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LOCALIZATION OF ORE IN THE SCHISTS AND GNEISSES OF THE MINERAL BELT OF THE FRONT RANGE, COLORADO[1]

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INTRODUCTION

That part of the mineral belt of the Front Range in Colorado which extends from Breckenridge northeast to Boulder and includes the well known Montezuma, Silver Plume, Georgetown, Idaho Springs, Central City, Caribou, Gold Hill, and Jamestown districts, was the first region in the State to attain importance as a source of gold and silver. It maintained a fairly steady production of these metals, as well as of copper and lead, until 1902, when a gradual decline began in production of gold, although a considerable output of silver, lead, and copper was continued until 1917.[2] Since the World War, mining throughout this belt has been at a low ebb, and, because of conflicting opinions regarding ore possibilities the writer has delegated in 1926 to study the region and to formulate guides for further exploration. The more significant of these guides are here given a brief preliminary presentation in advance of the complete report. This paper may be regarded as supplementary to an earlier one[3] in which the broad features of the geology of the Front Range were described, but in that paper little attention was given to many details of economic importance.

Although ore deposition did not begin in the mineral belt until early or middle Eocene time, the distribution and

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[1] Published by permission of the Director of the U. S. Geological Survey and the Colorado Mining Association.

[2] Henderson, C. W., Mining in Colorado: U. S. Geol. Survey Prof. Paper 138, pp. 77-85, 1926.

[3] Lovering, T. S., The geologic history of the Colorado Front Range: Proc. Colo. Sci. Soc. vol. 12, pp. 59-111, 1929.

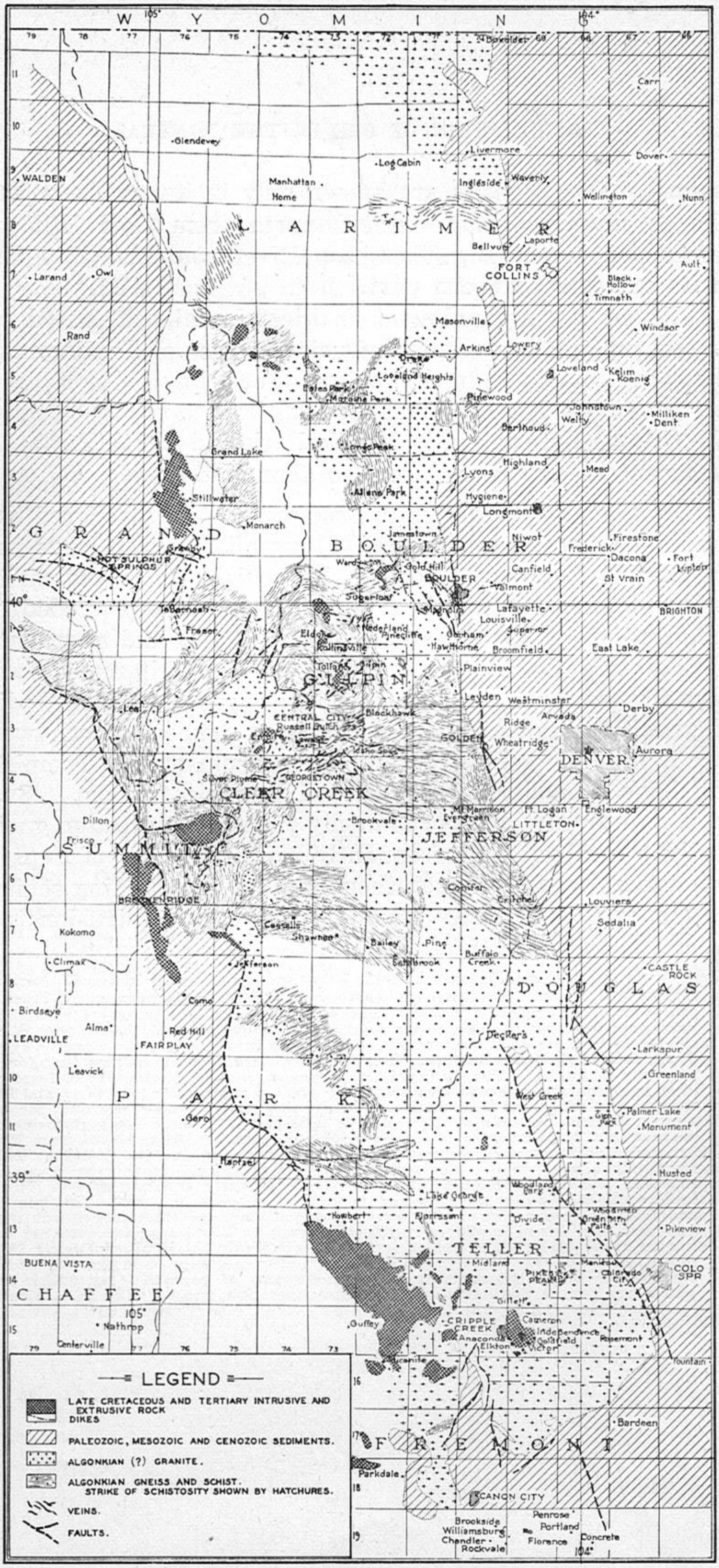
continuity of the deposits were greatly influenced by broad fundamental, as well as local, structural features, some of which were developed in pre-Cambrian and some in late Cretaceous and early Eocene time. These significant features, therefore, will be reviewed before the features of the ore bodies themselves are discussed and guides to exploration suggested.

REGIONAL STRUCTURE

Most of the Front Range consists of large masses of pre-Cambrian schist, gneiss, and granite, and small bodies of late Cretaceous and Tertiary porphyry. The regional structure of the gneiss and schist is shown in Plate I. It is comparatively simple as a whole, although the crenulations and the minor folding are very complex in some areas. Most of the schist and gneiss southeast of the mineral belt has a monoclinal dip to the north or northeast at moderate or steep angles, but within the mineral belt the schist and gneiss are commonly folded into sharp synclines and anticlines which trend northeast. On the northwest side of the mineral belt a well marked anticline, which has not been completely mapped, trends northward into Estes Park.

Several large masses of Algonkian(?) granite cut the schists and gneisses. Their distribution, as shown in Plate I, suggests that they acted as strong buttresses which withstood the stresses of Tertiary mountain building better than the less competent schists and gneisses, and thus helped to localize the fracturing of the mineral belt. The Pikes Peak batholith is the largest granite body in the Front Range, and extends from Georgetown south to Canon City. It contains workable ore deposits only in or near Tertiary volcanic pipes, notably at Cripple Creek. Northwest of Georgetown several townships are occupied by a small batholith of Silver Plume granite. Few ore deposits have been found within this batholith except near its southeastern border. The Coal Creek area of granite extends from Ralston Creek near Black Hawk to Gold Hill just north of Boulder, and has not been carefully

PLATE I



Geologic map of the Front Range, Colo.

mapped. Ore deposits are known only in its northern half. The granite area that extends north from Gold Hill and Jamestown to the Big Thompson River contains veins only in its extreme southern part.

Extrusives are unknown in the mineral belt, but dikes, stocks, and small irregular intrusive masses of Tertiary porphyry are common. In the region to the south and north such intrusive rocks are rare except near Miocene volcanic centers like Cripple Creek; and in Middle Park and North Park. At such centers extrusives are also abundant.

Relation of Intrusives to Schistosity.—It is believed that the intrusion of the Algonkian (?) granites was in large part responsible for the development of schistosity in the earlier sediments, and that much of the metamorphism preceded the solidification of the granites. Early aplites and pegmatites were abundantly injected into the schists, and in many places have formed large masses of injection gneiss[4]. Many bodies of granitic magma in the same early igneous epoch were forced into the schists before metamorphism was complete, and have a moderately developed gneissic texture. Such masses of granite gneiss commonly grade into injection gneiss at their borders, and frequently no sharp line of separation can be drawn between them and the surrounding schists. As planes of schistosity were present before intrusion took

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[4] There is a very marked difference between injection gneiss, granitized schist, granite gneiss, and schist. Furthermore, there is a difference between early injection gneiss and late injection gneiss. The early injection gneiss was formed by a very fluid injection of granitic material that usually followed the bedding of the schist, cutting across it very rarely. This early injection gneiss is nearly everywhere sill-like if it is abundant. It is probably related to the magma that formed the granite gneiss. The early injection gneiss can be distinguished from the later injection gneiss because of the much greater granulation of quartz and feldspar in the early injection gneiss. Where the early granitic material becomes more abundant than the schist which it intrudes, it forms a hard gneissic rock containing a few stringers of biotite schist and can be distinguished from granite gneiss only through the greater amount of shearing and the fact that it has commonly a gray color. The granite gneiss was formed from granitic magma that was much less fluid than the material in the early injection gneiss. It also follows fairly definite horizons and is usually sill-like in form. The quartzes and feldspars show a moderate amount of crushing and granulation, but much less than that found in the early injection gneiss. Granite gneiss does not contain as many stringers of schist as a correspondingly thick mass of early injection gneiss, but near the schist borders of a granite gneiss body there is usually a transition zone that contains many thin seams of pegmatitic or aplitic rock which can not be distinguished from early injection gneiss. The late injection

place, these early granite masses more commonly occur as sills than as dikes. Some of the sills of granite gneiss and injection gneiss are very persistent, and may be traced for miles in the Central City district. The later granitic magmas, such as the Silver Plume granite and its associated pegmatites and aplites, as well as the Tertiary porphyries, show much less tendency to follow the schistosity, and commonly occur as cross-breaking masses. Where the schistosity trends northeast and is steep, however, Tertiary dikes are commonly found parallel to it.

EARLY TERTIARY HISTORY OF THE REGION

The earliest Tertiary intrusives found in the Front Range—felsites, basic andesites, basalts, and peridotites—are believed to be contemporaneous with the Denver formation, which is at present classified as early Eocene(?) by the U. S. Geological Survey. The writer has presented evidence in his earlier paper on the Front Range for regarding the Denver formation as late Cretaceous[5], but the formation will be referred to here as Eocene(?), in accordance with the present Survey classification. During the Denver epoch the Front Range was rising, and it is probable that the complex

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gneiss is formed by the injection of the very latest pre-Cambrian rock into the schist—the pegmatite magma associated with Silver Plume granite. This late pegmatite is generally cross-breaking, but sends out many thin seams and arms parallel to the schistosity. Where these are abundant they form a typical injection gneiss. This late injection gneiss, however, is erratic in its distribution. There may be a thick mass of late injection gneiss following a given horizon for a short distance and then playing out rapidly or breaking across abruptly to a new horizon. The pegmatitic and aplitic seams of this late injection gneiss show very few strain effects. The quartz and feldspars are found fresh and ungranulated.

Granitized schist is different from any of these rocks. It is formed near intrusive bodies such as the Pikes Peak granite or the Archaean quartz monzonite and is due to the introduction of extremely fluid magma into the schist. This material was apparently so tenuous that it did not form the typical injection gneiss. Instead the solutions fed local centers of crystallization with the result that large metacrysts (resembling phenocrysts) developed. These metacrysts are chiefly orthoclase inter-grown with quartz, and they are generally aligned parallel to the schistosity. As they become abundant, the schist looks more and more like a coarse grained granite gneiss. Granitized schist is usually restricted to areas of intense metamorphism, and the shape of the granitized mass has no relation to planes of schistosity, but generally forms as an aureole around some local center of granitic intrusion.

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[5] Lovering, T. S., op. cit. pp. 91-93.

series of northwest and north trending folds which finally developed began at this time, although the Denver formation shows no angular discordance with the underlying Laramie formation. Folding continued with gradually increasing intensity during the Denver epoch and culminated in the Laramide revolution, when monoclinal folds, overturned folds, and thrust faults relieved the orogenic stresses which had accumulated. The monoclinal folds strike from north to northwest; the overturned folds and the thrust faults nearly everywhere strike north-northwest. The thrust faults dip northeast, and the folds are overturned toward the southwest and are commonly broken by reverse faults dipping northeast. After the formation of these folds and thrust faults, but still in early Eocene time, large bodies of quartz-monzonite porphyry were intruded. This intrusive activity was localized along the zone of the folded and faulted schists and gneisses of the mineral belt between the Pikes Peak and Silver Plume granites and around the western and northern borders of the Coal Creek area of granite. Tertiary igneous rocks are rare elsewhere in the Front Range, except at the Miocene volcanic centers already mentioned. Faulting preceded and followed the intrusions and produced the vein fissures that are more conveniently described later.

The larger stocks in the mineral belt caused feeble contact metamorphism of the country rock in some places. These stocks were cut by later dikes of granite-porphyry and alkalic andesite before the first strong wave of metallization occurred. It is believed that emanations from the deep parts of the differentiating quartz-monzonite magma formed the ore deposits of Summit, Clear Creek, and Gilpin counties. These ore deposits were formed before the Flattop peneplain was developed in late Eocene time and, as shown above, well after the Laramide revolution. They are provisionally classed as late lower or early middle Eocene.

GENERAL GEOLOGY OF THE MINERAL BELT

Resume of Structure.—All veins in the mineral belt of the Front Range resulted from the mineralization of earlier or pre-mineral faults. These early faults, not all of which became veins however, formed in response to regional stresses and have a definite pattern related to the regional geology. The mineral belt, as already noted, comprises sharp, northeasterly trending anticlines and synclines of pre-Cambrian rocks. Within this belt the general trend of the veins is either parallel to the edges of the belt or parallel to the schistosity, which coincides with the strike and dip of the schists and gneisses. Thus where the belt strikes northeast almost all the veins strike northeast, but where the belt strikes east the veins strike both east and northeast. However, northwesterly-trending veins in pre-mineral faults are not uncommon; and as their prevailing dip is northeast, it is probable that they are related to the early reverse faults that are associated with folds of northwesterly trend along the borders of the range.

The meager data now available suggests that, after the early period of reverse faulting, shearing movements occurred throughout the mineral belt, resulting in faults with large horizontal components of movement. Faults of this period generally have a more easterly strike than those of earlier or later periods. Normal faulting and some reverse faulting accompanied and followed the development of the shear faults, and continued actively through the period of mineralization, but rapidly diminished in importance after metallization was complete. In the northeastern part of the mineral belt most of the pre-mineral faults show a large amount of horizontal movement. In some the north wall moved eastward, and in others westward. In the central and southwestern parts of the belt, however, the movement in the shear faults was more uniform, and in general the north wall moved east. The vertical component of movement differs in different places; at Central City the north walls are commonly downthrown, whereas at Idaho Springs, Georgetown, Silver Plume, and Montezuma, in the comparatively few cases where the direction of movement is known, the south or southeast walls are downthrown.

Local Examples—The following local examples illustrate the data on which the foregoing generalizations are based. Near Nederland, in the Jumbo and Conger veins which strike north-northeast and dip steeply to the east and west respectively, the movement is reported by a company geologist to be nearly horizontal, the east wall moving south. In the Cold Spring and Orange Blossom veins a few miles northeast of Nederland, the strike is north of east and the veins dip steeply to the south and north respectively. The movement on both of these veins has been ascertained by the writer. The north walls moved west in a nearly horizontal direction. In the Central City district the Dyke or Pozo vein follows a strong reverse fault which dips to the south; the Elizabeth vein (near the breast of the Argo adit) apparently faults the Gunnell vein, throwing the northern part down; in the Slaughter House vein, which displaces the South Gunnell vein, the downthrown side is also on the north. Grooves on the walls of the Kansas vein, consistent in three widely separated places, indicate that the movement of the walls was nearly horizontal, the grooves pitching about 15 degrees west. Much of the movement in the easterly trending veins and faults of the Georgetown quadrangle was nearly horizontal, according to Spurr[6]. The southern side commonly moved west and slightly downward. He also noted that the movement was more nearly vertical in the veins of the Idaho Springs district than in the veins farther west.

In the Montezuma district the nearly vertical, east-west Ida Belle vein is later than the Williams Range thrust fault, and the south wall of the vein moved west almost horizontally. In this same district the Bell-Meteor-Wing vein, the Bullion vein, and the Saints John, or Comstock vein, follow reverse faults striking northeast and dipping northwest, whereas the Silver King vein, whose walls have deep grooves pitching about 70° northeast, follows a normal fault which strikes northeast and dips southeast. Some post-mineral normal faults strike north-northeast and dip east. Thus in the

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[6] Spurr, J. E., Garrey, G. H., and Ball, S. H., Geology of the Georgetown quadrangle, Colo.: U. S. Geol. Survey Prof. Paper 63, p. 162, 1908.

Montezuma district, in the few veins and faults where the direction of movement could be definitely recognized, the downthrown wall was consistently on the south in the northeasterly fissures and the direction of movement was moderately steep; in the east-west veins the movement was nearly horizontal and the south wall moved west, corresponding in this respect to the east-west veins near Silver Plume.

VEINS AND ORE SHOOTS

Distribution of Veins—Since the porphyry belt and the mineral belt coincide[7], a genetic relation between the porphyries and the veins has been inferred. In some places the intrusive rocks are much more abundant than in others, indicating local intrusive centers. The porphyries vary greatly in mode of occurrence, texture, and composition, but generally a local center has a group of porphyries which is characteristic of that locality only. The local intrusive centers are commonly also centers of mineralization, and may have ores which are as characteristic of them as are their porphyries. Such intrusive centers as are marked by an unusual abundance of dikes and small porphyry masses are associated with more extensive mineralization than the centers where large intrusive stocks are exposed. Thus the Central City and Silver Plume districts have proved to be more extensively mineralized than the Montezuma or Empire districts. This relation accords with Butler's generalization that ore deposits are most abundant near intrusive centers where erosion has not gone too deep[8].

A zonal arrangement of the ores can usually be found around local centers of mineralization, and in many places the outer zones of separate centers overlap. The changes of ore in depth and their relation to the metallizing center have a practical importance in the search for ore, as illustrated by the example of zonal distribution of ore considered below.

The distribution of the various classes of ore in the

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[7] Spurr, Garrey, and Ball, Op. cit., pp. 130-132.

[8] Butler, B. S., Relation of ore deposits to different types of intrusive bodies in Utah: Econ. Geol. vol. 10, pp. 101-122, 1915. See also: Emmons, W. H., Primary downward changes in ore deposits: Trans. Am. Inst. Min. & Met. Engs., vol. 70, pp. 964-997, 1924.

Central City district was early recognized by Collins[9], who in 1903 indicated a central area of pyritic gold veins, an intermediate zone of gold-silver veins, and an outer surrounding zone of silver veins. Later, detailed mapping by Bastin showed that the intermediate zone contains abundant lead and zinc, but that these metals are rarely important constituents in the ores of the inner pyritic zone. Bastin[10] states that the pyrite is early, and was followed by auriferous and argentiferous copper minerals, which in turn were followed by argentiferous lead and zinc sulphides. It seems probable that the early iron-rich solutions took the most direct route to the surface and formed pyritic deposits which largely clogged the more centrally located fissures. Solutions of the later stages, therefore, had to find their way around the central pyritic area except where renewed faulting had opened the pyritic veins. This relation suggests that in this area, where the ores are believed to have been derived from one central source, the greater distance traveled by the solutions that formed the outer zones would favor ore deposition at greater depths below the surface than in the central pyritic area. Such an ideal arrangement, however, is greatly obscured by other factors which control the localization of ore shoots.

Vertical Range of Ore Shoots—The vertical range of ore within individual mining districts of the Front Range mineral belt, is as much as 3,500 feet, and that of a single ore shoot may be great or small according to local controlling conditions. Some veins, like the Bismark vein at Silver Plume, contain single continuous ore shoots whose vertical dimensions may be as much as 1,800 feet; others, as the California-Hidden Treasure at Central City, have several shoots connected by thin or low grade stretches, and have been mined to depths as great as 2,200 feet.

Owing to the mountainous topography, however, vertical

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[9] Collins, G. E., The relative distribution of gold and silver values in the ores of Gilpin County: Trans. Inst. Min. & Met., vol. XII, pp. 480-499, 1903.

[10] Bastin, E. S., and Hill, J. M., Economic geology of Gilpin County and adjacent parts of Clear Creek and Boulder counties, Colo.: U. S. Geol. Survey Prof. Paper 94, p. 133, 1917.

range is better expressed in altitude above sea level than in depth below surface. The lowest altitudes at which ore has been mined differs in different districts. Ores near Boulder have been mined at altitudes as low as 6,500 feet above sea level; near Nederland as low as 7,700 feet; in the Central City-Idaho Springs district ore has been found as low as 7,300 feet in several veins; in the Georgetown-Silver Plume district very little ore has been found below an altitude of 8,700 feet; in the Argentine district little ore is known below an altitude of 11,500 feet; in the Montezuma district the lowest ore is at an altitude of 10,000 feet, although a few miles farther west ore is found at an altitude of 9,350 feet. An analysis of these altitudes suggests that the lowest level of ore deposition in paying quantities was distinctly higher in the west-central part of the Front Range than on either side, but this difference may have been caused by the Pleistocene arching of a nearly horizontal zone of ore deposition.

Ore may persist below the altitudes given above, but practically all the ore mined in the districts has been found well above them; some districts, however, have been much less thoroughly explored in depth than others. Long pre-mineral faults would in general be open to relatively greater depths and thus make possible correspondingly longer ore shoots, but all faults must eventually disappear along both dip and strike. In many places a zone of movement is marked by overlapping faults, and if such overlapping occurs along the dip as well as along the strike of a pre-mineral fault, blind ore shoots may exist in fractures which do not appear at the surface, but which are parallel and close to known veins. The lower limit of exploration in any district usually marks the bottom of a deep ore shoot, but not the end of the vein itself. The expense of deep exploration, however, is so high that comparatively little work is done in searching for deep blind ore shoots. In the few places where such exploration has been carried on, the search for new ore has seldom been successful, although the blind Pozo ore shoot was discovered by work from the Argo adit. Unfavorable structural conditions, rather than mere depth, may account for the high percentage of failures, but the high percentage itself should discourage deep exploration except where structural conditions, considered in the following discussion, are especially encouraging.

Localization of Ore—Surface enrichment of the ores of the mineral belt has been important only where the present surface coincides closely with that of the Flattop peneplain or the Rocky Mountain peneplain. In some veins which crop out on the Flattop peneplain, for example those on Wise Mountain in the Montezuma quadrangle, rich gold ore was limited to a depth of 25 feet from the surface, below which the ore turned abruptly into very low grade pyrite. In veins which crop out on the Rocky Mountain peneplain, such as those near the top of Republican Mountain at Silver Plume, rich secondary silver-lead ore may be found to a depth of 300 feet, passing into primary lead-zinc ore below this depth. It is believed that the ore shoots which crop out have no leached, barren zone at the surface, and it is probable that most of them have been discovered. For this reason attention in this paper will be directed chiefly to the features controlling localization of primary ore.

The influence of wall rock on an ore shoot has long been recognized in the Front Range mineral belt. The chemical character of the rocks has had little effect on ore deposition, and the explanation of most localizations of ore is to be found in the physical properties of the rocks and their consequent mechanical reaction to the regional stresses of early Tertiary time. Hard, brittle rocks, such as pegmatite, granite, porphyry, and gneiss, are the common wall rocks of the persistent ore shoots. Soft, weak, plastic rocks, such as the mica and hornblende schists, seldom form the walls of persistent ore bodies. The ore-forming solutions, in their journey from the magma to the surface, had to take the easiest possible route, and thus the most open fractures would generally serve as the conduits for the largest amount of metallizing fluid. The intersection of two fractures was more likely to be open than either fracture at a distance from the crossing, and the well known localization of ore shoots at the intersection of veins indicates that the solutions found an easy way toward the surface along such openings. The occurrence of ore where marked changes in the dip or strike are found, can usually be correlated with an ancient open space caused by the movement of the irregular walls of the fault. Thus, if the horizontal movement is small, ore tends to occur in the steeper parts of a vein following a normal fault, and in the flatter parts of a reverse fault.

In the complex pre-Cambrian mass, many different kinds of rocks may be traversed by one fissure, and the schistosity of the metamorphic rocks may be crossed by this fissure at a large angle in some places and trend parallel to it at others. A fault cutting a strong rock tends to open well defined fis-

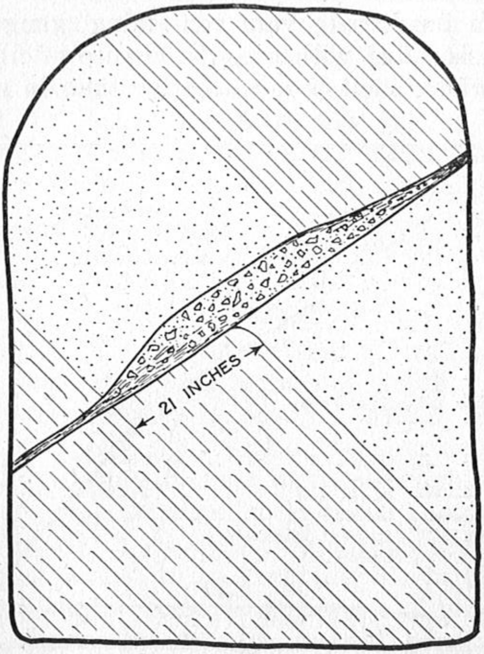

Fig. 1. Effect of a bed of quartzite on a small fault, cutting interbedded shale and quartzite.

sures, whereas it usually narrows on passing into a weaker rock. This is illustrated in figure 1 where the effect of a bed of quartzite on a small fault, cutting interbedded shale and quartzite, is shown. If the fault trends parallel to the schistosity of the wall rock it may lose its identity as a single fracture and the movement become distributed over several parallel or interlacing slips, forming a sheeted or reticulated zone. Unless the direction of the vein or the schistosity changes, such a zone is not likely to contain good ore in schist, although it is commonly productive in gneissic and granitic rocks. This relation is illustrated at the Silver Wave mine at Montezuma (shown in figure 2). The schistosity is parallel to the vein in some places and in others crosses it at an angle. The ore shoots occur where the vein breaks across the schistosity of the wall rock.

If many periods of brecciation are shown in an apparently barren but strong vein containing gangue minerals commonly associated with ore, the chance of finding an ore shoot somewhere in it is much better than in a vein which

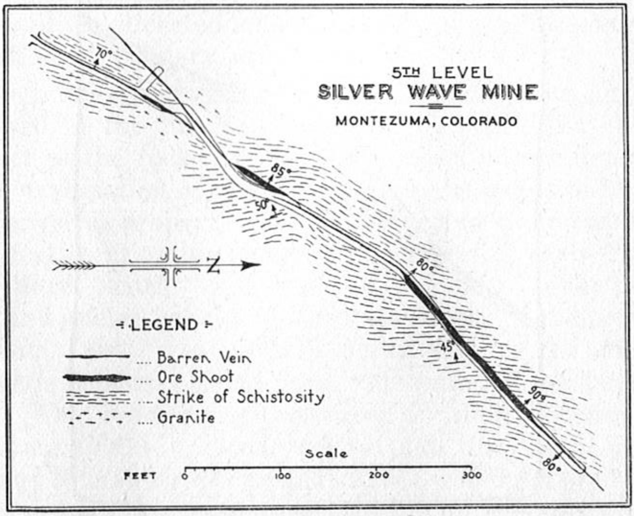

Fig. 2. Occurrence of ore shoots where vein breaks across schistosity.

apparently was never reopened after the barren filling was deposited; thus the paragenesis, or order of deposition, of the gangue and the ore may be very significant. Alteration of wall rock has been effected by solutions which were active before, during, and after ore deposition. The early alteration has little relation to ore channels, as is shown by the widespread formation of chlorite and epidote in the porphyry belt. Garnet, magnetite, hematite, tremolite, epidote, and fine grained quartz have formed early in the period of mineralization near some of the large quartz monzonite porphyry stocks which are closely related to centers of mineralization. Sericitization preceded and accompanied ore deposition, and is strongest in gold districts. It is commonly related to mineralization channels, though not necessarily to ore shoots. Pyritization and silicification of the wall rocks also preceded and accompanied ore deposition. The formation of carbonate gangue accompanied and succeeded the ore stage. The replacement of wall rocks by siderite and ankerite is very common near strong lead-zinc-silver veins, but rare near gold veins. Post-ore carbonates—generally calcite—are not related to channels of mineralization and seldom are important constituents of the rocks. Alteration to clay minerals is post-ore. Rocks slightly replaced by any of the above minerals can be found throughout the mineral belt, but strong or complete replacement by sericite, ankerite, pyrite, or quartz, generally indicates proximity to a channel of ore deposition.

The relation of fissuring to kind of wall rock becomes increasingly important with increasing depth. Close to the surface, open fissures may be common even in poorly consolidated clays and sands, but with increasing depth the fractures in such materials become tight, although open fissures may be abundant in stronger rocks much farther below the surface. Similarly in the districts under consideration, open fissures do not persist to as great depths in the relatively weak schists as in the stronger gneisses and porphyry intrusives. Accordingly in any one district profitably worked veins in schist are more abundant at high than at low altitudes. For these reasons it seems advisable to confine deep explorations to the stronger rocks.

Since structure and kind of wall rock appeared to the writer to be such important determinants of ore shoots, the practicability of mapping the pre-Cambrian structure in the Idaho Springs-Central City district was considered, but it was soon found that although the regional structure could easily be mapped, the movement on the many faults is so difficult to discover in the pre-Cambrian rocks that the detailed relations can be found only after considerable study, and will require mine maps and sections of large scale (at least 1 inch = 100 ft.) for adequate representation.

The general relations are shown in figure 3, which represents a geologic section along the line of the Argo adit. The marked influence of gneiss on the localization of ore is apparent. Most of the strong veins in the schist, such as the Frontenac, follow irregular but persistent masses of pegmatite. The Central City district is on the crest of an anticline in which the predominant rock is granite-gneiss and injection gneiss. The gneiss is interlayered with schist; and many veins cut alternate layers of schist and gneiss but contain ore shoots only where one or both walls are gneiss. The bands of granite gneiss are moderately persistent along both strike and dip and their continuations can be projected with reasonable certainty after a detailed study of the geology.

In both the Gem and California veins ore was found well below the level of the Argo adit at an altitude of about 7,300 feet. The Gem vein as shown in figure 3, is almost parallel to the dip of the granite-gneiss and is reported to be in that rock on its lowest level where ore was present. The California vein cuts across the granite-gneiss, and projection of the lowest band of gneiss found in the Argo adit suggests that it would be cut by the California vein on the lowest level near the shaft. Ore was found there, but as the vein should pass into schist below this point, it is improbable that deeper ore exists. Two hundred feet below the Argo adit the cross-breaking Concrete-Gunnell vein feathers or "horsetails" in

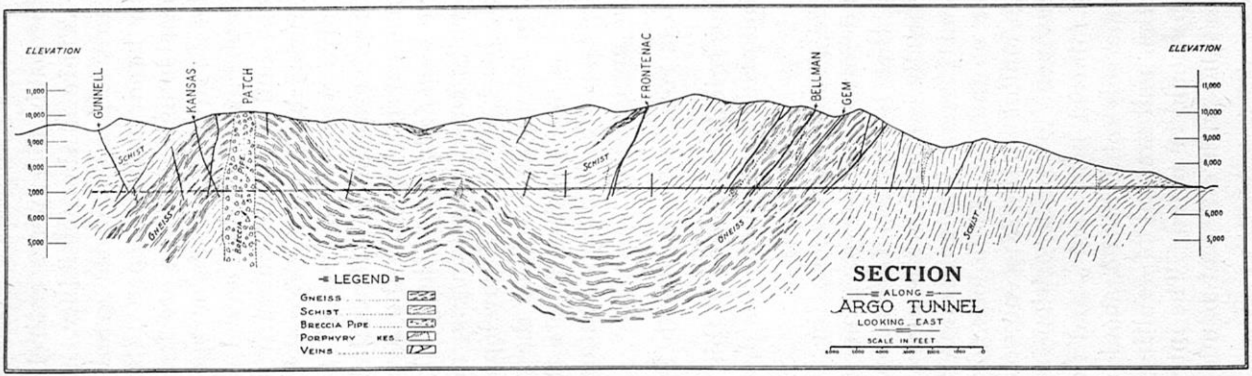

Fig. 3. Diagrammatic section along the Argo Adit from portal at Idaho Springs to end near Central City, Colo.

the schist and probably disappears entirely a short distance farther down. There is the possibility, however, that this, or a related fissure, is present in the granite gneiss, which it should cut a few hundred feet deeper. (See figure 3). The lean and unprofitable nature of the ore found in most of the veins cut by the Argo adit has discouraged deeper exploration. The adit extends under the central pyritic zone of the district, however, and it would be surprising if the veins which it cuts carried high grade ore nearby. As suggested earlier, better ores would be expected farther from the center of pyritic mineralization. Nevertheless, the extensive deep explorations, carried on from the Argo adit in some of which veins have been followed to the outskirts of the pyritic zone, have generally been disappointing, and the amount of ore found at this level per foot of development work is very much less than in the upper levels of the many veins which have been cut. It is also worthy of note that the ore in the deeper workings is more distinctly confined to strong wall rocks than in the upper levels.

SUGGESTIONS FOR DEVELOPING AND PROSPECTING

The data thus briefly presented in this paper may be expressed in the following suggestions for developing and prospecting:

As the large granite masses in the Front Range adequately resisted deformation, the pre-mineral fissuring and igneous intrusion that led to the formation of metalliferous veins were essentially confined to the narrow band of schists and gneisses that is now recognized as the mineral belt. There is little or no inducement to look for ore elsewhere in the Front Range, unless at the Miocene volcanic centers that were active subsequent to ore deposition in the mineral belt.

Within the mineral belt, faults and fissures, no matter how heavily or sparsely mineralized, should be mapped in detail. The direction and amount of faulting and the changes in strike and dip should be noted. The intersections of veins with one another and with different bands of schist, gneiss, or granite, should be projected. If the variations in dip of a vein are determined by geophysical methods, drilling, or exploration and mapping, the parts with steep dip should receive consideration if the vein occupies a normal fault; the flatter parts should be prospected in a reverse fault. If horizontal movement is prominent in a vein, changes in its course or intersections with other veins should be studied. Knowledge should be obtained of the wall rock and the position of the vein with reference to the nearest center of mineralization. Zones of pronounced sericitic, pyritic, ankeritic, sideritic, or silicic alteration should be investigated.

With these data in hand, it should be possible to ascertain the local factors controlling any ore shoot, and the scale of development could be planned accordingly. Thus in the Central City-Idaho Springs district, if a sparsely mineralized vein crops out in a schist area at the outer edge of the pyritic zone, and granite-gneiss is known to underlie the schist at no great depth, there is a strong probability that ore will be found where the vein cuts the granite gneiss. This is illustrated by the Pozo ore shoot. If a vein is followed downward through granite-gneiss into schist and the metal contents decrease where the schist is encountered, further sinking on the vein would be justified if a study of the geology indicates that the vein should cut another layer of granite gneiss below the schist and above an elevation of 7,300 feet. The occurrence of an ore shoot in the schist or in unexposed masses of pegmatite, granite, or porphyry, is so unpredictable that, if there is no likelihood of encountering gneiss above 7,300 feet, there is little justification for further development of the vein. The possibility of an ore shoot occurring in favorable wall rocks below an altitude of 7,300 feet is worthy of consideration, but exploration should be undertaken only after the costs of deep mining and the factors that should control ore occurrence at such altitudes have been carefully weighed.

Although the bottom limits of ore in the mining districts of the mineral belt seem fairly well defined by experience, in many districts there is considerable ground above these bottom limits that may be worth exploring. The writer believes that the best way to search for new ore bodies is to make a detailed study of a given locality, mapping the formations and fractures on a scale of about 100 feet to an inch. Then to explore those places where the combination of factors, which are believed to control ore deposition, is found to be most favorable.

DISCUSSION

George E. Collins, Denver, Colo.: Mr. Lovering's paper opens up what is, to me, a new conception. We have been accustomed in Gilpin County to assume that gneiss, schist, and pegmatite in the Idaho Springs formation, were an inextricable jumble; that the utmost we could do in mining was to predict from the dip and strike their occurrence a short distance beyond the place where we actually found them. The folding indicated on Mr. Lovering's section (Fig. 3) I never observed, and never heard of anyone else doing so. Bastin and Hill do not seem to have referred to it in their report[1]. If Mr. Lovering is right, and the folds of gneiss and schist can be mapped like ordinary folded sedimentary strata, which the schist at least probably originally was, and their position in depth inferred approximately from sections, the miner may be materially assisted.

In discussing the evidence for and against continuance of ore in depth, Mr. Lovering bases his argument on the depths to which, in various areas, mines have been worked. This is an argument based on history rather than on geology. When a geologist makes his appeal to history, he should rely, as far as possible, on contemporary authorities; and weigh the competency of the authorities cited.

It is assumed that when mining stopped at a given depth, it was for the reason that the veins ceased, or virtually ceased, to carry ore at that depth. This assumption over-

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[1] Bastin, Edson S., and Hill, James M., Economic Geology of Gilpin County and adjacent parts of Clear Creek and Boulder Counties, Colorado. U. S. Geol. Survey Prof. Paper 94, 1917.