulphurets. It is, therefore, clear that descending waters produce enrichment below the level at which oxidized products are found.

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* "Preliminary Report on the Mining Industries of the Telluride Quadrangle, Colorado," by C. W. Purington, 18*th Ann. Rept. U. S. Geol. Surv.*, pt. iii., 1896–97, pp. 825–826.

† "Mining Geology of the Cripple Creek District," by R. A. F. Penrose, Jr., 16*th Ann. Rept. U. S. Geol. Surv.*, pt. ii., 1894–95, p. 129. "Geology and Mineral Resources of the Judith Mountains of Montana," by W. H. Weed and L. V. Pirsson, 18*th Ann. Rept. U. S. Geol. Surv.*, pt. iii., 1896–97, p. 592.

Our conclusion is, *that we have positive evidence that the belt in which descending waters are effective in producing rich secondary concentrates, as explained on pp.* 73–97, *extends to very considerable depths.*

ILLUSTRATIONS OF SECONDARY ENRICHMENT AND DIMINUTION OF RICHNESS WITH DEPTH.

The processes have now been explained by means of which a rich upper belt may be produced. If the argument be correct, it is an inference from this that ore-deposits which have undergone a second concentration are likely to diminish in richness with depth, provided a considerable belt be considered. It remains to give instances, the facts of which confirm the actuality of the processes explained, and illustrate diminution of richness with depth.

At Ducktown, Tenn., at the level of groundwater a belt of rich black copper (copper-glance) appears, which varies from less than one to about two and one-half meters in thickness. Above this belt is gossan very poor in copper, below it is a very low grade cupriferous pyrrhotite.* In this instance it can hardly be doubted that originally the lean cupriferous pyrrhotite extended not only to the present surface, but probably much higher than this. The downward moving waters have transported copper to its present locus near the level of groundwater. Here the copper salts have reacted upon the iron sulphide and produced rich sulphurets.

A case which has been, perhaps, more closely studied than that of any other in the United States is that of the deposits of Butte, Montana. Here Douglas states that rich oxysulphurets are found near the surface. These rich oxysulphurets occur in greatest depths and richness on the summit of the hill, "where it seems as if the copper, leached out of the 400 feet of depleted vein, had been concentrated in the underlying ore, and had thus produced a zone of secondary ore about 200 deep, which contains, as might be expected, about thrice its normal copper-content."†

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* "The Persistence of Lodes in Depth," by W. P. Blake. *Eng. and Min. Jour.*, vol. lv., 1893, p. 3. Also, "The Ducktown Ore-deposits and the Treatment of the Ducktown Copper-ore," by C. Henrich, *Trans.*, xxv., 1896, 206–209.

† "The Copper Resources of the United States," by Jas. Douglas, *Trans.*, xix., 1891, p. 693.

Emmons says of the Butte deposits:*

> "Secondary deposition, or transposition of already deposited minerals, has played an unusually important role. In the case of the copper veins it has not been confined to the oxidizing action of surface waters, which has resulted in an impoverishment of the ore-bodies, but below the zone of oxidation it has resulted in the formation of the richer copper minerals bornite, chalcocite and covellite, in part at least by the breaking up of the original chalcopyrite. Unusual enrichment of the middle depths of the lodes has thus been caused. Whether the two processes of impoverishment and enrichment have been differing phases of the action of descending waters, or whether the latter may have been a later result of the rhyolite intrusion, has not yet been definitely decided. It is, however, fairly well determined that the enrichment of the copper deposits is so closely associated with the secondary faulting that it may be considered to be a genetic result of it."

Brown states of the same area that oxidized products extend to the level of groundwater. These oxidized products, according to Brown, promptly change at water level in normal sulphurets. "There follows below a region of varying height, of valuable rock, which again slowly deteriorates in depth; this deterioration, however, being so retarded finally as to be scarcely appreciable."† He further says that above the level of groundwater is gossan "carrying high values in silver, and particularly in gold."‡ Thus at Butte we have in the belt above the level of groundwater enrichment in silver and gold and depletion in copper as compared with the material below the level of groundwater; and at and below the level of groundwater we have rich sulphide of copper which grade into leaner sulphurets. In the case of the Butte deposits it can hardly be doubted that the comparatively lean sulphides in the deeper workings represent the product of a first concentration, and that the modifications of this material found above and below the level of groundwater represent the work of downward moving waters. To account for the high values of gold and silver above the level of groundwater, one must suppose that this belt has received contributions of these metals from the upward extension of the veins which have now been removed by erosion. The great richness of the copper below the level of groundwater Douglas clearly attributes to the downward

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* "Economic Geology of the Butte District," by S. F. Emmons, *Geol. Atlas of the U. S.*, Butte special folio, Montana, 1897.

† "The Ore-deposits of Butte City," by R. C. Brown, *Trans.*, xxiv., 1895, p. 556.

‡ Brown, *loc. cit.*, p. 555.

transportation of the material from the depleted copper veins. However, a part of this material was doubtless derived from an upward extension of these veins precisely as in the case of the gold and silver. For my own part I have little doubt that the precipitation of the rich sulphides was produced by reaction upon the lean sulphurets, as given in the equations pp. 75, 85–86. Indeed, these equations were written out with reference to the facts of the Butte deposits.

Penrose cites the Arizona copper deposits as instances of secondary concentration. These deposits he regards as produced by leaching of the copper from a lean copper-bearing pyrite, and its segregation at the places where the rich ores occur. In this process Penrose, however, says that the volume of the deposit must be decreased; but he makes the point that the smaller amount of the rich product is more valuable than a larger lean deposit, because more easily mined and more readily reduced.*

This process of concentration is further described by Douglas, who notes, also, that the changes have resulted in the production of enriched sulphides from very lean sulphides in the Copper Queen mine. Here, according to Douglas, a large very low-grade copper-bearing pyrite deposit running from the 200- to the 400-foot level contains rich oxysulphides and black sulphides on the outside, and in the interior is mainly lean pyrite.†

The original material in the Arizona locality is as plainly a lean cupriferous pyrites as in Tennessee. Here, however, on account of the peculiar climatic conditions the alterations have not extended to a uniform depth. Instead of the rich belt being a sheet which diminishes in richness below, it occurs in a zone about the entire residual cupriferous pyrites masses. The principles of concentration are, however, identical, and the rich sulphurets are unquestionably due to reactions between the oxidized salts and the lean sulphides. The rich oxidized products of this area, doubtless, were produced directly from the enriched sulphurets. Therefore, in the formation of the rich oxidized

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* "The Superficial Alteration of Ore-deposits," by R. A. F. Penrose, *Jour. of Geol.*, vol. ii., 1894, pp. 306–308.

† "The Copper Queen Mine, Arizona," by Jas. Douglas, *Trans.*, New York Meeting, Feb. 1899, p. 20.

products there were two stages of alteration; first, the production of rich sulphurets by the reaction of oxidized products upon the lean pyritiferous material, and after that oxidation of the rich sulphurets, which occur partly *in situ*, but also, doubtless, has taken place with more or less of transfer of material from one place to another.

An excellent illustration of an enriched upper belt in the case of gold is furnished by the gold-quartz veins of Grass Valley, California, where, according to Lindgren, the decomposed belt of weathering about 50 meters deep contains "from $80 to $300 per ton, while the average tenor in depth is from $20 to $30."* Furthermore, the rich 50 meters, which contains from four to ten times as much gold as the sulphurets below the level of groundwater, is depleted in silver. However, in some veins the sulphurets extend almost to the surface. Lindgren further states that the sulphurets below the level of groundwater continue with undiminished richness to a depth of 500 or more meters.† He adds that the California region is one in which denudation has extended to a depth of 500 to 1500 or more meters.‡ From these facts it is highly probable, as suggested by Lindgren, that the sulphurets similar to those below the level of groundwater were deposited above the present surface of the country. If this were the case the only possible explanation of the belt of weathering rich in gold and depleted in silver is that descending waters have abstracted a large part of the gold from the 500 to 1500 meters removed by erosion, and have deposited it in the belt of weathering. Its precipitation there was, doubtless, mainly due to the reaction of the oxidized products upon the sulphides, producing sulphurets richer in gold. Later, these rich sulphurets have been oxidized, leaving the enriched belt of free gold. The silver apparently has been transported downward to a greater extent in this belt. One would expect that correlative with the belt above the level of groundwater poor in silver, there would be a belt at and below the level of groundwater richer in silver than that above. Upon this point Lindgren does not give us information.

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* "The Gold-quartz Veins of Nevada City and Grass Valley, California," by Waldemar Lindgren, *17th Ann. Rept. U. S. Geo. Surv.*, 1895–96, pt. ii., p. 128, 1896.

† Lindgren, *loc. cit.*, p. 163.

‡ Lindgren, *loc. cit.*, p. 183.

Another very interesting case of the richness of the belt of weathering in gold, as compared with the unaltered sulphides below, is furnished by the Australian gold-fields, where the belt above the level of groundwater is several times as rich as the unaltered tellurides and sulphides below; some mining men say ounces above to pennyweights below.*

This rich belt is from 50 to 400 feet. In a portion of the mines of some districts—for example, the Kalgoorlie district—when the bottom of the oxidized zone is reached, the ores are so lean as to be valueless, so that mines which were profitable in the weathered zone were not profitable below that zone.† Many of the mines of that district, however, are profitable below the weathered zone. If it had not been for the secondary enrichment of denudation and downward transportation of material, many of the mines would not have been exploited, although Hoover thinks, that in this strange country, the downward concentration is more mechanical than chemical. Thus the secondary concentration by descension is no less an important part of the genesis of the gold-ores of Australia than the first concentration by ascending waters.

The lead- and zinc-deposits of the Mississippi valley (see pp. 76–83), are believed to be clear cases of the importance of the action of descending waters. This has already been shown for Wisconsin. In the lead and zinc districts of Missouri the galena is at a high horizon, and the sphalerite at a low horizon, precisely as in Wisconsin. Moreover, the arrangement of the different kinds of materials in the veins is very similar to that in Wisconsin, the order of deposition of the minerals from above down being (1) blende, (2) galena, (3) pyrite. This corresponds to the order of the more important deposits in Wisconsin, except that before the blende, marcasite formed. (See p. 78.) Lead-bearing ores in Missouri occur in the Cambrian limestones; zinc-ores occur in the sub-Carbonaceous limestones; and lead- and zinc-ores occur in the Lower Silurian rocks.‡

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* "The Genesis of Certain Auriferous Lodes," by J. R. Don, *Trans.*, xxvii. 1898, p. 596.

† "The Alterations of the Western Australian Ore-deposits," by H. C. Hoover, *Trans.*, xxviii., 1899, pp. 762–764.

‡ "The Lead and Zinc Deposits of the Mississippi Valley," by W. P. Jenney, *Trans.*, xxii., 1894, pp. 187–188, 197, 199–200.

In Wisconsin the ores occur mainly "in the Galena, Trenton, and subordinately, Lower Magnesian limestones."* However, in all of these districts the ores which have been taken out are very largely above the 50 meter level. The probable explanation of these relations is as follows: The ores were disseminated in various sedimentary strata, and possibly, also, to some extent in the pre-sedimentary rocks. They were concentrated through a comparatively wide vertical range by ascending waters. But the position of the rich ores near the surface is due to secondary concentration by descending waters, concentration going on *pari-passu* with erosion in such a manner that the rich ores are continuously deposited above and below the level of groundwater, as explained in the previous pages. As denudation passes downward, and thus the level of groundwater descends, also the horizon of rich concentrates descends.

The Leadville deposits furnish an instance of the decrease of the richness in silver with depth. Emmons says: "There is a fair foundation for the generalization that in the deposits, as developed at the time of this investigation, the ores were growing poorer in silver as exploration extended farther from the surface."†

Another case of the diminution of richness of sulphurets with depth is furnished by the nickel mine of Lancaster Gap, which, however, were not worked beyond a depth of about 75 meters, presumably because "the ores decreased in richness as depth was attained."‡

In addition to these specific instances of the production of a rich upper belt, some general statements have been made which need to be referred to. One of these is made by Douglas in reference to sulphuret mines as a whole. Says he, in the conclusion of his discussion as to the copper resources of the United States, with reference to the various Appalachian deposits, "Like all sulphuret mines, they became poorer as depth was attained."§

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* "Geology of Wisconsin," vol. iv., p. 451.

† "The Geology and Mining Industry of Leadville," by S. F. Emmons, *Mon. U. S. Geol. Surv.*, No. 12, 1886, pp. 554-555.

‡ "The Nickel Mine at Lancaster Gap, Pennsylvania," by J. F. Kemp, *Trans.* xxiv., 1895, pp. 626, 884.

§ "The Copper Resources of the United States," by Jas. Douglas, *Trans.*, xix., 1891, p. 694.

Penrose,* in 1894, discussed the superficial alteration of ore-deposits. He says:

> "As a result of these various changes, certain materials are sometimes leached from the upper parts of ore-deposits, which have become porous by alteration, and carried down to the less pervious unaltered parts. Here they are precipitated by meeting other solutions or in other ways, and hence the richest bodies of ore in a deposit often occur between the overlying altered part and the underlying unaltered part. This is not always the case, but it is true of some copper, silver, iron and other deposits."†

De Launay,‡ in 1897, emphasizes the frequent occurrence of rich products near the surface, which in some cases are oxidize products, and in others are sulphides. He, however, explains the richness of the deposits by the abstraction of more soluble material. This frequently results in transforming a low grade product into a rich ore. By this process a poor sulphide may be changed to a rich sulphide, as, for instance, cupriferous pyrites or chalcopyrite may be transformed to covellite or chalcocite by abstraction of iron sulphide. It is a natural deduction from De Launay's§ explanation, that the volume of the material is decreased, although he does not make this point.

De Launay further emphasized the point that the ore-material of veins may have been repeatedly transferred from one place to another, and suggests that a part of the material now found in veins may have been transferred from vein material which was once above the present surface of denudation.

While it is believed to be a very general case, if a long enough scale be used, that ore-deposits diminish in richness with depth, it is well-known that above the level of groundwater the valuable materials may be almost wholly dissolved and deposited at or below the level of groundwater by the reactions above stated, as at Ducktown, Tennessee, or partly dissolved and transported below, as at Butte, Montana. Thus, for a certain depth the ores may increase in richness. This exception, however, does not affect the common rule as to diminution of richness with increasing depth.

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* "The Superficial Alteration of Ore-deposits," by R. A. F. Penrose, Jr., *Jour. of Geol.*, vol. ii., 1894, pp. 288–317.

† Penrose, *cit.*, p. 294.

‡ "Contribution a l'Étude des Gites Métallifèrous," by M. L. De Launay, *Annales des Mines*, 9th ser., vol. xii., 1897, pp. 151–152.

§ De Launay, *cit.*, p. 194.

GENERAL.

It is apparent from the foregoing that there has been a general understanding that a rich upper belt has been produced in many ore-deposits. Le Conte,* who appreciated this, suggests that the rich belt may be explained by supposing that precipitation by ascending waters does not occur at great depth, because the solutions do not get saturated until comparatively near the level of underground water. However, it is to be remembered that the upper part of a fissure is that receiving abundant lateral waters which have taken a comparatively brief journey under conditions of low pressure and temperature; whereas the solutions lower down have taken a longer journey under conditions of high pressure and temperature. In this connection it might be further supposed that the varying richness could be partly explained by the lessening temperature and pressure of the rising solutions. But if this be true, one would expect the most insoluble constituent to be precipitated deepest down. In the case of the lead-zinc-iron deposits this would make the galena most abundant at depth, the sphalerite most abundant at a higher level, and the iron sulphide the dominating constituent at the highest levels. In the case of the copper-iron deposits, the rich sulphides of copper would be in the lower levels and the cupriferous pyrites at the higher levels.

As already seen, Penrose's explanation of the phenomenon of a rich upper belt is that the concentrates have been produced by downward transportation and precipitation by meeting other solutions. De Launay's explanation of the phenomena is enrichment by the abstraction of the more soluble and less valuable material, thus producing a smaller quantity of relatively rich product.

While the reactions between the oxidized products and the sulphides are emphasized, and are believed to be the most fundamental and widespread, my own explanation† is, mainly,

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* Le Conte, *loc. cit.*, p. 12.

† Just as I am sending this paper to the press in its revised form (a preliminary proof edition was published and distributed in February, 1900), I am in receipt of a paper upon "The Enrichment of Mineral Veins by Later Metallic Sulphides," by Walter Harvey Weed (*Bull. Geol. Soc. Am.*, vol. ii., pp. 179-206).

that oxidized soluble products are produced in the belt of weathering; that these *in situ* or lower down react upon the lean sulphides. In this way a belt of rich sulphurets is formed. Later, in consequence of denudation, these rich sulphides pass into the belt of weathering. Here they are again exposed to the oxidizing forces, where *in situ* they are largely transformed to oxides, carbonates, etc., a belt of rich oxidized products above the groundwater is formed. However, in part, when oxidized, they are taken into solution, again transported downward, and again react upon the sulphurets. In arid regions where the amount of downward-moving water is small, the oxidized products formed from the rich sulphurets are likely to remain in large part *in situ*. Where, upon the other hand, water is abundant the sulphides when oxidized are in large measure likely to be carried downward, and again react upon the sulphides below and further broaden and enrich the belt of sulphides. Thus, under different climatic conditions, we may

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This paper strongly emphasizes the enrichment of an upper belt through the action of descending waters. Moreover, the paper includes the reactions of the oxidized products upon the poor sulphurets, thus producing rich sulphurets. Many occurrences are given which illustrate the enrichment of sulphides by descending waters, including copper, silver and zinc deposits. Some of the illustrations given by Mr. Weed I also have used. Others are additional to those given by me. In general it may be said that Mr. Weed's paper and that part of my own which deals with secondary enrichment by descending waters are supplemental and support each other; since each did his work and arrived at his conclusions in entire ignorance of the fact that the other was working along a similar line.

Upon one point only is there difference of opinion between us. Mr. Weed, in his general statement, says that the part of the veins "below the permanent groundwater level consists of the unaltered sulphides which composed the original ore of the vein. This part constitutes the zone of primary sulphide ore" (p. 181). However, while Weed makes the above general statement, he appears to appreciate that in individual cases rich oxidized sulphides may be produced below the permanent groundwater level, for he says that at Elkhorn, Montana, this level is only 185 to 210 meters below the surface, whereas the sulphides enriched by descending waters extend to the depth of 600 meters (p. 204). If my reasoning be correct, the zone of secondary enrichment by descending waters will ordinarily extend far below the permanent groundwater level, in many instances to the depth of several hundred meters. Indeed, not only the Montana instance, but other illustrations given by Mr. Weed confirm this conclusion. In the pyrite deposits of Spain and Portugal, described by Vogt, the ores decrease in richness to the depth of 350 meters (p. 198). Also in Norway, if I understand Mr. Weed correctly, the diminution of richness of the copper deposits with depth extends from 350 meters to over 700 meters.

have a rich oxidized zone, a rich sulphide zone, or both, in varying proportion.

While the reaction between the oxidized products and the sulphides has been strongly emphasized in this paper because it is believed to be the most fundamental of the causes producing a rich upper belt, it is understood that other factors may also help in this process. As already pointed out, reduction and precipitation of the metals of descending solutions may take place through the agency of organic matter or other reducing materials contained in the rocks, or by meeting ascending solutions carrying precipitating agents; also near the surface more than an average amount of original precipitates from ascending solutions is a possibility in some cases. (See pp. 96–97.)

Summarizing, it appears to me, therefore, that the existence of a rich upper belt in many deposits, and the frequent diminution of richness of the ores in passing downward from the surface to some distance below the level of groundwater, cannot be explained as the work of ascending waters alone or as the work of descending waters alone; but is fully explained as due to the work of ascending and descending waters combined. Ascending waters produce a first concentration. A second concentration by descending waters produces the rich products. Moreover, these rich products are found in the few meters or few hundred meters of the outer crust of the earth. When it is remembered that the greater part of the ores which have yet to be abstracted from the earth comes from the first 500 or 700 meters, and when it is further considered that the effect of descending waters may be felt to these depths, it becomes evident that the process of second concentration by descending waters is a very important one indeed, so far as the economic value of ore-deposits is concerned. Indeed, as a result of it there is concentrated in the extreme outer shell of the crust of the earth a large portion of the products which during the first concentration may in many cases have been distributed over 1500 or 3000 meters or more, but which have now been largely removed by erosion. We therefore conclude that for a large class of ore-deposits that *a second concentration by descending waters cannot be said to be one whit less important in the genesis of ores than a first concentration by ascending waters.*

It follows from the foregoing that one of the most important classes of ore-deposits is that produced by the joint action of ascending and descending waters.

THE PRECIPITATION OF ORES BY DESCENDING WATERS ALONE.

For the sake of simplicity and continuity of exposition, the effects produced by descending waters have been applied to deposits which have been first concentrated by ascending waters. However, it is perfectly clear that a concentration by descending waters alone may be adequate to produce ore-deposits. Indeed, this is definitely known to be true of some of the most important ore-deposits, as for instance many of the iron-ores. A conspicuous case is that of the Lake Superior iron-ores, which very well illustrate the process of formation of ores of this class. Since the genesis of the Lake Superior iron-ores is fully discussed by me in the Twenty-first Annual Report of the U. S. Geological Survey, this class of ores is not further discussed here.

SPECIAL FACTORS AFFECTING THE CONCENTRATION OF ORES.

In Part I. it has been shown that the underground circulation may be effective to the bottom of the zone of fracture, and in Part II. it has been seen that the concentration of ores is an orderly but complex process. However, the discussion has not taken into account a number of the special factors which affect the concentration of ores. The general discussion may need great modification to adapt it to a particular district. To illustrate my meaning, it may be well to consider some of the additional factors affecting the deposition of ores, and to point out the more obvious possible modifications of the general theory which may result from them. The effect of (1) variations in porosity and structure, (2) the character of the topography, and (3) physical revolutions, will be briefly considered.

Variations in Porosity and Structure.

There are many ways in which variations in porosity and structure may affect the concentration of ores by influencing the circulation of waters.* The different strata of the sediment-

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* Compare Emmons's "Structural Relations of Ore-Deposits," *Trans.*, xvi., 1888, 804–839.

ary rocks vary greatly in porosity. The igneous rocks, and especially the lavas, also vary much in porosity. The metamorphosed equivalents of either sedimentary or igneous rocks may differ in porosity. The contact of rocks frequently furnishes trunk-channels for underground circulation. Bedding partings produced by shearing stresses during deformation furnish sheet channels parallel to the strata, or openings on the anticlines or synclines. Some strata when deformed may yield by fracture, furnishing channels for water-circulation, while interlaminated strata may yield by flowage, thus remaining relatively impervious. These various irregularities may combine in different ways.

All irregularities in porosity and structure may modify, as in many cases profoundly, the simple general statements of the present paper (pp. 28–36, 53–58) concerning the character of underground circulation and the concentration of ore-deposits. At some future time it may be possible to divide the modifications of the general circulation due to variation of porosity and structure into classes, but for the present this cannot be done. The modifications of the general circulation which occur in many individual districts must first be studied and described, after which generalizations may possibly be made. However, some general statements may be made in reference to certain modifications of the general underground circulation.

The Complexity of Openings.—In the general discussion an ore-deposit has been spoken of as if it were a single continuous mass formed in a large opening. It is clear this is not the fact, but, on the contrary, that many ore-deposits have very complex forms. An ore-deposit in a single large opening is exceptional. From large single openings to openings of an extraordinarily complex character, there are all gradations. A trunk-channel of circulation may be a set of distributive faults; it may be a group of parallel or intersecting sets of openings along joints; it may be the minute parallel openings of fissility; it may be a group of openings along bedding planes; it may be the shrinkage openings formed within or along the borders of cooling magma; it may be the openings in an autoclastic rock or reibungs breccia along a fissure; it may be the multitude of openings of a sandstone or a conglomerate.

Consequent upon the many irregularities, trunk-channels of circulation may vary from vertical to nearly horizontal attitudes. But ore-deposits ordinarily have important vertical components, although they may be found in nearly horizontal positions. In such cases the trunk-channels forming the deposits had probably vertical components somewhere else.

It is hardly necessary to give illustrations of ore-deposits for each of these complex conditions. However, as very excellent illustrations of veins of a very composite character may be mentioned the Cripple Creek deposits* and the gold-quartz veins of Nevada City and Grass Valley, California.† The essential point, so far as the discussion of the foregoing pages is concerned, is that ore-deposits commonly occur at places where there are trunk-channels for ascending or descending waters, or both. In order that metalliferous material shall be brought to a place and deposited in large quantity, there must be long-continued circulation. It matters not whether a trunk-channel is a single passage or is composed of an indefinite number of minor passages, the principles given on the previous pages are applicable to the deposition of ores in such trunk-channels.

In various regions the conditions are so exceedingly complex that ore-deposits close together may differ from one another greatly. This is the best evidence that, notwithstanding their continuity, the underground trees of water circulation have been, if not independent, at least partly so.

This is well illustrated by the ore-deposits of Butte, Montana. Here, apparently, the metallic contents of the individual feeding streams and even the trunk-channels are very different within short distances. At this place are two main zones of mineralization. The more important product of one of these mineral zônes is silver sulphide, which is associated with sulphides of lead, zinc and iron, and with silicate of manganese. The chief product of the other mineral zone is copper, but this copper carries silver in important amounts.‡

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* "Mining Geology of the Cripple Creek District," by R. A. F. Penrose, Jr., *16th Ann. Rept. U. S. Geol. Surv.*, pt. ii., 1894–95.

† "The Gold-Quartz Veins of Nevada City and Grass Valley, California," by Waldemar Lindgren, *17th Ann. Rept. U. S. Geol. Surv.*, pt. ii., 1895–96, pp. 158–160, 259.

‡ "Notes on the Geology of Butte, Montana," by S. P. Emmons, *Trans.*, xvi., 54, 1888.

Impervious Strata at Various Depths.—Slichter's theoretical investigations on the motions of groundwaters show that, in order to discuss the flowage under any given set of conditions, it must be assumed that the flowage is limited only by an impervious stratum.* It is, of course, understood that there is no such thing in nature as an absolutely impervious stratum, but there are many strata which are practically impervious. Wherever there is an impervious stratum in a district, this must be counted as the limit of circulation in that direction. The impervious stratum may be a plastic shale which yields to deformation without fracture; it may be a rock intruded after deformation has occurred, thus making a barrier. If an impervious stratum exists at a given depth, the effective underground circulation for that district is there limited or divided, whether the stratum be at the depth of 100 or 1000 or more meters. Of course there will be all gradations, from practically impervious strata to strata which merely check the circulation. It is believed that in the average case the limit of effective circulation is probably much less than the theoretical limit of 10,000 meters given by the depth of the zone of fracture.

However, if an impervious stratum be but 100 meters from the surface and fissures be limited to that depth or interrupted, the laws given pp. 28–36 will commonly apply to the circulation above the stratum. Therefore such a fissure may be occupied by ascending water in the lower part and by descending water in its upper part. Hence an ore-deposit contained in such a shallow fissure may be the result of a single concentration by ascending or descending waters, or of two concentrations, the first by ascending and the second by descending waters.

The foregoing statement in reference to the practical limits of underground circulation for the ore-deposits of a given district may be true even if below the impervious stratum there are other strata, fed from a distance, in which circulation is occurring.

Such lower pervious strata may have circulations of their own independent of the higher circulations, and this circulation may produce ore-bodies. This is beautifully illustrated by the Enterprise mine of Rico, Colo. (see Fig. 9, p. 128), described by

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* "Theoretical Investigation of the Motion of Groundwaters," by C. S. Slichter, *19th Ann. Rept. U. S. Geol. Surv.* for 1897–98, pt. ii., pp. 329–357, 1899.

Rickard,* in which the ore is confined to fissured and broken limestones and sandstones below a black shale, which when bent did not fracture, and therefore afforded no channels for water circulation.

In this connection it may be well to mention the Mercur district of Utah (see p. 130), where a silver ledge and a gold ledge about 100 feet apart each occur in limestone below a shale-like stratum of altered porphyry. Spurr regards the silver ledge as produced by an earlier mineralizing period, and the gold ledge as resulting from a later period of mineralization.† It may be suggested that the true explanation of the existence of two mineral ledges so near together and of such different mineral character is that in this district there were two independent circulations separated by impervious strata, the upper one, producing the gold ledge, being between the two impervious porphyry belts, while the lower one, forming the silver-deposit, was below the lower impervious layer.

That a difference of opinion exists as to the source and manner of deposition of the lead and zinc deposits of the upper Mississippi valley has already been mentioned. (See p. 83.) I believe that these deposits furnish an instance of two concentrations where an impervious stratum limiting the concentrating circulation was at a very moderate depth.

The succession for this district in descending order, according to Chamberlin,‡ is as follows:

Niagara limestone, 137 meters thick.

Cincinnati shale, originally 61 meters thick (in Iowa called the Maquoketa shale).§

Galena limestone, bearing organic matter, 76 meters thick.

Trenton limestone, bearing organic matter, 12–30 meters thick, with mean of 21 meters, having at its top an oil-bearing shale,|| "two or three to several feet in thickness at

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* "The Enterprise Mine, Rico, Colo.," by T. A. Rickard, *Trans.*, xxvi., 1897, 976-977; also Figs. 19, 36, 40.

† "Economic Geology of the Mercur Mining District, Utah," by J. E. Spurr, 16*th Ann. Rept. U. S. Geol. Survey*, pt. ii., 1894–5, pp. 367–369.

‡ Chamberlin, *op. cit.*, pp. 407-419.

§ "Lead and Zinc Deposits of Iowa," by A. G. Leonard, *Iowa Geol. Survey*, vol. iv., 1897, p. 23.

|| Blake, *Bull. Geol. Soc. Am.*, vol. v., pp. 28-29; also *Trans. Am. Inst. Min. Eng.*, vol. xxii., pp. 629-632.

points,"* and containing throughout its mass various shaly layers, which, however, are "quite decidedly most prevalent near the base of the formation."†

St. Peter's sandstone, 15–46 meters thick.

Lower Magnesian limestone, 30–76 meters thick.

Potsdam sandstone, 213–244 meters thick.

Pre-Cambrian.

It is to be noted that the Galena limestone is bounded by impervious shales above and below, and that the same statement applies to a less extent in reference to the Trenton limestone. As to the impervious character of the thick Cincinnati shale above the Galena, there is no doubt. One might, however, question the impervious character of the thin bed of shale at the top of the Trenton, but that this is relatively impervious is strongly indicated by the fact that in the Shullsburg and other districts, as pointed out by Blake, the ore-deposits stop at the top of this layer.‡ While in the Trenton the impervious shales are more prominent at the top and near the bottom, there are more or less impervious layers within the Trenton.

The strata dip to the southwest. Chamberlin says for Wisconsin, "The strata on the north side of the lead region are 500 feet (152 meters) higher than those of the south side, and if traced farther the difference in altitude would be found greater. Beds on the eastern side are 350 feet (107 meters) higher those on the west side."§ Superimposed upon the general southwest monocline of the district are a number of subordinate anticlines and synclines, and the ores are mainly confined to the synclines.|| At the time of this deformation the brittle limestones were probably fractured, producing the present complex system of intersecting joints; but the plastic shales were deformed with comparatively little fracturing. The time at which the deformation occurred is not definitely known, but in all probability it antedated the deep erosion and concentration of ores in the district.¶

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[*] Clamberlin, *cit.*, p. 412. [†] Chamberlin, *Geol. of Wis.*, vol. iv., 1882, p. 409.

[‡] "Lead and Zinc Deposits of the Mississippi Valley," by Wm. P. Blake, *Trans. Am. Inst. Min. Eng.*, vol. xxii., 1894, pp. 629–632. (Discussion of Jenney's paper.)

[§] Chamberlin, *cit.*, p. 422. [||] Chamberlin, *cit.*, pp. 432–438.

[¶] "Lead and Zinc Deposits of the Mississippi Valley," by W. P. Jenney, *Trans. Am. Inst. Min. Eng.*, vol. xxii., 1894, pp. 208–209. Discussion of Jenney's paper, by Wm. P. Blake, *op. cit.*, pp. 628–629. Chamberlin, *op. cit.*, pp. 427, 485.

Areally the ores occur to a much greater extent east of the Mississippi river than west of it; that is, mainly east of the main line of drainage. As to horizons, by far the greater quantity of ores which have yet been abstracted are found in the Galena limestone.* However, considerable quantities of ores have been taken from the Trenton, and subordinate quantities from the St. Peters and Lower Magnesian. The ores occur in the Galena from the top to the bottom. In cases where erosion has not cut deep into the Trenton, the ore-deposits are apt to be found near the overlying Cincinnati shale. For instance, in Iowa, where the shales are close at hand as a continuous formation, Leonard† states that the ore occurs "mostly near the top of the Galena limestone, within the upper 50 or 60 feet (15 meters to 18 meters)." Where the drainage lines have cut through the Galena into the Trenton or lower formations, the ores of the Galena are likely, in large measure, to be near the bottom of the formation, and considerable bodies may rest upon the oil-rock which marks the beginning of the Trenton.

Following Chamberlin, I think it probable that a large part of the material of these ores was once disseminated through the sedimentary rocks, and especially the limestones. My conception of the probable process of concentration in the Galena limestone is as follows:

While in the Wisconsin lead district the Niagara limestone and Cincinnati shale are only found on occasional mounds, as pointed out by Chamberlin,‡ there is no question but that these formations once extended over the entire district. As already noted, the Cincinnati shale is a very impervious stratum. Until it was cut through by the drainage, it is probable that effective concentration of the ores did not begin. When it was once cut by erosion, then I conceive the main concentration history of the ore-deposits to have begun. The Mississippi river and areas adjacent were the places where the drainage was the lowest. However, these were not the places first cut through by erosion, for the difference between the level of the Mississippi drainage and the tributaries adjacent is not so

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* *Geol. of Wis.*, vol. iv., pp. 407, 457, 481.

† Leonard, *cit.*, pp. 43, 61.

‡ Chamberlin, *cit.*, pp. 410–412.

great as the dip of the strata to the southwest. In all probability, therefore, the Cincinnati was first cut through, and the Galena encroached upon by erosion north and east of the lead and zinc district. This is probable from the fact that at the present time the Mississippi river for the most part in the lead district is on the Trenton, and never reaches deeper than the St. Peters; while the majority of the smaller streams in the northeastern part of the lead district have cut into the St. Peters, and the headwaters of some of them, notably the Pecatonica, Platte, the Grant river, have cut through the St. Peters into the Magnesian; while still farther to the northeast, north of the divide, occupied by the Lancaster branch of the C. & N. W. Ry., the strong Wisconsin has cut down to the Cambrian.*

It is to be remembered that the pervious strata overlain by impervious strata along the Mississippi river bear water under pressure, as is shown by numerous artesian wells. The feeding area is the higher ground to the northeast. It is highly probable that the broken brittle Galena limestone was a formation which was capable of carrying water to considerable distances, and in considerable quantities, although probably not comparable in these respects to the St. Peters or Potsdam sandstones. The lead and zinc district of Wisconsin is wholly south of the divide between the Wisconsin river and the tributaries of the Mississippi. When the Wisconsin drainage north of the divide had cut through the Cincinnati shale, this furnished a feeding area to the Galena limestone. When later the Mississippi tributaries south of the divide had cut through the Cincinnati shale into the Galena, the waters entering north of the divide escaped.

As erosion continued, the area in which the Cincinnati was cut through and the Galena penetrated, gradually extended to the southwest until the Mississippi itself had cut through the Cincinnati. During this time the water entered the Galena limestone at the higher elevations, that is, to the north and east, followed along this formation, and escaped at some lower point toward the Mississippi river. While the water to the greatest extent followed the upper portion of the Galena, it is believed that this broken formation was searched to its deepest

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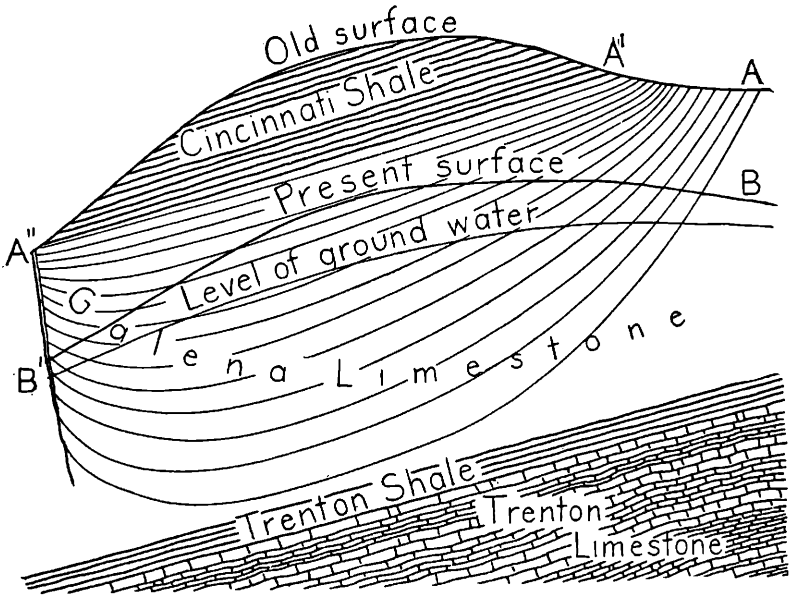
* See "Atlas of Wisconsin," pls. i. and viii.

part according to the laws of flowage given pp. 28–36. The places of escape were near the top of the formation, and, therefore, the waters of the trunk-channels leading to these places were ascending.

As erosion slowly progressed, the zone of rising waters and escape slowly migrated from the northeastern part of the lead and zinc district to the southwestern part. The nature of the circulation at a given time is roughly represented by Fig. 7, a northeast-southwest vertical section. The surface of the country is shown by A, A′, A′′, in which A, A′ is the cross-section of a northwest and southeast belt, where waters enter, and A′′ is in a parallel belt to the southwest, in which the waters escape. The numerous curved lines below the Cincinnati shale are intended to represent the circulation. The downward-moving lateral-moving waters, in the early stages of their journey, were oxidizing and dissolving waters. When, through the organic matter contained in the formation, the oxygen had been exhausted and the oxidized products reduced, the waters were sulphuretted

FIG. 7.



Ideal Vertical Section of the Flow of Underground Water in the Galena Limestone of the Upper Mississippi Valley.

waters, as explained pp. 67–69. The upward-moving waters in the trunk-channels (A″ B′) were precipitating waters, as explained pp. 56–57. And especially the material was likely to be precipitated where the waters came in contact with abundant organic material.

Where the limestone itself contained much carbonaceous substances, the material precipitated might have been widely disseminated; but as the carbonaceous material was more abundant in the clay layers, which, to some extent at least, represented places where clay openings and ore-deposits now exist, the ore material was still more largely precipitated. The transfers of ore material at this time were, indeed, exceedingly complex, but because of a combination of all of the factors considered in the general part of this paper, the material was precipitated to a greater degree in the trunk-channels where the water was ascending than anywhere else.

In an early stage of the process the first concentration by ascending waters took place in the northeastern part of the district. By the time that erosion had cut through the Cincinnati into the Galena in the southwestern part of the district, and ascending waters were concentrating ores, the northeastern part of the district might have been a feeding area where waters were descending, and a second concentration taking place. Therefore, the second concentration by descending waters was going on in the northeastern part of the district at the same time that the first concentration by ascending waters was occurring to the southwest. At the present time the erosion has cut sufficiently deep so that the second concentration by downward-moving waters has extended quite to the Mississippi river, and, indeed, to the west of it. At the present time the condition of affairs, except the circulation, is represented by Fig. 7 below the line B, B′, which may be taken as the present surface of erosion.

This general statement as to the order of events concerning the district as a whole would also apply to the local anticlines and synclines. Other things being equal, where there were anticlines there erosion would first cut through the Cincinnati shale, and water make its way into the Galena formation. Later, when erosion had cut deep enough to expose the bottoms of the adjacent synclines, there the water entering at the anticlines arose and escaped, and a first concentration occurred in the synclinal areas. Later, when erosion had cut deeper, a second concentration by descending waters occurred; and thus these concentrations were localized in the synclines, where, according to Chamberlin, they now occur. In this connection it is to be remembered that the anticlines and synclines of the district are very gentle. Therefore, the conditions are here different from those of a district where there are sharp, strongly pitching folds covered by impervious strata. (See pp. 124–131.)

My conception of the process of concentration of ores in the Galena limestones is, therefore, that of a circulation practically limited above by the Cincinnati shale and largely limited below by the impervious oil shale of the Trenton. To what extent ascending waters from the St. Peters, Cambrian and pre-Cambrian rocks under the pressure of considerable head were able to work up through the more or less impervious shales of the Trenton limestone is uncertain. For the purposes of this paper it makes little difference whether during the time of deposition of ores in the Galena limestones by ascending waters the circulation was practically limited by the Cincinnati shale above and the Trenton below, or whether a contribution of waters ascended from greater depths. For a given point where the Cincinnati shale had just been removed, the first concentration occurred by ascending waters, and later when the Cincinnati shale had been removed farther to the southwest the second concentration by descending waters took place. The belt of second concentrates by descending waters slowly migrated downward as erosion extended into the Galena. Where the denudation has gone a little way into the Galena, the ore-deposits are found near its upper part. Where denudation has gone well down into the Galena, the ore-deposits are found near its lower part. Where the lines of drainage are considerably below the Galena the second concentration and downward migration of the ores has resulted in the formation of considerable deposits directly upon the petroleum oil-rock at the top of the Trenton. In these cases the materials exploited are probably the second concentrates from the entire Galena formation.

The precipitation of the lead- and zinc-ores by reactions of the oxidized products upon the remaining sulphides, and by the reducing action of the organic material contained in the rock and the organic material coming down from above, have already been considered. (See pp. 79–83.) However, in this connection it should be noted that the position of the ores upon the oil-rock is probably explained through the reducing action of solutions slowly oozing up through the shale; for the ore is not mainly precipitated in the oil-rock, but immediately above it. In this connection it is to be remembered that all of the pervious strata capped by impervious strata in this region bear waters under pressure. Therefore, water would slowly pass up through the shale, for no formation is absolutely impervious.

It will be seen at once that the above theory of circulation explains the formation of rich deposits near the top of the Galena, as in Iowa, and these deposits are very difficult to account for solely upon the theory of descending waters. It accounts equally well for the formation of rich ores in the middle and lower horizons of the Galena where denudation has gone further. It accounts for the much wider distribution of the ores east of the Mississippi river than west of the Mississippi river, since the strata west of the Mississippi river continue to dip to the southwest; and the drainage west of the river has cut only for a little way deep enough so that the process of concentration as above outlined could occur.

In the parts of the Upper Mississippi valley district where erosion has cut deeply into the Trenton, and especially where it has gone into the St. Peters, a similar history is applicable to the Trenton formation; only the Trenton is more variable in its porosity than the Galena, and the deposits may not have been wholly derived from the Trenton formation, but may have received a subordinate contribution from the Galena formation which has been removed by erosion in part or altogether.

In the application of the foregoing it is, of course, understood that the action of ascending and descending waters in a given fissure is not wholly successive; but is in large measure simultaneous. In the early stages of the deposition of an ore-deposit in a given fissure, ascending water would be likely to be the dominant factor; in an intermediate stage both ascending and descending waters would be at work; and in the later stages of the process, and at the present time, descending waters are the dominant, and, perhaps, in the cases of many of the deposits where the oil-rock of the Trenton is near the surface, almost the sole factor.

At the bottoms of valleys the waters have continued to be essentially ascending instead of descending to the present time. The fact of their present ascension Chamberlin[*] notes. Thus in these places a second concentration has not occurred, and, therefore, such places are deficient in workable ore-deposits, as noted by Chamberlin.[†] (See p. 137.)

The case of the lead and zinc district has been dwelt upon, as it seems to me to illustrate almost ideally the practical limitations of circulating water by impervious strata. It shows that precisely the same principles of ore deposition are applicable when the limit of circulation is less than 100 meters deep that apply when the circulation extends to the very bottom of the zone of fracture.

If my views be compared with those of the ascensionists, typified by Jenney, and the descensionists, typified by Chamberlin, it will be seen that I occupy an intermediate position. Upon the fundamental point as to whether or not the ores are derived from a deep-seated source or are derived from sedimentary rocks, I am inclined to follow Chamberlin, although I do not feel certain that some of the material for the ores were not derived from a deeper source.

The account given pp. 76–83, 116–124, in reference to the ore-deposits of the Upper Mississippi valley is not even approximately complete. To give a satisfactory account of the genesis of the ore-deposits of this district, would require a detailed study and a monographic report. Such a report upon many phases of the problem—a remarkable paper—has already been written by Chamberlin.[‡] When the study is completed, it will be possible to explain not only the general order of mineral succession vertically, but the multifarious and complex distributions, such as the cycles of depositions already mentioned.

Pitching Troughs and Arches.—Another interesting special case of influence of porosity and structure is that where alternately pervious and impervious layers are in a set of pitching folds. The varying porosity may follow from original difference in the porosity of the layers, or it may result from the deformation itself. The more rigid strata may be deformed by fracture, and the less

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[*] Chamberlin, *op. cit.*, p. 565.

[†] Chamberlin, *op. cit.*, p. 563.

[‡] "Ore-deposits of Southwestern Wisconsin," by T. C. Chamberlin, *Geol. of Wis.*, vol. iv., 1882, pp. 366–571.

rigid by flowage. Also, the convex sides of the brittle layers are likely to be more fractured, and, therefore, more porous than the concave sides. This would place the more porous parts of a stratum in contact with the confining impervious stratum below at the synclines and above at the anticlines. Furthermore, where the strata are closely folded, unless there is very great distortion of the strata, openings will form between the layers at the synclines and anticlines, thus furnishing trunk-channels.

Any combinations of porous layers with impervious layers in folds are likely to give trunk-channels for underground water at the troughs above impervious strata, and at the crests below impervious strata. When descending waters come into contact with an impervious stratum, they are deflected toward the synclines, and there finding the trunk-channels, they follow the troughs downward along the pitch. When ascending waters come into contact with an impervious stratum, they are deflected toward the anticlines, and there finding the trunk-channels, follow the arches upward along the pitch. Therefore, ore-deposits produced by descending waters are often found in pitching troughs underlain by relatively impervious strata; and ore-deposits produced by ascending waters are rather frequently found in pitching arches overlain by impervious strata.

The Lake Superior iron-ores furnish an admirable illustration of the concentration of ores by descending waters in pitching troughs which are on impervious basements. Since these ore-deposits, which fully illustrate the principles of concentration of ores by descending water in pitching impervious troughs, are fully discussed elsewhere, ores of this class will not be here further considered.

A case in which ore is probably deposited by ascending waters in arches, because there concentrated by impervious roofs, is furnished by the Bendigo gold-district of Australia.* The typical position for the gold in the district, according to Rickard, is immediately below a slate, on top of a sandstone. The slate is the impervious stratum and the sandstone the pervious stratum. The ores are, presumably, in part, in the openings between the

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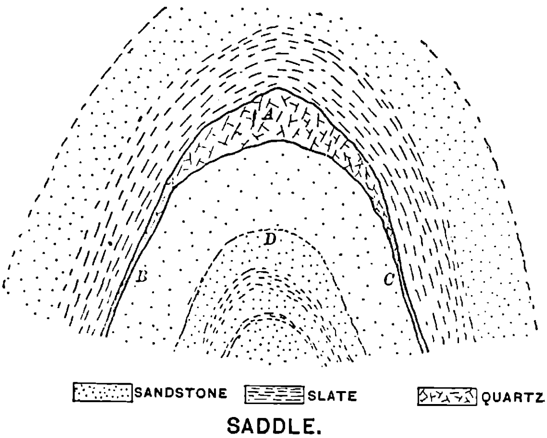
* "The Bendigo Gold-Field," by T. A. Rickard, *Trans.*, xx., 1891, pp. 463–545.

layers made by folding.* (Fig. 8.) Moreover, in this district there are a large number of alternations of pervious and impervious strata, as a result of which a number of concentrations have occurred one above the other. While Rickard does not specifically speak of the pitch of the anticlines, the longitudinal sections show that they do have a marked pitch. Rickard's explanation of the location of the ores† is that the apices of the anticlines would furnish more open passages than the synclines, but why at a given level this would be so does not appear. This explanation may possibly be to some extent applicable, but the pitching arches concentrating the ascending solutions below impervious strata are believed to be the main cause of the localization of the gold.

Fig. 8.



The Concentration of Ore by Ascending Water at a Crest below an Impervious Stratum. After Rickard (*Trans.*, xx., 467, Fig. 2).

Another excellent illustration of ore-solutions concentrated by an impervious roof is furnished by the Mercur district, Utah, described by Spurr,‡ where two ore-bearing beds, one called the silver ledge and the other called the gold ledge, about 100

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* Rickard, *loc. cit.*, Fig. 2, p. 467. See also Fig. 12, p. 481; Fig 13, p. 483; Fig. 37, p. 499; and Fig. 38, p. 501.

† "The Origin of the Gold-Bearing Quartz of the Bendigo Reefs," by T. A. Rickard, *Trans.*, xxii., p. 319.

‡ "Economic Geology of the Mercur Mining District, Utah," by J. E. Spurr, *16th Ann. Rept. U. S. Geol. Surv.*, pt. ii., 1894-95, pp. 365-7, 395, 399-401, 449, 454; see also Pl. xxxiv., Figs. 44 and 45, and Pl. xxv., p. 360.

feet apart, occur in a limestone below seams or beds of shale-like material, which, however, is very much altered porphyry. The ores are especially localized where fissures reach these beds, and thus displace them, and in some cases form local arches, although Spurr does not mention this latter fact. Moreover, the entire ore district is located upon a general anticline, furnishing a general pitching arch.

Another exceedingly interesting illustration of the deposition of ores below an impervious stratum in pitching arches is that furnished by the Enterprise mine of Rico, Colorado, described by Rickard in a paper already cited.* In this district above the ore-bodies is an impervious shale which is not broken at all, or very rarely, by the fissures. The ore occurs in two places, (1) in nearly vertical fissures extending indefinitely downward below the shale, but not upward into it. The verticals are cut by cross-fissures, and where the intersections occur the fissures are likely to be unusually rich. (See pp. 59–62.) The larger masses of ore are found in crushed or fractured limestone below the black shale and above the fissures. Moreover, these bodies are narrow laterally, and are parallel to the strike of the verticals and also of the cross-veins. Figs. 9 and 10 show that they occur below anticlinal flexures of the shale made by the deformation resulting in the faulting in the more brittle rocks below. Rickard regards the deposits as the result of ascending waters, since the fissures continue downward but do not extend upward into the shale. It is believed that when the Enterprise deposit is further studied it will be found that the flexures of the shale furnishing the anticlinal arches have a pitch (and indeed this is indicated by Fig. 10), and that the waters issuing from the verticals and the cross-fissures followed these arches upward until the pitch somewhere brought them to the surface, at which places the waters escaped as springs; for the waters of the ascending circulation must have somewhere escaped, and that they could not do through the impervious shale.

At this point it may be suggested that where ore-deposits occur in connection with pitching anticlines and synclines, that their positions furnish a criterion by which it may be decided

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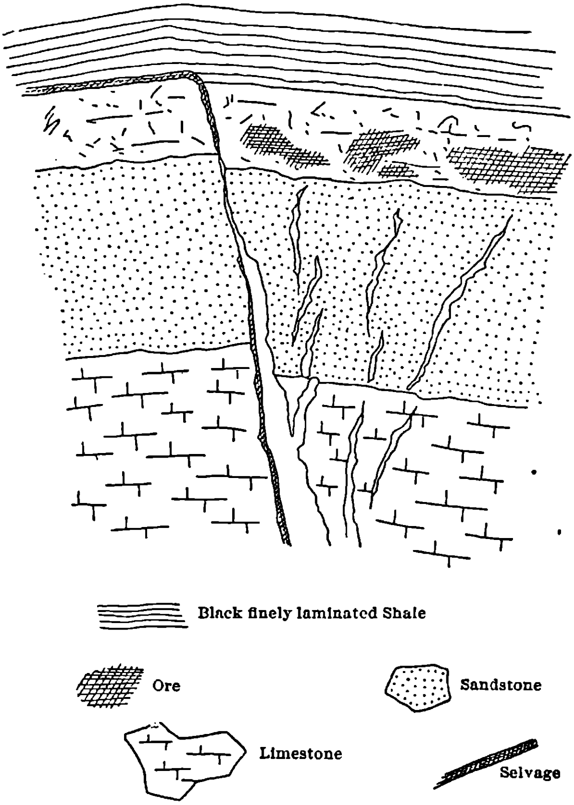
* "The Enterprise Mine, Rico, Colo.," by T. A. Rickard, *Trans.*, xxvi., p. 906, *et seq.*

whether their first concentration was accomplished by ascending or descending waters. Where the ores occur in pitching arches bounded above by impervious strata, the presumption is that they were concentrated by ascending waters; where the ore-deposits occur in pitching troughs bottomed by impervious strata, the inference is that they were concentrated by descending waters; for, as already explained, it is difficult to see how waters can be converged at such positions by moving in the reverse directions. Of course, this criterion cannot be too rigidly applied, for independently of the impervious strata, openings which so frequently occur on anticlines and synclines might

FIG. 9.

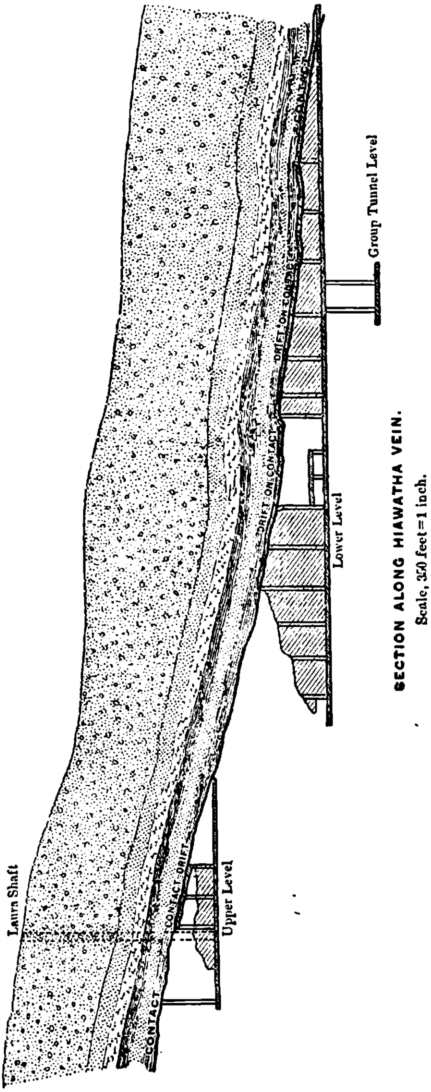


JUMBO NO. 2. VEIN AT THE CONTACT

Ore below a Gentle Arch of Impervious Shale, where the Feeding Fissure Coming from Below Ends at the Bottom of the Impervious Layer. After Rickard (*Trans.*, xxvi., 961, Fig. 36).

furnish trunk-channels which could be taken advantage of by ascending or descending waters. Thus in the Bendigo gold district of Australia, while the more important ore-deposits are in anticlines, occasionally an ore-deposit is found on a syncline.*

Fig. 10.



Longitudinal Section of the Hiawatha Vein, Enterprise Mine, Colo., Showing the Position of the Ore below an Impervious Stratum, and the Pitch of the Same. After Rickard (*Trans.*, xxvi., 974, Fig. D).

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* "The Bendigo Gold-Field," by T. A. Rickard. *Trans.*, xx., 1892, p. 484. See Fig. 6, p. 475.

If the above criterion be applied to the Leadville ore-deposits, the conclusion would be that the sulphides of Leadville were deposited by ascending waters, since they mainly occur on anticlines or anticlinoria below a relatively impervious porphyry and in a much-broken limestone, mainly the blue limestone.* The plates of the Emmons atlas show that the ore more largely occurs on anticlines and on the flanks of the folds than in synclines, although some subordinate synclines on anticlinoria contain ore-bodies. When deposited as sulphides the ores were probably somewhat more uniformly distributed than at present along the base of the porphyries. Later, when the second concentration occurred by downward-moving waters, the material which in many places was on denuded anticlines was in part carried down the limbs of the folds under the porphyry into the limestone. At this time doubtless, also, the limestone would be largely dissolved and the materials would be carried not only down along the dip but across the beds, thus producing the very great irregularities which are characteristic of the bottoms of these deposits. If the above explanation be correct, the Leadville ores would present another case in which both the ascensionists and descensionists have had a part of the truth.†

In this connection it may be suggested that the positions of the ores in reference to the limestone and porphyry in the Leadville district are remarkably similar to those of the ores in the Mercur district in reference to almost identical formations. The forms of the deposits, their irregular under-surface in the limestone, and the regular surface at the porphyry are all identical. Both Emmons and Spurr agree that the ore in the Mercur district was deposited as sulphides by ascending waters. If this be true, the same explanation is probably applicable to the Leadville district.

A pervious layer or other opening furnishing a trunk-channel for circulating waters may be bounded on both sides by impervious strata. In this case the ore-deposit may be produced by ascending or descending waters. But where the strata

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* "Geology and Mining Industry of Leadville," by S. F. Emmons, *Mon. U. S. Geol. Surv.*, No. 12, 1886, chap. vi., pp. 539-584.

† "Geology and Ore-Deposits of Iron Hill, Col.," by T. E. Schwarz, *Trans.*, xviii., 1890, 180.

are folded into pitching anticlines and synclines, the positions of the ores with reference to the folds would determine whether the precipitating waters were ascending or descending. An excellent illustration of ore-deposits at the openings of anticlines *between* relatively impervious strata, presumably formed by ascending waters, are the gold-bearing quartz-ores in the slates and quartzites of Nova Scotia, described by Faribault.* Here there are a great many parallel deposits directly at the anticlines or on some parts of the anticlinal folds, the deposits being separated by layers of relatively impervious slate. Furthermore, the largest deposits are located on the great pitching anticlines rather than the subordinate ones.

Porous pitching troughs below an impervious stratum or above an impervious stratum or between impervious strata may have a different origin from those mentioned. Very frequently such troughs are produced in part or in whole by intrusive igneous rocks. For instance, if sedimentary strata have a monoclinal dip and a dike cuts across the strata, a pitching trough may be produced, as, for instance, in the Penokee district.† An intruded igneous rock may follow the contact between folded strata, and thus furnish a trough or arch bounded by an impervious formation. Various other ways will immediately occur to one in which pitching troughs or arches with impervious basements or roofs or both, may be produced. It matters not how the trough or arch be produced, provided a porous stratum or an opening between the layers furnish a trunk-channel, such a trough or arch will be favorable for the concentration of ores. Of course, other favorable conditions must co-operate with these in order to produce an ore-deposit.

Combinations of pervious and impervious strata, united with joints, faults and other structures which affect some impervious strata and do not others, may furnish extraordinarily complex sets of conditions which I am not able to discuss in a general way; but such will undoubtedly yield interesting results when studied in special cases.

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* "The Gold Measures of Nova Scotia and Deep Mining," by E. R. Faribault, Paper read before the Canadian Mining Institute, March, 1899. Published by the Mining Assoc. of Nova Scotia, 1899. Pp. 11, with plates.

† "The Penokee-Gogebic Iron-Bearing Series of Michigan and Wisconsin," by R. D. Irving and C. R. Van Hise, *Mon. U. S. Geol. Surv.*, No. 19, 1892.

Pre-Existing Channels and Replacements.—When it is understood that ore-deposits ordinarily form in trunk-channels, the question as to whether ores are deposited in pre-existing openings or are replacements is easily answered, as a general proposition. It has been shown that solutions cannot be appealed to to explain the original formation of channels (see p. 14). The existence of channels for underground circulation must be explained by the original structures of rocks, or by the effects of deformation, as already indicated. It therefore follows that ore-deposits are, to some extent at least, deposited in pre-existing openings.. However, the conditions for vigorous circulation are also those for reactions upon the wall-rocks. It has been fully explained that solution and deposition are commonly simultaneous processes. Wherever there is a trunk-channel it is certain that the walls of the openings will to some extent be dissolved, and at the same time or subsequently metalliferous minerals be precipitated. Indeed, either enlargement by solution and subsequent precipitation of ore or synchronous solution and precipitation by which the wall-rocks are replaced in various degrees molecule by molecule by the ore, or both together, are almost universal phenomena.

I therefore believe that the large majority of ore-deposits, if not all, are partly deposited in pre-existing openings and are partly replacements of the wall-rocks. However, in some cases the filling of the pre-existing cavities is the more important or even dominant process, and in other cases substitution for the wall-rocks is the more important or dominant process.

Other things being equal, the main masses of ore-deposits are more likely to be in pre-existing cavities in refractory rocks, such as quartzite, granite and porphyry; and ore-deposits which are largely replacements are more likely to occur in easily soluble rocks, such as limestone. The gold-quartz veins of California give an excellent illustration of the deposition of ores in pre-existing cavities in refractory rocks, such as siliceous argyllite, diabase, diorite and granodiorite.* This instance is all the more interesting since the wall-rock itself is greatly modified, and has lost and gained various elements. Ore-deposits which are largely replacements are well illustrated by the

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* Lindgren *cit.*, pp. 172–257, 259, 261; also pp. 146–157.

silver-lead deposits of Eureka, Nevada, and Leadville, Colorado, and by the gold deposits of the Judith mountains, Montana.*

Replacements are likely to be important also in proportion as the trunk-channels are complex rather than simple. This follows from the law of mass action. In proportion as a trunk-channel is complex, the surface of action upon the wall-rock for a given quantity of solution is large. As conspicuous examples where there are large surfaces of action may be mentioned sandstones and conglomerates, and the reibungs-breccias or crushed rocks along fault zones. Where the trunk-channels are very complex, the rocks even if refractory may be replaced to a considerable extent by the metalliferous ores. A conspicuous instance of this in a sedimentary rock is that of the copper conglomerate deposits of Lake Superior, where many grains, pebbles and boulders of porphyry are partly or wholly replaced by metallic copper. In some places the metallic copper occurs as partial or complete skulls surrounding the boulders of porphyry; in other places these skulls are thicker, and in still other places the entire masses of the boulders, as described by Pumpelly,† are fully replaced by the metallic copper. While the conglomerate deposits of Lake Superior are in part replacements, they also are in large part, fillings of pre-existing cavities between the clastic particles. An excellent example of replacement in igneous rocks where there is complex distributive faulting and thus a large surface of contact for substitution, is furnished by the Cripple Creek district, in which according to Penrose,‡ ore mainly occurs replacing and blending into various igneous rocks.

In case of substitution the entire mass of the rock may be continuously replaced. This is particularly likely to occur

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* "The Silver-Lead Deposit of Eureka, Nevada," by J. S. Curtis, *Mon. U. S. Geol. Surv.*, No. 7, pp. 98–99. "Geology and Mining Industry of Leadville," by S. F. Emmons, *Mon. U. S. Geol. Surv.*, No. 12, pp. 556, 569. "Geology and Mineral Resources of the Judith Mountains of Montana," by W. H. Weed and L. V. Pirsson, *18th Ann. Rept. U. S. Geol. Surv.*, pt. iii., 1896–97, pp. 594, 598.

† "Copper District," by R. Pumpelly, *Geol. of Mich.*, vol. i., for 1869–1873, pp. 37–38. "Paragenesis and Derivation of Copper," by R. Pumpelly, *Am. Jour. Sci.*, vol. ii., 1871, pp. 28, 29.

‡ "The Mining Geology of Cripple Creek, Colorado," by R. A. F. Penrose, Jr., *16th Ann. Rept. U. S. Geol. Surv.*, pt. ii., pp. 140–141, 144–146, 161–162.

where the rock is uniform in structure and composition, as limestone or dolomite. Where, however, the rock is of complex composition such as granite or porphyry; or where there are different kinds of rock present, as, for instance, diorite and granite, the replacement will usually be largely selective. This selective replacement may apply to the mass of the wall-rock, to the individual fragments of it, to clastic fragments of sandstones or conglomerate, to the different constituent minerals in a single fragment. The particular minerals or masses which are most soluble in the solutions present will be most rapidly dissolved.

Where the wall-rock varies greatly in the solubility of its minerals, the selective replacement of the country-rock may extend for some distance from the central deposits. The readily-soluble minerals are dissolved, and in place of them there are precipitated the metalliferous minerals. This process is ordinarily called impregnation. Selective replacement of this kind is well illustrated by the Butte, Montana, granite, in which "the basic constituents of the granite are naturally attacked first; then the feldspars, and finally the quartz itself may be removed, so that in some parts there are found large masses, composed entirely of metallic minerals."*

In the variable solubility of the country-rock lies the partial explanation in regions of heterogeneous rocks of the frequent occurrence of the main masses of the ore-deposit in the more soluble rock. For instance, where limestone and sandstone, limestone and quartzite, limestone and diorite, limestone and trachyte, limestone and porphyry, limestone and granite, or limestone with almost any other rock occur in intimate association and ore-deposits are found, the ore is likely to be largely in the limestone.† The partial explanation of this relation is undoubtedly the more ready solubility of the limestones. However, other factors enter into the matter. It has already been explained that the country-rock may furnish solutions which

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* "Notes on the Geology of Butte, Montana," by S. F. Emmons, *Trans.*, xvi., 1888, 57.

† "The Copper Ores of the Southwest," by Arthur F. Wendt, *Trans.*, xv., 25-27. "The Silver-Lead Deposits of Eureka, Nevada," by Jos. Story Curtis, *Mon. U. S. Geol. Surv.*, No. 7. "Geology and Mining Industry of Leadville," by S. F. Emmons, *Mon. U. S. Geol. Surv.*, vol. xii., p. 540.

react upon the mineral-bearing solutions, and thus cause precipitation (see pp. 62–64). Furthermore, where limestone and stronger rocks are deformed together, the limestone, having less strength, is more likely to be crushed and broken in a complex manner and thus furnish trunk-channels for circulation.

In conclusion, I insist that ore-deposits form where there existed original trunk-channels of circulation. These trunk-channels may have been greatly enlarged by solution. This, indeed, is the general tendency above the level of groundwater, but the general tendency below the level of groundwater is to cement rather than to enlarge the openings (see p. 48). Ore-deposits formed along trunk-channels will commonly, if not universally, be to some extent in pre-existing openings and to some extent as a substitution for the wall-rock. Where the trunk-channels are simple and the rocks are refractory the ore-deposits to a large extent are likely to be in pre-existing openings. Where the trunk-channels are complex and the rocks soluble the ore-deposits to a large extent are likely to be replacements.

Character of the Topography.

Effect of the Vertical Element.—Where the topography is marked the underground circulation is likely to penetrate much deeper than in regions where the variations in topography are slight.

In mountainous and elevated plateau regions the lithosphere is likely to have more numerous, larger, and deeper openings than low-lying areas. Elevated areas are those of comparatively recent orogenic or epeirogenic movement. Therefore they are regions in which the rocks have recently been deformed and fractured, and hence the processes of cementation would have been less likely to have closed the openings. In regions of very steep topography the tendency for the material to glide down the slope under the stress of gravity also tends to widen openings which have been once formed. Such movements are known to be effective to the depth of hundreds of meters. It is hence clear that elevated and rough regions are those in which the underground circulation is likely to find large, numerous, and deep openings.

Furthermore, elevated and mountainous regions are those in which the underground water has the greatest difference in head, and this is favorable to deep circulation.

Thus, in mountainous regions, like the Cordilleras, it would be expected that the underground circulation both ascending and descending would be effective to greater depths upon the average, than in regions of gentle topography like that of the lead and zinc district of southwestern Wisconsin (see Fig. 7, p. 120), where it is perhaps probable that the scope of the effective circulation, ascending and descending, is confined to a vertical distance of 500 meters or less.

Unfortunately, the majority of descriptions of mines do not say anything as to the level of groundwater. In the San Juan district of Colorado, which is a region of very rugged topography, Purington states* that the level of groundwater is far below the surface, and that oxidizing effects are produced at a depth of 300 meters or more, thus confirming the conclusion that the zone of descending water is increased by rugged topography, and it can hardly be doubted that the zone of effective ascending circulation is equally increased.

Effect of the Horizontal Element.—The horizontal position of an ore-deposit with reference to topography often has an important influence upon its richness and magnitude. If the correct theory of circulation of underground waters and the deposition of ores has been given, certain corollaries follow from this theory with reference to this point.

(1) Commonly ores deposited by ascending waters would be formed below the valleys, or at least below the lower parts of the slopes; for these are the places where waters are ascending in the trunk-channels. (2) Commonly ores deposited by descending waters would be formed below the crests or below the upper slopes of elevations; for these are the places where water would be descending. Probably the upper slopes would be more favorable places than the crests; for at an annular belt upon the upper slope of an elevation the quantity of descending waters would be greater than at the crests. (3) Commonly ores which receive a first concentration by ascending waters and a second concentration by descending waters would be on the slopes,

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* "Preliminary Report on the Mining Industries of the Telluride Quadrangle, Colorado," by C. W. Purington, 18*th Ann. Rept. U. S. Geol. Surv.*, pt. iii., 1896-97, pp. 825–827.

probably in many instances nearer the valleys than the crests. At such places the meteoric waters falling at the higher elevations would have sufficient head to deeply search the zone of fracture for ores. Therefore, the ascending circulation in trunk-channels would be strong. Furthermore, at such places the level of groundwater would be a considerable distance below the surface, and abundant descending waters would be concentrated in the upper parts of the openings. (See Fig. 6, p. 55.) The downward migration of the belt of weathering would furnish the final favorable condition for the accumulation of a large amount of second concentrates by descending waters.

Admirable illustrations of ore-deposits corresponding to the second of the corrollaries are furnished by the iron-ore-deposits of the Lake Superior region. These are the products of descending waters, and the great majority of the ore-deposits are found near the tops of hills or upon the upper slopes.

An excellent illustration of the third corrollary is furnished by the lead and zinc district of the upper Mississippi valley. Chamberlin* notes that in the valleys of Wisconsin part of the district the waters generally ascend to the surface; therefore, at such places only a first concentration would be expected, and it is the general impression among miners that a lode makes better on the slope of a hill "than at the summit or at the foot of a hill."† Furthermore, it is held by the miners that the lodes which run parallel to a contour of a hill "like an eave-trough," are more likely to be rich than those which run toward the summit of the hill.‡ Both of these practical conclusions of the miners are fully explained by the theory of a first concentration by ascending waters, and by a second concentration by descending waters when considered in connection with the topography.

The above conclusions concerning the relations of ore-deposits and topography are only perfectly applicable in regions in which the drainage lines have been reasonably stable. The Lake Superior region and the lead and zinc district of the upper Mississippi valley are regions of stable topography. The main drainage lines have probably not been greatly modified

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* Chamberlin, *cit.*, p. 565.

† Chamberlin, *cit.*, p. 563.

‡ Chamberlin, *cit.*, p. 356.

since they were established at the close of the Cretaceous period of base levelling. This is certainly true of the lead and zinc district; but in the Lake Superior region the drainage lines have been to some extent modified by the glacial invasions.

In regions in which there have been recent important changes in the positions of the drainage lines and elevations, the generalizations are only partly applicable. It is well known in consequence of the varying hardness of rocks, in consequence of their structure, in consequence of the unequal strength of streams and unequal declivity, that drainage lines are almost constantly shifting, and in many regions somewhat rapidly. Consequent on this shifting, many ore-deposits which, when below valleys, received a first concentration by ascending waters, are now well up on slopes or even at crests. A change of this kind would be especially favorable to the development of ore-deposits which are due to two concentrations, the first by ascending and the second by descending waters. In an early stage of the history of a deposit it would be in the most favorable place to receive a first contribution of ore. Later, when, as a consequence of a topographic change, it was on higher ground, it would then be in a favorable place for the work of descending waters. Although it is difficult to prove, I have little doubt that many ore-deposits have had this very favorable history.

Many other ways could be suggested in which changing topography would be favorable or unfavorable to further concentration of ores. However, I shall not attempt this, but suggest that geologists in various regions study the ores in connection with the topographic development of the region. Such studies will furnish facts upon which safe generalizations may be made.

Physical Revolutions.

The genesis of many ore-deposits is undoubtedly further complicated by physical revolutions of various kinds. After an ore-deposit has partly formed, either by ascending or descending waters or both, the region may go through a physical revolution, and after the revolution the concentration of the ores may again be taken up by Nature's processes.

After an ore-deposit has been formed the country may be reduced to the level of the sea either by denudation or subsidence; there be deeply buried under sedimentary rocks; may be again uplifted, and undergo a second cycle of reactions which affect the nature of the ore-deposits. An ore-deposit partly formed may be buried deep under volcanic rocks. This undoubtedly has occurred on a great scale through the great period of Tertiary vulcanism in the Cordilleras of the West. The ore-deposits there buried are placed in a new environment, and are undergoing a second cycle of concentration or depletion. When in the future denudation shall have stripped off these volcanics, these ore-deposits will be at the surface. This may not occur while man occupies the earth, but doubtless similar things have occurred with reference to extensive areas where mines are now being worked. It is well known that when fissures once form, these are places of weakness, and that movement has again and again recurred along the old planes. Thus, where the conditions once become favorable for ore-concentration they may recur in the same places through various revolutions. Physical changes of various other kinds may take place. Each of the complex changes in physical history will produce its effect upon an ore-deposit.

General.

It is clear from the foregoing that an ore-deposit may not represent the work of a single period of ascending waters, but may include several alternating periods of ascension and descension, and in this way irregularities in certain of the ore-deposits in very ancient rocks may be explained. However, it appears probable in many cases that the main work of ore deposition has been the result of a single concentration by ascending waters and a single concentration by descending waters.

Any of the special and local factors above discussed and others may in an individual case be so conspicuous as to appear to be a controlling factor in the formation of an ore-deposit. One might say that the existence of a given trough was the cause of the production of an ore-deposit. The truer statement would be that the factor under consideration is one essential factor among many. The porosity of a formation, the existence of a pitching trough, favorable topography, the presence of igneous rocks furnishing heat to make the waters active, and many other special factors, may, in a given case, all be essential factors, without the help of any one of which an ore-deposit would not have been produced. But no combination of these special factors will form an ore-body, if a source of the metal is not available upon which the underground waters may act. In short, each case of the formation of an ore-deposit requires the fortunate combination of many favorable factors, working harmoniously together, the absence of any one of which may prevent the concentration of the ore-deposit.

ORE-CHUTES.*

No fact is better known concerning ore-deposits than that they vary in the most remarkable fashion, both in size and richness. Moreover, these variations are both vertical and horizontal. Frequently rich deposits decrease in size or are wholly cut off with extraordinary abruptness. Other equally rich deposits may appear somewhere else on the same level or on another level in an equally strange and apparently inexplicable manner. The ore-masses of exceptional richness are generally called ore-chutes. Sometimes they are spoken of as pay-streaks, at other times as bonanzas, at other times as chimneys. In this paper ore-chute is used as a general term to include all deposits of exceptional richness or size, of whatever origin. At various places in this paper factors have been mentioned which produce ore-chutes. However, because of the very great economic importance of ore-chutes, it seems to me advisable to consider under one heading some of the more prominent of these factors, even at the risk of repetition.

Ore-chutes may be grouped into those which are largely explained (A) by structural features, (B) by the influence of the wall-rocks, and (C) by a secondary concentration by descending waters.

(A) One large class of ore-chutes may be explained principally by structural features. These structural features may be (1) the varying size, (2) varying complexity, (3) flexures, (4) intersections of fractures, and (5) later orogenic movements.

(1) A fracture through a mass of rocks is necessarily uneven. Where there are movements, it follows that the walls will not

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* For a general discussion of ore-chutes in fissures, see "The Mining Geology of the Cripple Creek District," by R. A. F. Penrose, Jr., *16th Ann. Rept. U. S. Geol. Survey*, part ii., 1894–1895, pp. 162-166.

be adjusted to each other. Where projections or complex surfaces are opposite each other, the fissure may be represented by a mere seam. Where, on the other hand, depressions or two concave surfaces are opposite each other, a widening may occur which in some cases is sufficient to produce a great room. Rooms may be partly or largely produced by solution. Rooms may be connected by comparatively large channels. Thus there may be in a single mine a succession of rooms filled with rich deposits connected with rich chimneys. It is evident from the above that there may be every variation in the width of an ore-deposit due to this factor, from zero to many feet.

It has been shown, other things being equal, that the underground circulation will follow the largest openings. Thus, wherever there are rooms, and especially where there are rooms with connecting passages of considerable width, there the most abundant circulation will be converged. Moreover, the solutions of this circulation will be derived from various sources. Hence, in the large openings more ore and very frequently richer ore will be deposited than in the narrower openings, where the solutions are both less abundant and less complex.

(2) Ore-chutes are frequent where the fractures, instead of being simple, are complex; that is, where there is a crushed zone, or zone of brecciation and mashing. It has been pointed out (pp. 62–64) that some ore-deposits are largely due to reactions between the solutions and the rocks through which they pass. Such an ore-deposit is most likely to be rich at a crushed zone, where there is every opportunity for much greater interaction between the solutions of the trunk-channels and the rocks through which it circulates than where there is a single fracture, even if the space furnished by the latter is greater than that furnished by the multitude of smaller openings. (See p. 133.)

(3) Very frequently the rich chutes of ore are located by flexures, the ore being either at the crests of anticlines or at the bottoms of synclines. As pointed out (pp. 124–131), this is especially likely to be the case where, in connection with the folds, there are impervious strata. Under such circumstances, as has already been fully explained, ore is likely to be converged from ascending solutions in the arches of pervious

strata below impervious strata, and by descending waters in troughs of pervious strata above impervious strata. In the cases cited, such as those of Australasian and Nova Scotian gold-ores and the Lake Superior iron-ores, these relations are perfectly clear; but doubtless in many mines there are minor flexures which have been overlooked, but which may be sufficient to control the movement of the circulation, and thus produce the chimneys of ore. These minor flexures may be parallel with the dip of a deposit, or they may pitch to the right or to the left of a deposit as one looks down the dip.

(4) The intersections of fractures furnish one of the most frequent explanations of ore-chutes. The intersections may be those of faulted fissures; those of fissures and joints, or the intersections of joints. In many instances one set of fractures carries the larger ore-deposits, and the intersecting set or sets of fractures are known as side fractures. In other instances the main deposits may occur in more than one set of fractures, and still other sets of less importance constitute the side fractures.

In all cases where intersecting fractures occur, there solutions will be contributed from two or more sources. The solutions will invariably have different compositions, and, therefore, precipitation will be likely to occur at the junctions. In some cases more than one set of fractures may furnish metalliferous material, while in other cases the metalliferous material may be contributed by one set of fractures and the precipitating agents by the others. In these instances where the intersecting veins all carry ore, it is easy to see why the deposits at the intersections should be unusually large and rich. However, where the side veins are small or are wholly filled with gangue material, their importance in the genesis of ore-deposits has been very generally overlooked. In many instances there is little doubt that the metallic material has been precipitated in a main fissure at or near where the side veins join through the influence of the solutions contributed by the latter veins. A very clear case of the influence of side veins is that already cited of the Enterprise mine, of Rico, Colorado, where the pay-chutes are especially rich in the main fissures at the places where barren side veins intersect them. Where ore-chutes are found to be connected structurally with barren side veins, a consideration of the minerals themselves and the minerals in the side veins ought to lead to more exact knowledge concerning the manner of the precipitation of the metal; for presumably the precipitation of the metals was connected with some of the compounds which occur as gangue in the side veins.

Side fractures may be at right angles to the main set of fractures or incline to them. They may extend directly down the dip or pitch to the right or left along the dip. Therefore, almost any curious distribution of the rich chutes may occur. In some cases a side stream either bearing metals or precipitating agents, or both, may not issue equally all along a fault or a joint, but may be largely converged into a single channel or strong spring which enters a fissure. In such cases, especially if the spring empties where there is a room produced by the structural features discussed under (1), bonanzas may be formed, such as those of the Comstock lode.

While the relative influence of the different sets of intersecting fractures is very complex, in an individual mine a close study of the number, order and relations of the fractures and joints, many of which are, perhaps, almost imperceptible, may furnish rules which will enable one to more intelligently search for ore.

Between the two cases of a trunk-channel produced by flexure, described under (3), and by cross fracture described under (4), there is complete gradation.

(5) Late orogenic movements explain certain ore-chutes. After openings have received a first contribution of ore, and are, perhaps, fully cemented by ore and gangue materials, orogenic movements frequently recur, which again fracture the ground and produce openings. Some parts of a deposit may escape fracture, while other parts may be broken. The fracturing of the broken parts may be simple or complex. The complex fracturing may produce zones of parallel fractures, zones of intersecting fractures, brecciated zones, or even zones in which the material is finely mashed. Between the parts of the deposit which have no fracturing and those in which the fracturing is of the most complex sort, there may be all gradations. The fractures may be confined to a narrow belt of a deposit or to one side of it. It may be confined within varying limits laterally or vertically. All of the above statements in refer-

ence to the main deposits applies equally well to intersecting sets of deposits; also, entirely new sets of openings may be produced. Therefore, an ore-deposit which has received a first contribution, and again is subjected to orogenic movements is in such a condition that it may again receive a contribution of ore material under the same complex laws as at first. This ore material will be distributed in the same irregular manner as that of the first contribution. Therefore, the new material will not only be distributed irregularly, but will be superimposed upon the old material, which also had an irregular distribution, and thus there will be extraordinary variations in richness.

(B) Ore-chutes in many cases are explained by the influence of the wall rocks. It is well known that where ore-deposits intersect a complex set of rocks, that the pay-chutes are likely to have a decided preference for one rock rather than the others. For instance, if a fissure passes from granite to diorite, or from either of these to limestone, or from any of these to sandstone, the character and richness of the deposit may vary greatly as the rock changes. For this variability, due to the character of the wall rocks, different explanations apply in different cases. (1) In some instances the restriction of the ore-chutes to one rock is largely explained by the more ready solubility of that rock. This is particularly applicable to the substitution deposits, the wall rock being dissolved *pari-passu* with the deposition of the ore. By the solution of the soluble rock sufficient room is furnished for a large ore-deposit. The above is undoubtedly the partial explanation in many cases of the preference of the ores for limestone rather than to the adjacent more insoluble rocks. (2) In other instances the preference of the rich and large bodies to one wall-rock rather than another is due to the fact that the wall rock itself, by reaction upon the solutions, precipitates the ore material. This may also partly explain the preference of certain ore-deposits for limestone. (3) In still other instances the wall rock itself furnishes solutions containing metalliferous material which is precipitated in the trunk-channels, or furnishes solutions capable of precipitating metalliferous material in the trunk-channel.

(C) A third class of ore-chutes are those produced by the processes which have been so fully explained in this paper, viz.:

the secondary enrichment of a deposit by descending waters, the first enrichment of which was produced by ascending waters. By this process rich ore-bodies, either oxidized or sulphuretted, or partly each, which are limited in depth by the distance to which the descending waters are effective.

General.—Of necessity, in this analysis, the various factors which may produce ore-chutes have been separately treated. However, in a given case it is rare, indeed, to find that the entire explanation lies in the application of a single one of them. To explain an ore-chute of an individual mine, ordinarily a number of the above causes need to be combined, and in some cases, doubtless, other causes which have not been treated. No study is more important economically, more fascinating, or more difficult in a given district or mine than to ascertain the particular combination of factors which produce the ore-chutes.

From the foregoing it is plain that no general statement can be made in explanation of ore-chutes. In each individual district, more, in each individual mine, still further, in each individual part of a mine, all the phenomena there occurring must be closely studied in the light of a correct theory of ore-deposition in order to reach an explanation applicable to the particular case.

It is well known in the districts which are mineralized that the workable ore-deposits are ordinarily confined to relatively small areas, although, so far as one can see, the amount of metalliferous material to furnish ore-deposits may have been the same throughout the districts. The explanation of the lack of workable ore-deposits for larger parts of the districts ordinarily lies in the lack of the favorable combination of the various special factors mentioned, and doubtless many others which have not been considered. As better illustrating my meaning, I may again mention the iron-ores and copper-ores of the Lake Superior region. The iron-bearing formation has an extensive occurrence throughout the Lake Superior region. The workable iron-ores are, however, confined to small areas, in which there have been happy combinations of ancient and recent metamorphism combined with favorable structural features. The Lake Superior copper-deposits equally well illustrate the principle. All of the mines now being exploited are confined to an exceedingly narrow area on Keweenaw Point. But the copper-bearing rocks occupy an extensive area about the entire Lake Superior basin. Moreover, these copper-bearing rocks are mineralized in many places, as is shown by the widely disseminated copper. But, unfortunately, in many areas a little copper is concentrated in many amygdaloid or sandstone belts rather than in a single amygdaloid or sandstone. For instance, in certain districts scores of amygdaloid beds lie upon one another. The scoriaceous upper surface of each of these beds bear metallic copper, but none of them in sufficient amount so that the copper is a workable deposit. Had the copper deposited in a number of these amygdaloid formations been concentrated in one of them, a workable ore-deposit would have been produced.

From the foregoing it is clear that an investigation of the local factors in a district should include both those which are favorable to concentration of ores and those which prevent the concentration of ores, for a study of the latter in many districts may prevent the expenditure of large sums in exploration where the mineralization is general but the conditions are not such as to have concentrated the valuable material in sufficient quantity at any one position to warrant exploitation.

A treatise on ore-deposits, including descriptions of individual districts, necessarily deals in each area with the special factors which are important in that district. These special factors may be considered so conspicuous that the entire attention is given to them. However, it is to be remembered that each of these is subordinate to the general principles controlling the deposition of ore-deposits in all districts.

THE CLASSIFICATION OF ORE-DEPOSITS.

Before giving the classification of ore-deposits which follows from the foregoing treatment, it may be well to briefly recall the most fundamental features of the water circulation which produces the ore-deposits. First comes the action of the downward-moving, lateral-moving waters of meteoric origin which take into solution metalliferous material. These waters are converged in 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 second concentration not less important than the first, as result of descending, lateral-moving waters. In other cases a concentration by descending, lateral-moving waters alone is sufficient to explain some ore-deposits. It, therefore, 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 complete theory must be a descending, lateral-secreting, ascending, descending, lateral-secreting theory.* The descending, lateral-moving, and ascending waters are alike driven by gravity. Each performs its own work.

We have now only to bring together in summary the different groups and classes of ore-deposits which have been considered to have a satisfactory genetic classification of ores deposited by underground waters. As already noted, ore-deposits may be divided into three groups: (A) ores of igneous origin, (B) ores which are the direct result of the processes of sedimentation, and (C) 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 groundwater, group (C) 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 form of sulphuret; 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.

(c) Ores which receive a first concentration by ascending waters and a second concentration 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 and chlorides above the level of groundwater, and rich and poor sulphurets, tellurides, metallic ores, etc., below the level of groundwater. At or near the level of groundwater these two kinds of products will be more or less intermingled, and there will frequently be 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. A conspicuous example of deposits of this kind are the iron-ores of the Lake Superior region.

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 a first concentration, and that descending waters have produced a second concentration, as a result of which there is placed in the upper 50 to 500 or possibly even 1000 meters of an ore-deposit a large portion of the metalliferous material which originally had, as a result of the first concentration, a much wider vertical distribution.

To the foregoing classification objections will at once occur. It will be said that there are no sharp dividing lines between the groups and classes. To this objection there is instant agreement. Transitions are everywhere the law of nature. In another place* I have explained that there are gradations between different classes of rocks, and this statement applies equally well to ore-deposits. I even hold that there are gradations between ore-deposits which may be explained wholly by igneous agencies, and those which may be explained wholly by the work of underground water, or by processes of sedimentation. Ore-deposits which have received a first concentration by igneous agencies or by processes of sedimentation are sure to be reacted upon by the circulating underground waters, and thus a second, or even a third concentration may take place.

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* "The Naming of Rocks," by C. R. Van Hise, *Journ. of Geol.*, vol. vii., 1899, pp. 687–688.

The first concentration by igneous or sedimentary processes may be the more important or dominant process, or the additional concentration or concentrations by underground waters may be the more important or dominant processes. In some cases, therefore, the ores may be referred to as produced by igneous agencies, in others as produced by processes of sedimentation, in others as produced by these in conjunction with underground waters, and in still others as produced mainly by underground waters. Moreover, there will be found to be undoubted gradations between the different classes of deposits formed by underground waters. Ore-deposits which are precipitated almost solely by ascending waters will grade into those in which descending waters have produced an important effect, and thus there will be transition between classes (a) and (c). Similarly there will be every gradation between classes (a) and (b), and between classes (b) and (c). If this be so it will not infrequently happen that a single fissure may fall partly in one class and partly in another. Thus, a single ore-deposit may belong partly in class (a) and partly in class (c). However, in most cases a deposit will primarily belong to one of the three classes. Indeed, not only are there gradations between different varieties of the ore-deposits among themselves, but there are gradations between the ore-deposits and the rocks, for the ore-deposits, in many cases, are not sharply separated from the country-rocks, but grade into them in various ways.

In answer to the above objection concerning gradations, it may be said that I know of no classification of ore-deposits which has yet been proposed to which the same objection may not be urged with equal or greater force.

However, this retort does not give any criterion by which the usefulness of the above classification may be tested. The test is, does this classification give us a more satisfactory method of studying ore-deposits than has heretofore been possible? Will an attempt to apply this classification assist mining engineers and geologists in accurately describing ore-deposits? Will the classification, to a greater extent than any previous one, give engineers rules to guide them in their expenditure in exploration and exploitation? By these criteria I am willing that the classification shall be tested.

As an illustration of the practical usefulness of the classification, is the connection between genesis and depth. 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 is warranted. 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 oxidized 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 which we cannot hope will be duplicated at depth. However, this class of deposits may grade into first class, 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 peculiar to the belt of weathering 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 deposit belongs has a direct practical bearing upon its exploration and exploitation.

It is my hope that mining engineers and geologists will study ore-deposits in various regions in reference to the principles discussed in this paper. It appears to me that he who does this will be capable of interpreting better than before the phenomena which he finds in the ore-body or bodies with which he is particularly concerned. Of course, it is fully understood that few ore-deposits will illustrate all of the principles above given. It is appreciated that for a certain ore-deposit some few of the principles given on the foregoing pages may be the dominating ones, and that others are unimportant. But this is precisely what I should expect.

In addition to the points specially emphasized in this paper, accurate descriptions should be made of the relations of the different minerals of ore-deposits; of the occurrence of each mineral with reference to the wall-rocks; and their variations in composition, relations and richness at various depths, reckoning both above and below the level of groundwater. Moreover, such a study should include close observation of the gangue-minerals in their relations to one another and to the valuable minerals; for in many instances they may give important testimony as to the origin of the ore-deposit. In this paper, the gangue-minerals have been altogether ignored. Furthermore, a study should be made of the changes of country-rocks and wall-rocks. When a comprehensive study of various ore-bearing districts has been made, including all of these factors, and the special factors discussed on pp. 112–140, it is believed that a more satisfactory treatise upon ore-deposits may be written than has yet appeared.

Such a study of ore-deposits must be a difficult one, involving as it does, a working knowledge of petrography, of mineralogy, and of modern physical chemistry. Undoubtedly, the story of many ore-deposits will be found to be exceedingly complex, and not to come fully within the scope of the principles discussed in this paper. So far as any ore-deposit fails to do this, it will give us data upon which to state a more nearly complete theory of ore-deposits than that here proposed.