Some Problems in the Origin of the Mineral Veins*

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OF THE VARIOUS MINERAL DEPOSITS which man finds useful, by far the greater number fall into two general classes. One of these classes results primarily from the action of the surface agencies of sediment formation. The outstanding problems relating to this class lie largely in the realm of sedimentation and secondarily in the field of structural geology.

The second important class presents other, and to my mind, even more difficult questions. The temperatures prevailing in the interior of the earth are enormous. Daly[1] suggests maxima of about 1400-1600° C. The rocks here have a composition wholly different from those at the surface; the essential distinction consists in their carrying in solution large quantities of volatile matter, especially water or steam. Much of this internal material of the earth becomes a true liquid as it progresses outward toward the surface, where the confining and solidifying pressures existing at greater depths are reduced. This molten magma contains within it in embryo most of the metallic and many of the non-metallic minerals of industrial civilization. Mineral deposits formed from such solutions may be described as of magmatic origin, the word "magmatic" being here used in the larger, genetic sense.

Among deposits of magmatic origin there are again many sub-heads, based upon genesis. These subheads do not merit consideration here: the excellent discussion by Niggli,[2] who first dealt with their segregation in quantitative terms, has become a classic by now and is known to all students of the science. The segregated products from such hot solutions or magmas make up the greater part of what is here called the "mineral veins". It is with such rising solutions and with their relations to the mineral veins that I wish to deal in what follows. As will be noted, the term "mineral vein" is extended, for the purposes of this paper, to mineral deposits in all kinds of openings, whether fissures or not—an extension dictated by a need to show the relations between various types whose similarity in genesis but dissimilarity in form is conspicuous.

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* Address of the retiring President, May 3, 1935.

[1] Daly, R. A., Igneous rocks and the depths of the earth, McGraw-Hill Book Co., New York, 1933, pp. 234, 303.

[2] Niggli, Paul, Versuch einer natuerlichen Klassifikation der im weiteren Sinne magmatischen Erzlagerstaetten, Wilhelm Knapp, Halle, 1925, especially pp. 4-15.

Time is too short to discuss the composition of these mineralizing solutions. Suffice it to say here that they were formerly regarded as highly alkaline, but there is now strong reason to believe that in their early stages they are acid, rich in chlorine and fluorine, and that they become neutral or alkaline only as they approach the surface and reach late stages in their activity.[3]

APPROACHES TO THE PROBLEM

The reader may well ask, courteously but insistently, how anything at all is known about the behavior of the solutions underground and about their rôle in the deposition of minerals. Is the concept entirely subjective? Such a question frankly asked deserves at least a brief answer. The reply is of interest to the layman because it sheds light on geologic methodology. It may be of interest to the geologist because it carries in its train observations and conclusions of possible far-reaching significance.

There are three kinds of evidence. The first we may designate as geologic field observation of end products, followed by inference. The danger of such an approach formerly lay in the first step, the observation. Today, with perfected observational technique, it lies more frequently in the inference. An ideal case of observation followed by deduction (so simple as to be matched by the experience of many geologists) was observed in the Ibex mine at Leadville, Colorado: here a room had been opened by the removal of all ore in a certain body; five years later when revisited the room showed on the floor a deposit of green copper carbonate an inch thick, clear evidence of one kind of mineral deposition at the present day. Since the water by which the deposit was made dripped from the roof, we may conclude that descending waters form peculiar kinds of copper ores, in which the carbonate, rather than the sulphide radicle, predominates.

A more complex illustration of a similar reasoning may be cited. Many fissure veins, apparently formed by deposition of mineral matter in rock crevices, include fragments of the surrounding rock. It has been suggested from the position of such rock inclusions that the mineralizing solutions were dense and viscous, so as to buoy up the separate blocks of the country rock.[4] To this Emmons has replied with the demonstration from observations in mines that the progressive deposition of mineral matter around a rock fragment, still loosely attached to the wall or resting against it, may separate the rock fragment gradually from that wall until it comes to lie in the middle of the newly deposited mineral matter.[5] Moreover, Talmage has shown by observation that fragments that seem to be isolated may, in another section

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[3] Bowen, N. L., The broader story of magmatic differentiation, briefly told: Ore deposits of the western United States, Am. Inst. Min. Met. Eng., New York City, 1933, pp. 119-122, 128.

[4] Spurr, J. E., The ore magmas, McGraw-Hill Book Co., New York City, 1923, pp. 86-156.

[5] Emmons, W. H., The state and density of solutions depositing metalliferous veins: Amer. Inst. Min. Met. Eng., Trans., vol. 76, pp. 314-317, 1928.

farther away, be found still to be attached to the wall and hence not really "floating" in the vein matter at all; they merely appear to be unattached to the wall because they are not immediately contiguous to it at the point where studied.[6] These and numerous other field observations, plus inference and experimentation, lead us, after some pitfalls, to the conclusion that the solutions from which our mineral veins are deposited have low viscosity, despite the apparently contrary testimony of included fragments of wall rock.

Finally, in some cases the mine and its ore bodies are no longer accessible because of flooding, and the facts themselves must be inferred. Thus, at the Hilltop Mine, near Alma, Colorado (Fig. 1), the question arose as to why the ore occurred where it was found. A study of the plan of the stopes or openings as shown on the mine map pointed clearly to the occurrence of ore along fissures, though all ore had been removed and the mine itself was flooded and could therefore not be visited. A careful examination of the surface geology served to confirm this conclusion.

In recent years the microscope has been one of our most useful allies in outlining the laws that govern mineral genesis. For this purpose the petrographic microscope with transmitted light was not greatly helpful because most of the ore minerals are opaque. But about 1915 the reflecting microscope came into general use, and microscopic observation of the behavior of unknown minerals when treated with various reagents soon grew to be the readiest means for identification. A recent innovation now in general use is the reflecting microscope with polarizing nicols. The light enters through a polarizer, the plane of polarization is rotated by reflection, and the analyzer is then used much as in the petrographic microscope. Anisotropic minerals, such as marcasite, have at least a slight extinction which frequently serves to contrast them with isotropic ones, such as pyrite, despite identity in other characteristics, especially chemical composition.

Less readily resorted to but of increasing importance lately as bearing on the origin of the mineral veins is a second kind of evidence, chemical experimentation, in which the ultimate products resemble those of nature. I shall mention only one illustration. Buehler[7] and his associates have shown that soluble salts of lead may be made to react slowly with hydrogen sulphide in a U-tube filled with silica gel. The two reagents are placed in opposite arms of the tube. The products are small but well-formed crystals of galena (PbS). The possibility that our galena deposits are formed by analogous reactions from warm chloride solutions is thus brought to our attention.

By far the most striking and newest is the sort of evidence that is intermediate between field observation and laboratory experimenta-

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[6] Talmage, S. B., The significance of "unsupported" inclusions: Econ. Geol., vol. 24, pp. 601-610, 1929.

[7] Buehler, H. D., and Monroe, C. J., Laboratory formation of minerals: Mo. Geol. Survey 57th Bienn. Rept., Appendix V, pp. 1-4, 1933.

tion. Near the southeastern edge of the Aleutian Archipelago of Alaska is an active volcano, Mount Katmai. If previous reasoning, already outlined, is correct, this is a region in which ore deposition might well be anticipated. The bordering area, loosely referred to as the Valley of Ten Thousand Smokes, has therefore repeatedly been visited by scientists from the Geophysical Laboratory of Washington. In 1919 one of the porous lava fields was carefully surveyed and its minerals

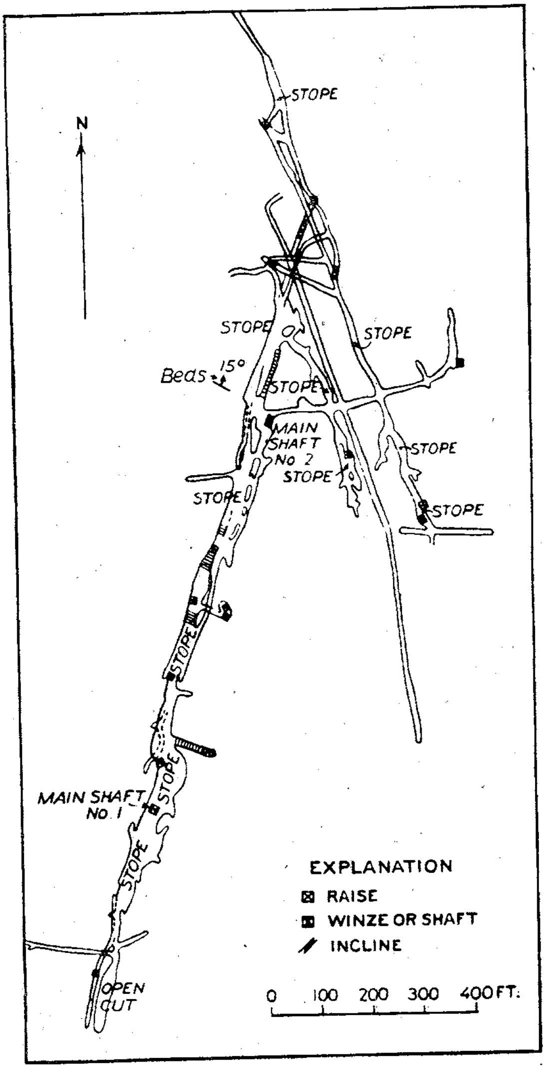

Fig. 1. Plan of Hilltop mine, Leadville, Colorado. The major part of the stoping is on northeast and northwest trending fissures.

studied. At one little gas vent Allen and Zies[8] recorded a temperature of 239° C., together with the formation of noteworthy amounts of magnetite. This locality was revisited in 1923 by Fenner,[9] who found that the temperature of the rock at the identical spot had fallen to 97° C., and that magnetite was no longer present; instead sulphides of lead, zinc and copper abounded. Here, then, was a natural experiment, as it were, enabling us to picture and to partially understand the sources and processes of ore deposition and to connect a change in temperature with a change in mineral character.

THE MODERN PICTURE OF MINERAL VEIN FORMATION

From evidence acquired by methods just suggested, we may outline our present-day concept of deposition of the mineral veins. As large masses of molten and highly heated igneous rock approach the surface they set up strains and mineralogic changes in the country rock that develop fractures. Along the resulting openings, the volatile constituents rise to regions of reduced pressure. In such openings they gradually deposit their contents, building up mineral crusts rich in the metals, rich also in such nonmetallic products as fluorite and barite, calcite and the ubiquitous silica gels and quartz. The fascinating story of the acceptance of this viewpoint has been well outlined by Adams,[10] and need not be further reviewed here.

The principal question, "Through what agency and from where did most of the mineral veins receive their contents?", may be regarded as settled, but many lesser problems remain to occupy us and to three of these I wish to direct your attention, however briefly, in the time remaining. That which has gone before is a mere restatement of what is now generally accepted. What follows is original and largely controversial matter.

PROBLEMS IN THE ORIGIN OF THE CONTACT METAMORPHIC ORES

In many mining districts the magma came close to the surface by intruding its way through the overlying sedimentary rocks before cooling and solidifying. Commonly the form assumed is that of a plug. The Bingham, Utah, district is such a region. Here an igneous mass, roughly cylindrical, about a mile wide, and made up of a granite-like rock, forced its way across beds of sandstone and limestone. At its edges its intense heat has altered the friable sandstone and made of it a dense, well-cemented quartzite. The greatest change is found in the calcareous sediments, however. Near the intrusion the former limestone is hard and dense and consists of calcium silicates, new minerals such as garnet having been developed. Farther away such new min-

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[8] Zies, E. G., The Valley of Ten Thousand Smokes,—the fumarolic incrustations and their bearing on ore deposition: Natl. Geogr. Soc., Contributed Techn. Papers, Katmai Series, Vol. 1, pp. 5-6, 1929.

[9] Zies, E. G., Op. cit., pp. 18-20.

[10] Adams, F. D., Origin and nature of ore deposits, an historical study: Geol. Soc. Amer., Bull., Vol. 45, pp. 375-424, 1934.

erals are lacking and the rock consists only of its normal constituent, $CaCO_3$; but its color, elsewhere blue-gray, is here altered to white and the rock is marmorized. Still farther from the intrusion the limestone is unaltered. With these changes in the country rock goes a general occurrence of ore. The ore minerals, chiefly galena, sphalerite, chalcopyrite, and pyrite, are especially conspicuous near the intrusion, forming irregular masses in the limestone where it has been most altered.

The recognition of the relation between ore and contact alteration can be traced through the studies of Van Cotta in 1865, of Von Groddeck in 1879, and of Vogt at Kristiania, Norway, in 1894[11] to those of Spurr, Garrey and their associates in the Mexican mining camps in 1908.[12] Spurr and Garrey reported a regular sequence of mineral development: the metasilicates formed nearest the intrusion; orthosilicates (strangely enough) were farther away; sulphides of iron were generally found still farther away; and quartz and carbonates were most distant. Thus it is suggested that the temperatures obtaining in successively more remote shells were dominating factors in determining where a particular mineral should be found with relation to the intrusive igneous rock, and that the minerals transported farthest were the most soluble at lower temperatures.

The fact that temperature is perhaps the prime factor in the distribution of contact metamorphic minerals is indicated in another way also. Emmons[13] has recently pointed out that few if any important contact metamorphic deposits are found around the larger stocks—those exceeding five miles in diameter. If we look upon the stock as the source of the ore minerals, the surprising absence of ore around large, as opposed to smaller, stocks can best be accounted for by the dispersing effect of the greater heat that is yielded by the larger body; smaller bodies carry no such great quantities of surplus heat; they do not "distil" the available ore to such great distances and hence the ore is found in denser quantity near the intrusion; even though the aggregate amount of mineralization may actually be less, concentration is greater.

To date most geologists have looked upon the metamorphism as essentially static; all the products involved were commonly supposed to have been deposited at one and the same time, the more remote as well as the closer halos, the ore minerals as well as the contact metamorphic silicates. Moreover, the time interval occupied by these changes was believed to have been relatively short. But a careful examination of the mineralogic relations shows certain anomalies inimical to this interpretation. Thus, at Ducktown, Tennessee, the primary copper and iron minerals, representing the chief values in that district, were found to be

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[11] Vogt, J. H. L., Beitrage zur genetischen Klassifikation der magmatischen Differentiations-Prozesses u. s. w.: Zeitschr. f. prakt. Geol., pp. 381-399, 1894.

[12] Spurr, J. E., and Garrey, G. H., Ore deposits of the Velardena district, Mexico: Econ. Geol., vol. 3, pp. 688-725, 1908. Spurr, J. E., Garrey, G. H., and Fenner, C. N., Study of a contact-metamorphic ore deposit, the Dolores mine, etc.: Econ. Geol., vol. 7, pp. 444-484, 1912.

[13] Emmons, W. H., On the origin of certain systems of ore-bearing fractures. Am. Inst. Min. Met. Eng., Trans. vol. 115, p. 11, 1935.

distinctly later than the silicates characteristic of the inner halos; specimens of zoisite and other silicate minerals even bear chalcopyrite on their cleavage faces (Fig. 2). At Bingham,[14] as well as at Bisbee, Arizona,[15] geologists have found evidence suggesting, though perhaps not proving beyond doubt, that the metallic sulphides were formed later than the silicates.

We are today about in a position to revise our earlier conception and to more fully outline the process of contact metamorphism, and my suggestion would be that we tentatively recognize several separate steps, as follows. The first effect of the intrusion, as already shown by Barrell,[16] is to produce fractures, partly because the magma forces its way by jostling the superincumbent rock, partly because the latter undergoes chemical changes which reduce its volume and thus result in shrinkage cracks. The second step, to a certain extent overlapping the first, is silicate development, silicic anhydride coming largely from the juices of the intruding rock, but calcium, magnesium, and possibly iron ions being furnished by the sediments.[17] Third in the sequence of events, apparently, comes iron oxide deposition. That this is a later stage is shown by several observations, among them the fact, as reported from the Calumet district, Colorado,[18] that veinlets and masses of iron oxides "chink in" around the silicates formed in Step 2 (Fig. 3). Moreover, this iron oxide development may actually follow solidification of much of

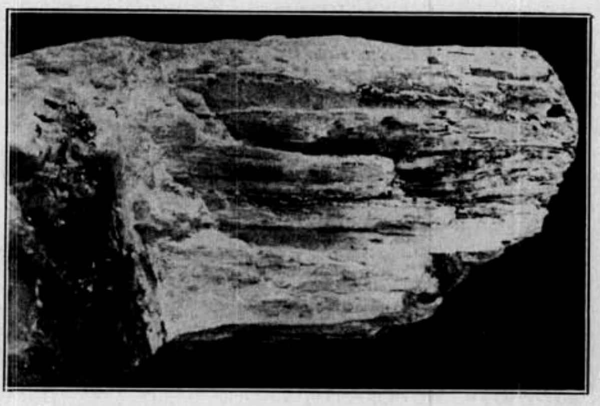

Fig. 2. Large zoisite crystal (white) bearing chalcopyrite (dark) on cleavage faces, Mary mine, Ducktown, Tenn.

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[14] Butler, B. S., Loughlin, G. F., Heikes, V. C., and Others, The ore deposits of Utah: U. S. Geol. Survey Prof. Paper III, p. 361, 1920.

[15] Ransome, F. L., The geology and ore deposits of the Bisbee quadrangle: U. S. Geol. Survey Prof. Paper 21, pp. 132-133, 150-153, 1904.

[16] Barrell, Joseph, Physical effects of contact metamorphism: Am. Jour. Sci., 4th ser., vol. 13, pp. 279-296, 1902. Barrell, Joseph, Geology of the Marysville district, Montana: U. S. Geol. Survey Prof. Paper 57, pp. 105-123, 1907.

[17] See, for example, Winchell, A. N., Petrographic studies of limestone alterations at Bingham: Am. Inst. Min. Met. Eng., Trans., vol. 70, pp. 884-899, esp. pp. 897-899, 1924.

[18] Rainwater, E. H., Osborn, E. F., and Behre, C. H., Jr., Geology of the Calumet district, Colorado: Geol. Soc. Amer., Proc. for 1933, pp. 103-104, 1934.

the igneous mass itself, for at Iron Springs, Utah, Leith and Harder[19] found veinlets of hematite cutting the intrusive rock that produced the metamorphism.

But after the iron oxides are formed the juices coming off from the deep, still liquid parts of the parent magma apparently change in composition and produce a fourth stage. Sulphide ions become prominent and the excess of oxygen is no longer present, for reasons already discussed by others.[20] Hence several minerals, the first among which is generally pyrite, fill crevices cutting across earlier minerals, or replace these earlier minerals. Crevice filling is well shown at Cornwall, Pennsylvania, where I observed a vein four inches wide and six feet long, consisting largely of pyrite but subordinately of chalcopyrite, which cut the magnetite ore body; similar facts are recorded by Callahan and Newhouse.[21] At Leadville, Colorado, pyrite replaces crystals of hematite in the contact metamorphic halo.[22] Thus, the fourth stage is represented by sulphide deposition following the deposition of the metallic oxides.

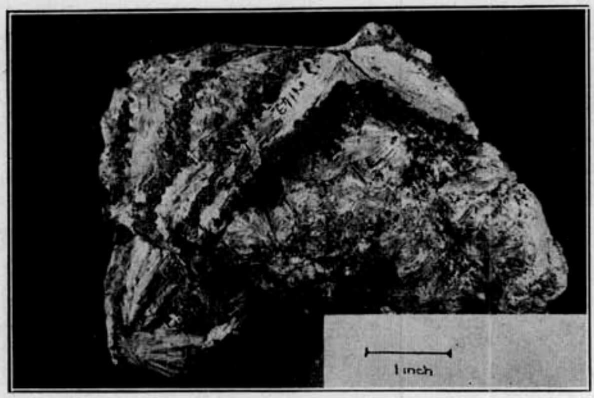

Fig. 3. Magnetite filling "chinks" between bands and crystals of a contact-metamorphic silicate (diopside), Calumet district, Colorado.

A fifth stage, finally, is shown by the substitution of other sulphides, such as pyrrhotite, for those first formed. It is under these conditions, for example, that chalcopyrite and pyrrhotite fill cracks in pyrite at Ducktown.[23]

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[19] Leith, C. K., and Harder, E. C., Iron ores of the Iron Springs district, southern Utah: U. S. Geol. Survey Bull. 338, p. 71, fig. 10, 1908.

[20] Butler, B. S., Some relations between oxygen minerals and sulphur minerals in ore deposits: Econ. Geol., vol. 22, pp. 233-245, 1927. Gilbert, Geoffrey, The significance of hematite in certain ore deposits: Econ. Geol., vol. 21, pp. 560-577, 1926. Lasky, S. G., The systems iron oxides; CO_2: CO and iron oxides: H_2O: H_2 as applied to limestone contact deposits: Econ. Geol., vol. 26, pp. 485-495, 1931.

[21] Callahan, W. H., and Newhouse, W. H., A study of the magnetite ore body at Cornwall, Pennsylvania: Econ. Geol., vol. 24, pp. 403-411, 1929.

[22] Emmons, S. F., Irving, J. D., and Loughlin, G. F., Geology and ore deposits of the Leadville mining district, Colorado: U. S. Geol. Survey Prof. Paper 148, pp. 147-148, and fig. 45, 1927.

[23] Emmons, W. H., and Laney, F. B., Geology and ore deposits of the Ducktown mining district, Tennessee: U. S. Geol. Survey Prof. Paper 139, pp. 42-58, 1926.

We are led, then, to the conclusion that the oxide ore minerals in our great contact metamorphic ore bodies are not simultaneous with the contact halos but represent, in the main at least, a subsequent deposit formed by solutions after cooling has progressed a ways. By the same token, the deposition of the sulphides is an even later step incidental to a further fall in the temperature of the intrusion.

Finally, we are tempted to venture the opinion, here offered only casually, that our so-called "contact metamorphic ore deposits" are not actually of contact metamorphic origin at all. Instead they are true mineral veins, at least as to genesis, and are only *found* at the contact. They occur there for two reasons: first, because sulphide ore bodies, like the contact halo, being in the last analysis the products of igneous emanations, generally accompany intrusions, the relations between contact aureole and sulphide ore being purely concomitant, not causal; and, second, because sulphide ores will be deposited by preference in preexisting openings, and a contact halo affords just such openings. In this possible explanation of the origin of the so-called contact metamorphic ore deposits we see again the importance of the ore-bearing liquors as a source of our mineral veins.

PROBLEMS IN THE ROUTES OF MINERALIZING SOLUTIONS

Until the beginning of this century a concrete picture of the movements of the solutions through the rocks was not available and, like the House of Peers in Gilbert and Sullivan's charming opera "Iolanthe", we

"———— Did not itch
To speculate on matters which
We *could* not understand."

Today we grasp this process better. I have mentioned the famous copper mining districts of Bingham and Bisbee. Most of the metal produced in each of these two camps comes from huge hills of igneous rocks, essentially quartz monzonite. A careful examination of such rock shows it to be intensely shattered. Tiny fissures, running through it in every direction, bear ore. In such a case the mode of ingress of the mineralizing solutions is therefore well established by geologic observation and inference, and mineralization must have followed the solidification of the rock.

In most deposits the fractures that might serve as channels of ingress are even more conspicuous and outline the mineral body, because they ultimately become choked with the deposit itself. Any of the well known fissure veins might be used to illustrate this type of origin. The form of such channels may be determined by studying the vein itself, or through inference from vertical sections drawn through the workings, or through a study of the ground plan, as illustrated in the Hilltop mine already mentioned.

In the case of still other mineral deposits there are reasons for assuming that the solutions have entered the rock from moderately distant igneous sources, but the channel of ingress itself is not obvious. We look for fractures or faults extending across the bedding planes and can find few or none. In such cases the burden of proof rests upon any geologist who might seek to maintain that the ore was derived by deposition from solutions travelling for appreciable distances through the rock mass.

For years, now, geologists have contended that the great lead and zinc deposits of Illinois and Wisconsin, as well as those near Joplin, Missouri, could not have been formed by solutions emanating from igneous rocks down deep because there seemed to be no recognizable larger fissures, no recognizable faults that carried to sufficient depth to serve as channelways.

The lead-zinc mines in northern Illinois are no longer accessible, but in two mines in the same general district, the Crawford and Trewartha mines near Hazel Green, Wisconsin, which we have recently carefully studied, we have been able to find just such fissures. They break across the beds, they displace the strata, and they are mineralized, that is, they carry openings in which ore is actually found. Along them, therefore, ore solutions were able to travel. It is well to remind ourselves that these observations do not prove that the solutions rose upward from igneous masses, but they do make possible acceptance of an ingress from such deep sources.

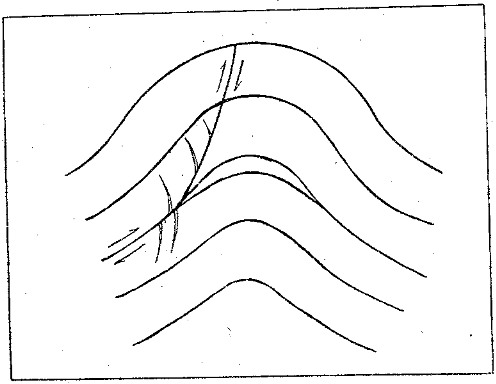

Fig. 4. Diagram of folded anticline composed of relatively competent beds. Arrows show direction in which faulting tends to move. Note minor tensional fissures subsidiary to the major fault.

Why, in certain districts like that just cited, are the fractures that serve as channelways so difficult to find? I believe that the answer lies in our failure to recognize the form which they might typically assume. In this connection I wish to direct attention to a diagram showing what happens if we compress a series of strata (Fig. 4). Let us remember that these beds already possess well-defined planes of parting, the bedding planes. When folded, the beds glide upon each other, the stratigraphically higher beds moving uphill with respect to the lower ones. Such movements produce shear by friction in the rock adjacent to the bedding plane along which the gliding occurred. Thus, even in advance of visible faulting that transected the beds, gliding planes and subordinate shear openings may be formed. On the crest of the fold, however, the gliding movement passes into a fault, generally a reverse fault. Accessory tensional fissures and, if the fault plane is curved, further movement between beds are likely to result and thus to furnish added channels.

Without seeking to analyze the process any further, we may note that the recognizable fault plane passes downward parrallel to the bedding and seems to disappear. But the movement, the consequent shattering, and the development of channels for ingress of ore solutions have now taken place, and the faulting may continue along the bedding, difficult to recognize though it be.

PROBLEMS RESPECTING THE SHALLOW-VEIN TYPE OF ORE

I now wish to turn to a more strictly mineralogic problem, represented by a class of ore deposits peculiarly interesting to the people of this State, the lead and zinc deposits of northwestern Illinois. In a local audience their former importance need scarcely be emphasized. Our lead ores have been worked since 1690, when, at Peoria, Illinois, lead was purchased from Indians by French traders. As recently as 1913 Wisconsin and Illinois together still produced 3 per cent of the world's zinc and it has been estimated that previous to 1905 the value of zinc produced by Illinois, Iowa, and Wisconsin totalled $10,000,000 and that of lead $50,000,000.[24] This mining industry was formerly the mainstay of the great smelters at LaSalle and Peru, Illinois.

The ores in Illinois and Wisconsin resemble in a most striking way other deposits widely scattered over the world. If the figures for 1913 are taken, such deposits produce annually about 20 per cent of the world's lead and more than 40 per cent of its zinc.[25] The Belgian zinc deposits of Moresnet, the center where large-scale zinc smelting methods were first developed, belong here; so do the yet more important ones of Silesia, now controlled by Poland. In Sardinia and in northern Spain there are others of the same general type. The class is best displayed, however, in the interior of the United States. Here it is represented by the deposits in Illinois, Iowa, and Wisconsin; by the so-called Tri-State district (actually embracing contiguous parts of the four states Oklahoma, Missouri, Arkansas and Kansas); by the lead, zinc, fluorite, and barite deposits of southern Illinois, eastern Missouri, and western Kentucky; and by the several zinc deposits in the Paleozoic rocks of the folded

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[24] Compiled from data furnished by the U. S. Bureau of Mines and the U. S. Geological Survey.

[25] Smith, G. O., and Others, World atlas of commercial geology, U. S. Geol. Survey, Washington, D. C., pp. 42-46, Plates 33-40, 1921.

Appalachians. In the United States this class of deposits has by common consent been designated the Mississippi Valley type of ore.

Certain features characterize these deposits wherever they are found. The mineralogy is simple. The common primary ore minerals are the usual iron sulphides (pyrite and marcasite), galena, sphalerite, and small amounts of chalcopyrite. The gangue minerals, too, are few and uniform. They consist chiefly of dolomite; calcite, in two contrasting habits whose crystal forms are essentially scalenohedral and rhombohedral respectively; well-crystallized barite; and, to a lesser extent but locally important, fluorite. Finally there are present in some deposits large quantities of crystalline and cryptocrystalline silica—quartz and chalcedony (chert) respectively. Peculiar interest attaches to the recognition of tetrahedrite in mines at Picher, Oklahoma;[26] to the finding of small amounts of enargite[27] in similar ores from northern Arkansas; and to the occurrence of small but distinct quantities of arsenic in ores from the Illinois-Wisconsin district. Tetrahedrite and enargite are generally regarded as minerals formed only from solutions of magmatic origin and the presence of arsenic in an ore suggests the presence of these minerals at least in small quantity.

There has been so much discussion as to the origin of ore deposits of this type that I hesitate to add another voice to the clamor. Yet there is one significant feature in their mineralogy that has, to my knowledge, only been touched upon in the most hesitant manner. This is their striking resemblance to certain facies of weak mineralization in districts where that mineralization has been universally attributed to solutions derived from magma bodies, solutions which may well be referred to as "rising" and "hot", without meaning to imply that they everywhere rose directly vertically or that they everywhere showed very high temperatures.

In order to illustrate the resemblance between the Mississippi Valley ores and the deposits made by weakly mineralizing but admittedly rising hot solutions, I shall take a leaf from some of my earlier work in Colorado mining camps. For an idea of a typical ore deposit where the mineralization is strong, Leadville, Colorado, may serve as an example. In such a deposit we would notice that the ore bodies follow fractures, the solutions having penetrated the country rock laterally, progressing along the bedding planes and selectively replacing certain layers. Such ores generally contain as much as 15 or 20 per cent zinc and 10 per cent lead, together with other metals, and represent bodies comparable in size to those in the Joplin district and far larger than those in northern Illinois; from these facts a picture is gained of the intense action of the mineralizing solutions. In such regions of concentrated mineralization even relatively insoluble siliceous rock, such as quartzite, may be replaced. Moreover, the mineral association is highly complex,

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[26] Bastin, E. S., Personal communication, 1933; Shipton, W. D., Personal communication, 1934.

[27] McKnight, E. T., Personal communication, 1934.

and the deposit thus appears to differ greatly from the Mississippi Valley ores mineralogically as well as structurally.

At a more distant part of the same district (Leadville), however, an entirely different picture confronts us. It should be borne in mind that ores containing 5 per cent or less of lead or zinc cannot ordinarily be worked in remote regions, such as the Rocky Mountains. Even the ore bodies that *can* be worked are "spotty" and small. Some, resembling our Illinois-Wisconsin ores, follow certain beds selectively. Others, like the vertical crevices in Illinois and Iowa, were evidently controlled by the occasional fissures found by the solutions, and along these fissures thin seams of ore were laid down or from them outward unimpressive quantities of minerals penetrated for short distances into the country rock. Most striking of all, however, is the mineralogy of such distant bodies: in the district selected as an example the predominant minerals are galena, light green or resin-colored sphalerite low in iron, pyrite, barite, scalenohedral calcite, and quartz.

It is appropriate here to make certain comparisons.[28] We see that the presence of iron sulphide (pyrite at first, later marcasite), sphalerite, galena, scalenohedral calcite, and barite is common to the Illinois-Wisconsin and to the distant facies of the Leadville ores. The relative importance of the scalenohedral form of calcite is especially striking. We find, moreover, in both types of deposits a cryptocrystalline silica. Thus, at the Ruby mine, near Leadville, a limestone breccia horizon is silicified, so that it looks almost like chert. Traces of similar silicification are known from the Illinois-Wisconsin lead-zinc district. In the Tri-State district the dark "jasperoid", as distinct from the white chert, is slightly earlier yet almost contemporaneous in origin with the sphalerite, and thus is strongly suggestive of the silicification mentioned at Leadville. Thus, reasoning by analogy, we are apparently justified in believing, contrary to the opinions of most earlier geologists, that the lead and zinc ores of northwestern Illinois and the adjacent parts of Iowa and Wisconsin were deposited from rising, warm solutions.

One more word on the subject may not be amiss, since it has a practical bearing. If the interpretation of the Illinois-Wisconsin lead and zinc ores as just given is correct, we may ultimately look toward a re-expansion of mining in that region on a moderate scale, due to deeper exploration. Such exploration will be most promising if conducted downward and immediately under the larger ore bodies now known, rather than in outlying parts of the district where only small deposits of lead and zinc minerals have been found close to the surface. At present, mining companies generally drill only to a specific horizon (the base of the Decorah formation). Deeper drilling might be anticipated in the search for ore, especially in the neighborhood of Galena, Illinois, and of Platteville, Wisconsin. The technical difficulties involved, such as

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[28] Loughlin, G. F., and Behre, C. H., Jr., Zoning of ore deposits in and adjoining the Leadville district, Colorado: Econ. Geol., vol. 29, pp. 230-244 and p. 247, 1934.

dewatering and hoisting, manifestly loom very large. Whether expansion is to be expected soon or in the more distant future depends upon many factors—upon the prices of the metals themselves and perhaps upon the price of silver (by which lead and zinc production from the mixed-metal mines of the western states is stimulated, with a corresponding glutting of the base-metal market); upon the attitude taken by local land owners in reducing initial and ultimate costs of such operations to the companies willing to take the financial risks involved; and upon the energy and enterprise of the mining corporations themselves.

CLOSING REMARKS

When I undertook to present this paper there was no intention to point the way toward any single general conclusion. In the discussion of the three phases of ore deposition which I selected I had hoped merely to contribute to a better understanding of some of the related broader theoretical problems. If I have succeeded in stirring your interest, even though it be adversely critical and combative, in certain specific questions connected with ore deposition, I shall have accomplished my primary purpose.