COPPER.

COPPER DEPOSITS NEAR SUPERIOR, ARIZONA.

By F. L. Ransome.

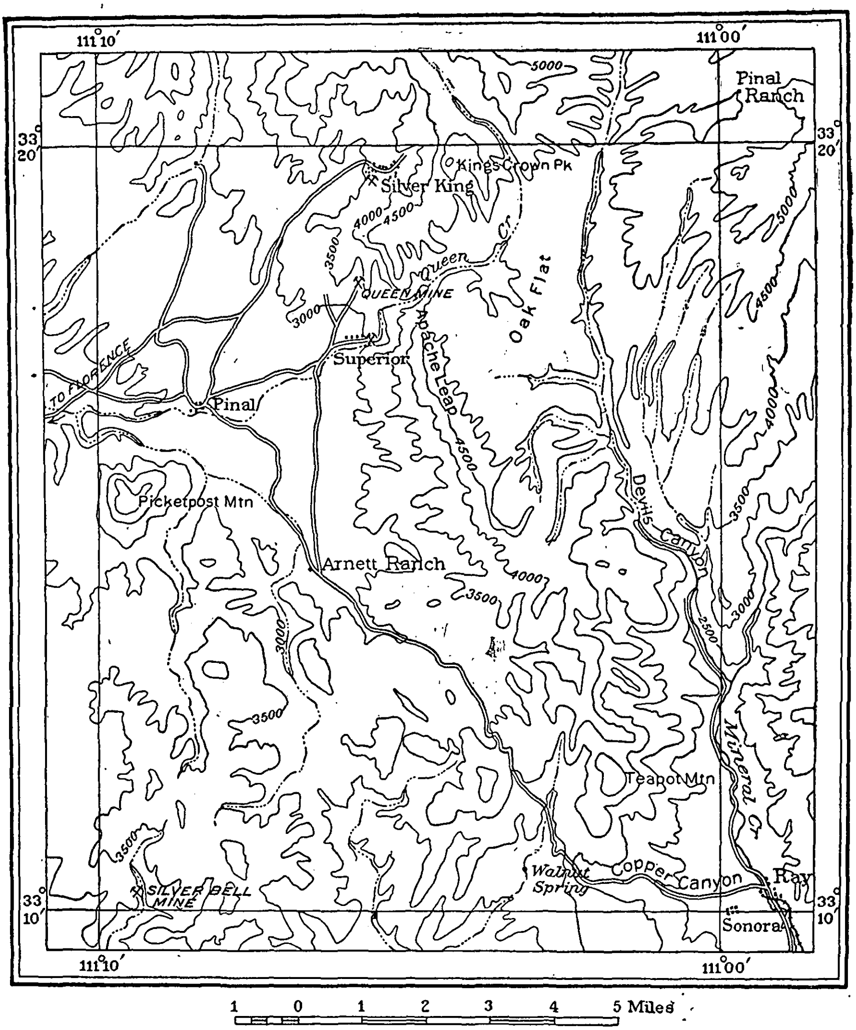
INTRODUCTION.

The little hamlet of Superior is in the south-central part of Arizona, in Pinal County. About it centers the present activity of the Pioneer district, in which the first mining locations, the Silver Queen and Silver King, were recorded in 1875. In a straight line Superior is 11 miles northwest of Ray (see fig. 11), but the intervening country is rugged, and Florence, 30 miles distant by road, is the usual point of rail shipment. The group of rough hills and mountains within which the district lies has no generally recognized name, although certain parts, such as the Superstition Mountains, have received distinctive appellations. It constitutes a northward prolongation of what, south of the Gila, is known as the Tortilla Range and it may appropriately be included under the same designation. To the northeast it merges into the Pinal Range and on the southwest it overlooks the lower and more open country around Florence and Phoenix. Superior is on the north bank of the westward-flowing Queen Creek, at the west base of a prominent and precipitous ridge known in part as Apache Leap.

The following notes are the result of only two days spent in the district, a time obviously too short for a thorough investigation of the geology and ore deposits, yet long enough to yield information which it is hoped may be worth recording.

GENERAL GEOLOGY.

The generalized geologic column of the region adjacent to Globe and Ray is shown in figure 12. At the base is the Pinal schist, cut by various pre-Cambrian granitic intrusions, some of which are of wide extent. Resting on the evenly worn surface of these ancient rocks in ascending series are (1) the Scanlan conglomerate, (2) the Pioneer shale, with generally some arkosic sandstone at its base, (3) the Barnes conglomerate, (4) the Dripping Spring quartzite, (5) a cherty dolomitic limestone[1] with a flow of rusty vesicular basalt at the top, (6) an upper quartzite,[1] (7) generally rather thin-bedded limestone with subordinate shale, carrying Devonian fossils, (8) thicker-bedded Carboniferous limestone, (9) andesite, andesite breccia, and tuff, supposedly of Cretaceous age, (10) the Whitetail con-



Contour interval 500 feet

FIGURE 11.—Outline map of Superior, Ariz., and vicinity.

glomerate, a heterogeneous accumulation of imperfectly rounded fragments, probably Tertiary in age, (11) dacite, with some associated tuff, probably Tertiary, and (12) the Gila conglomerate, a thick deposit of variable fluviatile gravels, with local silty facies, probably of early Quaternary age. For full descriptions of these

[1] Names will be given to these formations in a forthcoming report on the geology and copper deposits of the Globe-Ray region.

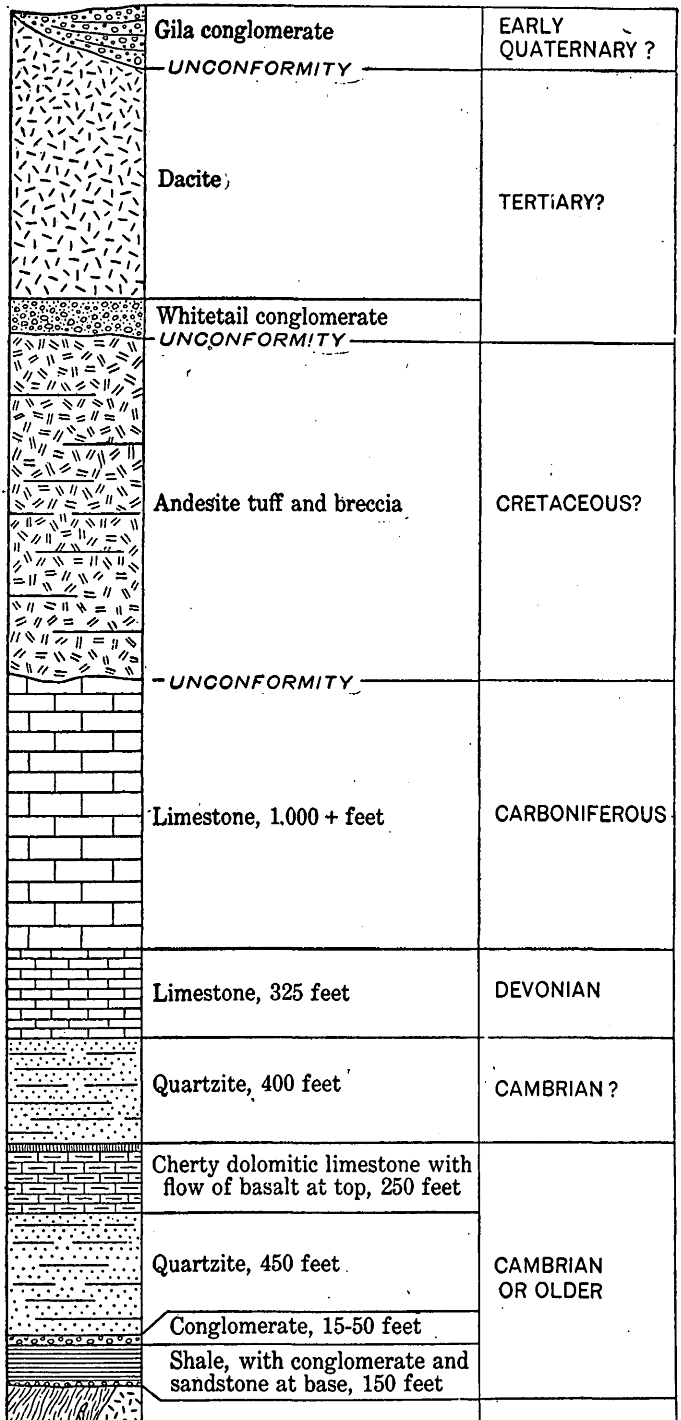


FIGURE 12.—Generalized columnar section for the region adjacent to Ray, Arizona.

formations the reader is referred to the geologic literature on the region.[1]

The age of formations 1 to 6 is not yet definitely known, as they have yielded no fossils within the Globe-Ray region. Without much question they are in part Cambrian, but some of the lower beds may be older than that period and there is a possibility that the upper quartzite may be post-Cambrian. In this part of Arizona no unconformity has been recognized anywhere in the series between the Scanlan conglomerate and the Carboniferous limestone, but reconnaissance work to the north, between Globe and Payson, suggests that one may be present.

In addition to the sedimentary and volcanic rocks mentioned the region contains some post-Carboniferous but pre-Tertiary intrusive rocks. The most abundant of these are diabase, which forms great irregular sheets and masses, especially in the pre-Devonian stratified rocks, and bodies of porphyritic to granular rocks ranging in composition from quartz monzonite or granodiorite to granite. These granitoid rocks are exemplified by the Schultze granite and associated porphyry of the Globe quadrangle, the granodiorite at Troy, and the quartz monzonite porphyry at Ray. They are younger than the diabase and are closely associated with the disseminated copper ores of this region.

The important formations exposed at Superior are, in ascending order, an intrusive sheet of diabase, the upper of the two pre-Devonian quartzites, the Devonian limestone, the Carboniferous limestone, and, finally, a flow of dacite, which forms the crest of Apache Leap and is the prevailing rock over a rough desolate country for 5 or 6 miles to the east. The general dip of these rocks is 35° E. The Devonian here appears to be fully as thick as in the Ray quadrangle and is similar in lithologic character, the uppermost bed being a shale which weathers into small yellowish flakes.

At the almost entirely deserted settlement of Silver King, which lies in a westward-opening embayment in the hills, at the north end of the Apache Leap ridge, 2½ miles north of Superior, the same formations as at Superior are exposed on the inclosing hillsides, but the rock close to the settlement is an intrusive mass of quartz diorite porphyry. This is surrounded by Pinal schist, which appears to occupy a considerable area of the hilly ground to the northwest, and it is intrusive also into diabase, just north of the Silver King mine.

A prominent structural feature near Superior is a strong fault (see fig. 13) which strikes a little west of north. The line of this

[1] Ransome, F. L., Geology of the Globe copper district, Arizona: Prof. Paper U. S. Geol. Survey No. 12, 1903; Globe folio (No. 111), Geol. Atlas U. S., U. S. Geol. Survey; Geology of the Globe district: Min. and Sci. Press, June 3, 1911, p. 747. The descriptions in the publications cited will be supplemented by those in the Ray folio, now in preparation.

fault is plainly visible north of the village and passes a few feet west of the Queen mine. The fault plane dips west, apparently at about 60°, and the displacement is normal. By this movement Carboniferous limestone west of the fault has been brought against diabase and quartzite east of it. The dislocation is believed to be younger than the dacite and is probably responsible for the steep west front of Apache Leap. The fault itself is concealed by alluvial deposits south of the Queen mine.

MINES.

The most noted mine in the vicinity of Superior is the Silver King, which was opened in 1875 and for many years produced high-grade silver ore from a deposit of the form commonly called by miners a "chimney." The mine ceased to be regularly productive about 1888 and has been continuously idle since 1898. In 1912 the ground was relocated, on the contention that it had been abandoned by its former owners. The production of the Silver King is variously reported as between $10,000,000 and $15,000,000. The lower figure is probably too high, but the Silver King Mining Co. is known to have paid dividends up to July, 1887, amounting to $1,950,000. The mine was worked through three shafts. The main shaft and large, compact stopes worked by square setting extend to a depth of 800 feet, below which a winze connects with the 950-foot level of the No. 2 shaft, which was used for pumping. The workings are now full of water.

The Queen or Silver Queen mine, about three-fourths of a mile north of Superior, although opened as early as the Silver King, and credited with some production about 1880, has only recently become important through the activity of the Magma Copper Co. The deposit, which occurs along a nearly east-west dike, is opened to a depth of 800 feet, with short levels at 200, 400, 500, 650, and 800 feet below the collar of the vertical shaft. The 200-foot level is merely an adit, 500 feet long, from which hoisting is now done instead of from the collar of the shaft, which is on the crest of the steep spur crossed by the dike. The ore from the Queen mine is hauled in wagons to Florence, two days being required for the 30-mile trip, at a cost of $5 a ton. The return rate on supplies is $7 a ton.

The Lake Superior & Arizona mine has its principal adit, the Carlton tunnel, on Queen Creek a few feet above the stream bed. The tunnel pursues a devious course for nearly 2,000 feet to the north-northwest, following in general the contact between the Devonian limestone and the underlying quartzite. At its north end the tunnel connects with a 26° incline about 1,800 feet long (see fig. 13), from which some short levels have been run along bedding planes in the limestone. The Holt tunnel, at the head of the incline, opens to the surface just north of Superior. This is the most extensively developed mine in the district, but although some oxidized copper ore was found in it, the quantity was discouragingly small, and work

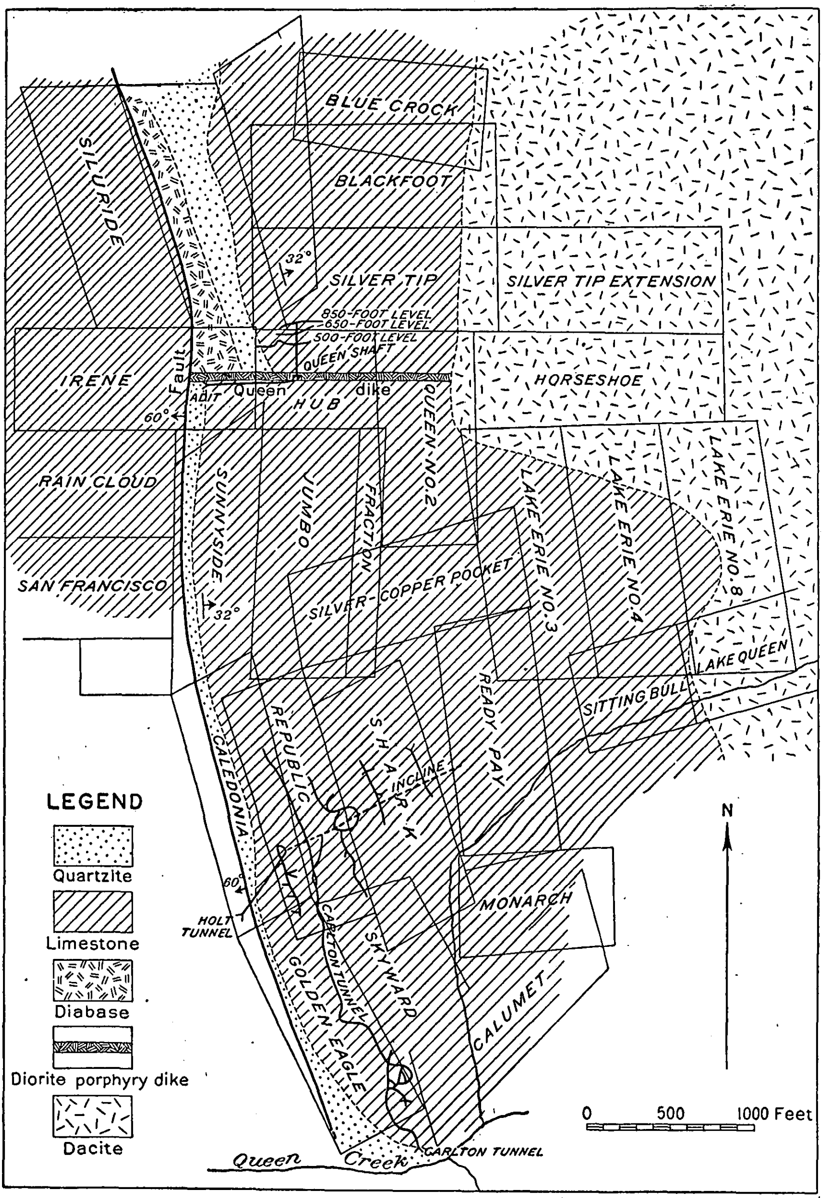


FIGURE 13.—Sketch map showing claims and the general geologic relations of the mines near Superior. From data furnished by the Magma Copper Co.

was abandoned a few years ago. It is reported that since the visit on which this paper is based exploration has been resumed.

SPECIAL FEATURES OF THE ORE DEPOSITS.

FORM AND OCCURRENCE OF THE ORE IN THE QUEEN MINE.

The ore of the Queen mine has been deposited in a nearly east-west dike of porphyry, which is so altered and decomposed that its original character is obscured. Apparently the rock was a rather fine grained quartz diorite porphyry. The width of the dike is variable, but probably nowhere exceeds 40 feet. In places small tongues of the intrusive rock extend into bedding planes, and other minor irregularities are due to slight faults, mostly slips along the bedding of the stratified rocks. The dike dips to the north, generally at 60° to 70°. The beds, which it cuts nearly at right angles to their strike, dip 32° E.

The dike occupies a fault fissure along which the major movement appears to have taken place before or during the intrusion. The movement was "reverse" in terms of fault nomenclature, or, as commonly stated, the footwall went down in relation to the hanging wall. Consequently an observer walking east on a level driven along the dike has on his right hand rocks higher in the stratigraphic column than those on his left. Moreover, in consequence of the general easterly dip of the beds, after he first sees limestone on the right hand, he must continue eastward for 400 to 450 feet before he reaches the same stratigraphic horizon on the left. The dip slip—that is, the component of fault movement that is measured in the fault plane in the line of dip—is roughly estimated as between 500 and 600 feet. By keeping these simple geometric relations in mind the reader will readily understand the following description of the ore bodies. The old work in the Queen mine was confined to ground above the original water level, which stood at a depth of about 400 feet. Some oxidized ore was taken from these upper workings, but it was left to the present company to show that this was insignificant in comparison to the rich sulphide ore below. Too little work had been accomplished in 1912 to place the shape and extent of the ore bodies beyond question, but such data as were obtainable indicated the existence of two distinct pay shoots lying in those parts of the dike where quartzite forms one wall and pitching to the east in the plane of the dike at approximately the same angle as the dip of the quartzite beds. These relations are shown diagrammatically in figure 14, which is a north-south section across the dike in the meridian of the shaft. In the plane of this section part of the upper body has suffered oxidation. As a rule these two prisms of ore are nearly or quite as wide as the dike, may measure 100 feet or more vertically from top to bottom, and, in the line of pitch, extend to depths that had not been determined at the time of visit. Apparently the best ore lies near the upper part of the quartzite, and in some places the dike contains good ore for short distances above the line of intersection of the upper surface of the quartzite with the side of the dike.

CHARACTER OF THE ORE IN THE QUEEN MINE.

The minerals composing the ore of the Queen mine are chalcocite, bornite, chalcopyrite, pyrite, and quartz. The usual oxidation products are found above the original water level and a very little covellite was noted in some of the lower-grade material, said to come from the 800-foot level. The ore is sorted and the better grades, shipped as crude ore, carry from 15 to 35 per cent of copper, with some gold and silver. In 1912 the mine, then just beginning its present period of activity, produced 129 tons of ore averaging 26 per cent of copper and carrying an average content of 0.07 ounce of gold and 0.29 ounce of silver to the ton. In the first-class ore chalcocite and bornite are the principal minerals. These occur as mixtures in various proportions and as nearly pure masses, particularly of chalcocite. The chalcopyrite is less abundant and is generally associated with pyrite, which is almost absent from the best ore.

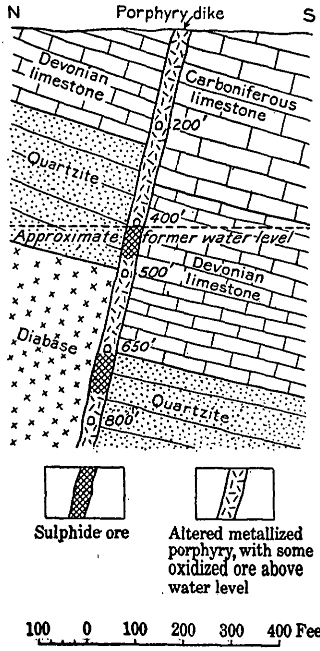


FIGURE 14.—North-south section across the Queen dike, showing the general relation of the ore shoots to geologic structure.

In the richer parts of the ore bodies the substance of the dike has been almost entirely replaced by masses of solid sulphides with comparatively little quartz, and to trace the stages of this replacement it is necessary to study the leaner material, such as is now thrown on the dump. In the least cupriferous material pyrite is the principal sulphide and occurs with quartz in an intricate tangle of veinlets that traverse the porphyry in all directions. The boundaries between the veinlets and the porphyry are not entirely sharp and it is clear that the pyrite and quartz have not only filled the cracks and openings in the rock but have to some extent replaced the porphyry. The gradations between this lean material and ore are twofold, one essentially structural and the other mineralogic. Where the fissures are numerous and in part of considerable size and where consequently the porphyry has been subject to vigorous metasomatic attack at many adjacent points the original material of the rock has been replaced by pyrite with generally rather subordinate quartz and probably a small proportion of chalcopyrite. Mineralogically the pyritic material grades through various mixtures of pyrite, chalcopyrite, bornite, and chalcocite into nearly pure chalcocite. All the sulphides mentioned occur also in disseminated form through the altered porphyry in the vicinity of the fissures.

As seen in place or in ordinary hand specimens, the ore shows only here and there a suggestion that the various sulphides may not be contemporaneous in origin, a suggestion so faint that to the casual observer the ore appears to be a mass of sulphides and quartz confusedly intergrown during a single period of crystallization. The study of polished sections under the microscope, however, reveals a more interesting relation.

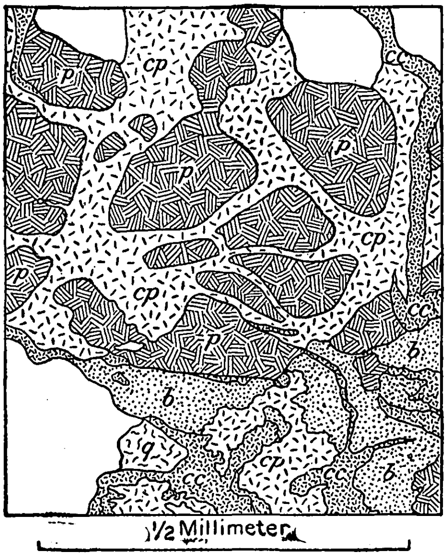


FIGURE 15.—Microdrawing of polished surface of ore from the 800-foot level of the Queen mine. Outlined with camera lucida. *p*, Pyrite; *cp*, chalcopyrite; *b*, bornite; *cc*, chalcocite; *q*, quartz; white area, hole or pit in section.

The general sequence of the sulphides proves to be pyrite, chalcopyrite, bornite, and chalcocite. The first mineral to be deposited in the fissured porphyry was pyrite. Subsequently this mineral was minutely and irregularly cracked and chalcopyrite was deposited as a mesh of microscopic veinlets in the pyrite. (See fig. 15.) In places the walls of these veinlets are smooth and distinct, but as a rule the outline of the chalcopyrite as seen in polished sections is rough and more or less indefinite. It is clear that many of the original cracks have been enlarged by the metasomatic replacement of pyrite by chalcopyrite. The structure, illustrated in figure 15, appears to correspond to that which L. C. Graton and Joseph Murdoch[1] have characterized as the "exploding bomb" structure.

After the deposition of the chalcopyrite the vein material was again cracked, and many of the fragments were considerably displaced. The resulting cracks and interstices, many of them wide, were filled with quartz, which forms the gangue of the sulphides.

The physical relation of the bornite to the chalcopyrite presents some perplexing features. In many places the two minerals are intimately associated in a structure that is strongly suggestive of

[1] The sulphide ores of copper—some results of microscopic study: Trans. Am. Inst. Min. Eng., New York meeting, February, 1913, advance ed., p. 45, fig. 2.

contemporaneous intergrowth (see figs. 16 and 17), such as has been carefully described by F. B. Laney.[1] No structure seen in the Superior ores, however, has exactly the appearance of ordered irregularity peculiar to a typical micrographic intergrowth such as is illustrated in plate 68 of Laney's paper. Moreover, further search shows that in some places the bornite traverses the chalcopyrite in veinlets that are obviously coincident with cracks. Very rarely, and generally for very short distances, these bornite veinlets may have smooth, parallel sides. As a rule, however, the boundary between bornite and chalcopyrite is very irregular, and all gradations may be found between distinct veinlets of bornite and isolated shreds and particles of bornite distributed thickly through the apparently unfissured chal-

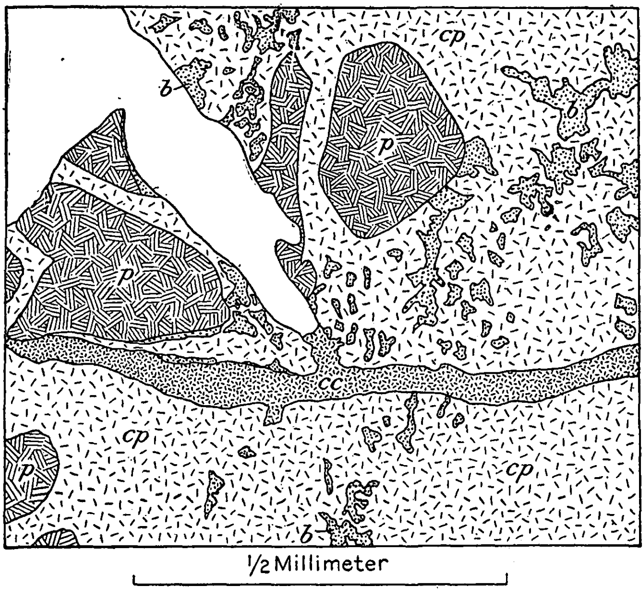


FIGURE 16.—Microdrawing of polished surface of ore from the 800-foot level of the Queen mine. Outlined with camera lucida. Shows remnants of pyrite (*p*), surrounded by chalcopyrite (*cp*) with bornite (*b*) in areas suggestive of intergrowth with chalcopyrite. Chalcocite (*cc*) in a distinct veinlet.

copyrite. There is a similar unbroken transition between the structure in which chalcopyrite is the host mineral and one in which bornite contains only a few scattered particles of chalcopyrite.

Although some of the bornite is thus clearly younger than the chalcopyrite, which it traverses in veinlets and has in part metasomatically replaced, the possibility that there may be two generations of bornite remains to be considered. The only support to this view is the intimate association of some of the bornite and chalcopyrite in apparent intergrowths unconnected with visible fissuring.

[1] The relation of bornite and chalcocite in the copper ores of the Virgilina district of North Carolina and Virginia: Proc. U. S. Nat. Mus., vol. 40, 1911, p. 519, pl. 68.

On the other hand, undoubted replacement veinlets of bornite may be fringed with precisely such apparent intergrowths or may die out as veinlets, to be continued along the same general line by a vague zone of bornite flecks in the chalcopyrite. Finally, the general arrangement of the bornite as a layer intervening between chalcopyrite and pyrite on the one hand and chalcocite on the other, as appears from the study of broad polished faces of the ore, reenforces the conclusion that the bornite is younger than most of the chalcopyrite.

The relation of the bornite to the quartz gangue is not as a rule very clearly shown, but a few of the bornite veinlets in chalcopyrite have a medial sheet of quartz which was the first filling of the fissure. The bornite was deposited later, chiefly by replacement of the chalcopyrite along the walls of the original quartz film. The bornite in a general way shows a pronounced tendency to occur near the periphery of quartz areas as seen in section, but this tendency has been obscured in part by the subsequent development of chalcocite along the same paths at the expense of the bornite.

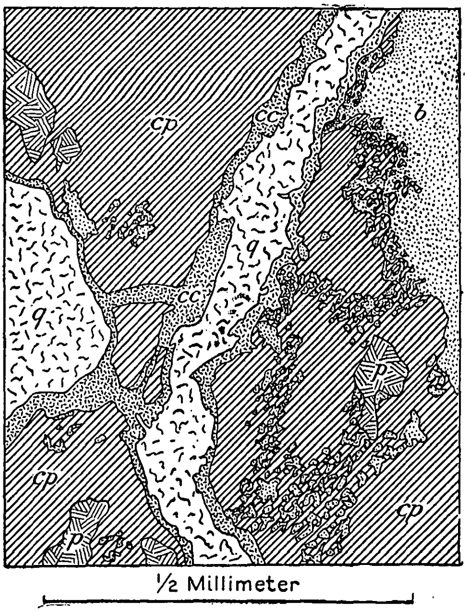


FIGURE 17.—Microdrawing of polished surface of ore from the 800-foot level of the Queen mine. Outlined with camera lucida. Chalcopyrite (*cp*) with residual pyrite (*p*), and younger bornite (*b*). The bornite in part seemingly intergrown with chalcopyrite. A quartz veinlet (*q*) bordered by chalcocite (*cc*).

The relations between chalcocite and bornite are very similar to those between bornite and chalcopyrite. After the deposition of the bornite fresh cracks were opened in the ore. Some of them appear to have been filled by a second and minor infiltration of quartz, although it is not certain that these quartz-filled veinlets do not belong to the earlier and main period of gangue formation. Be that as it may, many fresh cracks were certainly formed in the ore and were filled with chalcocite. Every contact between quartz and sulphides was searched by the copper-bearing solutions, and layers of chalcocite were deposited by replacement of the adjacent sulphide—in some places pyrite, in some chalcopyrite, but in most places bornite. (See figs. 17–19.) This deposition of chalcocite along the contacts between quartz and older sulphides has been noted by Laney[1] and a similar feature in silver ores has been described by E. S. Bastin.[2] Precisely as in the case of the bornite and chalcopyrite so with the chalcocite and bornite; there are all gradations from distinct chalcocite veinlets to apparent intergrowths between chalcocite and bornite. In one part of a polished section the bornite appears full of irregular flecks of chalcocite such as would ordinarily be considered as forming an intergrowth with the bornite; a slight shift of the section may bring into view an alignment of flecks which at once prompts

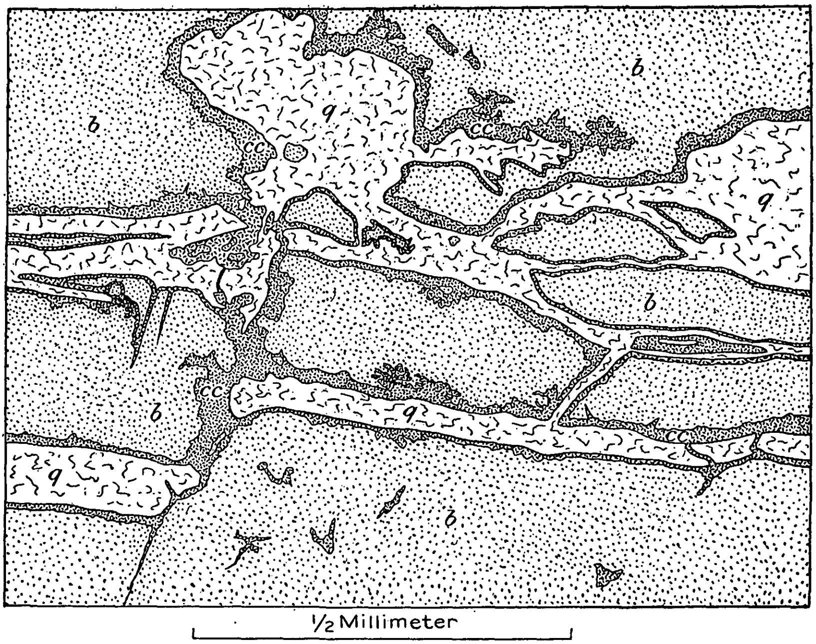


FIGURE 18.—Microdrawing of polished surface of ore from the Queen mine. Outlined with camera lucida. Characteristic irregular quartz veinlets (*q*) bordered by chalcocite (*cc*) which has developed from bornite (*b*).

the suggestion that their occurrence is related to fissuring; and another change in the field may perhaps show the linear zone to pass into a distinct microscopic fissure filled with chalcocite and fringed with an irregular border of the same apparent intergrowth. Even more clearly than in the case of bornite in chalcopyrite, the chalcocite in bornite differs on close inspection from thoroughly typical micrographic intergrowths. The little areas of chalcocite as seen in thin section are as a rule sharply and irregularly acuminate, as if the replacement had begun at the intersection of some very minute cracks and had extended out along those cracks for short distances,

[1] Op. cit., p. 518.
[2] Metasomatism in sulphide enrichment: Econ. Geology, vol. 7, 1913, p. 53, fig. 5.

while here and there are distinct suggestions of replacement along microscopic fractures.

The conclusion appears to be highly probable, if not inevitable, that all the chalcocite is younger than the bornite and that all the bornite is younger than most of the chalcopyrite, the reservation in the case of chalcopyrite being demanded by the existence of a very little chalcopyrite that has been deposited in veinlets with the chalcocite at or about the same time. It follows that in the alteration of the relatively unstable minerals chalcopyrite and bornite to the final stable form chalcocite the change is not limited to the walls of

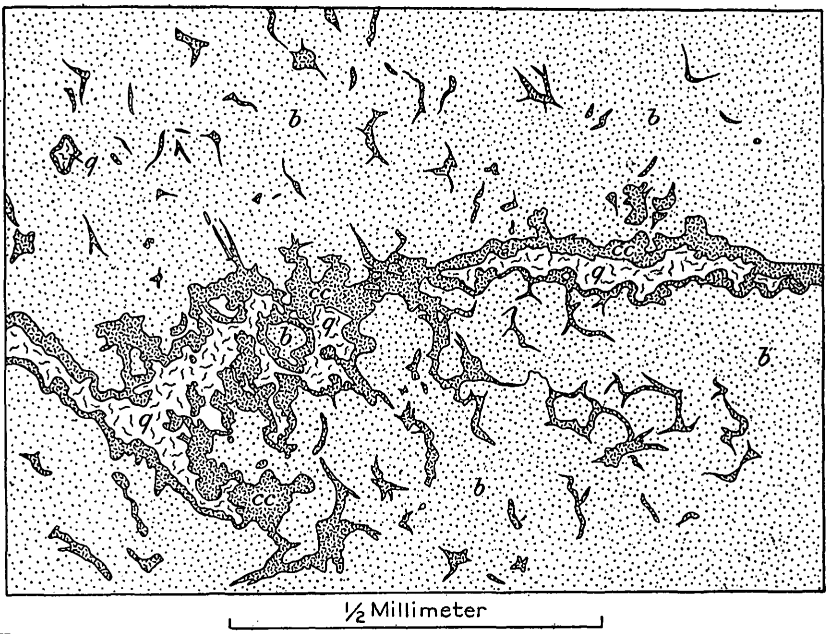


FIGURE 19.—Microdrawing of polished surface of ore from the Queen mine. Outlined with camera lucida. Bornite (*b*) showing infiltration of quartz (*q*) in irregular veinlets (perhaps when sulphide was chalcopyrite), followed by the formation of chalcocite (*cc*) at the expense of the bornite. Illustrates gradation between chalcocite formed along a fissure and chalcocite developing in the bornite without distinct fissuring and in forms suggestive of contemporaneous intergrowth.

visible cracks or openings, but takes place within the apparently solid mass of the older mineral. Graton and Murdoch[1] apparently refer to the same phenomenon when they state that "with bornite it appears that as soon as the solutions reach one portion of a grain the whole area may become unstable and break down, so that instead of finding the usual growing veinlet of the secondary mineral traversing and gradually replacing the one undergoing alteration, we often find in the case of bornite indefinite areas over part or all of which minute particles of the secondary minerals have developed." The

[1] Op. cit., p. 23.

change from bornite to chalcocite, however, can hardly be merely an internal rearrangement, but involves chemical interchange, at least to the extent of removal of the iron present in bornite. The sulphide minerals are probably permeable to solutions through openings too small to be seen by the ordinary microscope; in fact, were this not the case the formation of more than a molecular film of chalcocite on the walls of a fissure in bornite would be impossible, unless we admit that ions carried in solutions in the fissure may be handed on by chemical reaction from one molecule to another into the solid substance of the inclosing mineral. Moreover, in this connection it is well to remember that observations are made on polished opaque surfaces and that exceedingly minute cracks might have their edges burred by the mechanical action of polishing and so become superficially closed and invisible. Such cracks might not be revealed even by the etching which brings cleavage structure to light. Furthermore, such a section may in places be nearly parallel with a crack, so that wide areas of apparent intergrowth may be only a short distance from a crack lying perhaps only a fraction of a millimeter below the surface of the section.

If the origin of the apparent intergrowths in the ore of the Queen mine is correctly inferred, it follows that secondary processes in sulphide ores may produce structures which it is difficult and perhaps in some cases impossible to distinguish from contemporaneous intergrowths.

Covellite was noted in one hand specimen and a very little was seen in the polished sections. It is clearly secondary after pyrite and chalcopyrite, but apparently in this deposit represents an exceptional and transient stage in sulphide alteration.

ORIGIN OF THE QUEEN ORE.

It has been shown that the principal minerals of the Queen ore body were deposited in the following order: (1) Pyrite, (2) chalcopyrite, (3) quartz, (4) bornite, (5) chalcocite, possibly preceded by minor deposition of quartz and accompanied by an insignificant second generation of chalcopyrite.

The visit on which these notes are founded was altogether too brief to throw any particular light on the original source of the ore materials. It may reasonably be assumed on the basis of our general knowledge of ore deposition that some of the earlier minerals were deposited by ascending hot solutions. The term *primary* is commonly applied to such minerals, but the word denotes merely a sequential relation and as used by writers on ore deposits is often vague and may be actually misleading. I prefer to distinguish them as *hypogene* minerals. Similar objection may be made to *secondary* as it is frequently used, often tautologically with *enrichment*. The suggestion is offered that minerals deposited by generally downward-moving and initially cold [1] solutions may be termed *supergene* [2] minerals. It has been shown, for example, that chalcopyrite in the Queen ore is secondary in its relation to pyrite, yet both sulphides are perhaps hypogene. On the other hand, certain deposits of chalcocite in the red beds of the Southwest may be primary in the sense that the chalcocite has not replaced an older sulphide, and yet the deposit may be supergene in origin. As regards the Queen ore, the problem of chief interest and one open to at least a preliminary attack with data now available is to determine which constituents of the ore are hypogene and which are supergene.

Observation of microscopic sections establishes the depositional sequence but can not alone supply the answer to this question. It can not tell us at what point in the sequence the work of ascending waters ended and the work of descending waters began. Light must be gained from the circumstances of occurrence and from chemical considerations.

The field relations at the Queen mine are as yet imperfectly known. All the sulphides are present on the 800-foot level and the downward vertical gradation from rich ore to lean pyritic sulphide, if it occurs, is something that only deeper mining can expose to observation. Nevertheless, chalcocite appears to be the dominant sulphide on the upper levels, under the oxidized zone, and bornite and chalcopyrite form a larger proportion of the ore on the 800-foot level. This alone is suggestive of a supergene origin for the chalcocite, and in connection with what is known of other occurrences of this sulphide, particularly in the same region, such origin may be accepted without much question.

On the other hand, chalcopyrite (exclusive of the insignificant later generation) may on similar general grounds of probability be eliminated from the doubtful zone and assigned to the hypogene group. Its close association with pyrite and the fact that it is older than the quartz gangue point to hydrothermal deposition. Graton and Murdoch,[3] on the basis of wide metallographic observation, have concluded that the structural association of pyrite and chalcopyrite exemplified by the Queen ore is invariably "primary," and R. C. Wells[4] has shown that in "simple precipitative reactions" chalcopyrite is not likely to be deposited from acid solutions, such as are generally

[1] It should be remembered, however, that under certain conditions considerable heat may be generated in the process of sulphide oxidation.

[2] This word is obviously of hybrid construction, but the philologically more correct *epigene* is already too fully occupied in other uses to serve the present need.

[3] Op. cit.

[4] The fractional precipitation of sulphides: Econ. Geology, vol. 5, 1910, p. 13.

active in downward enrichment. With reference to the last statement, however, it must be said that the metasomatic replacement of pyrite by copper sulphide through the agency of sulphate solutions is perhaps not a simple precipitative reaction, at least so far as regards the iron which is already on the ground, ready to combine with copper as chalcopyrite, and that, moreover, under some circumstances supergene chalcopyrite certainly does form. Graton and Murdoch[1] suggest that this mineral when "secondary" probably belongs to the deeper part of the zone of enrichment, where the solutions may be deficient in acid. It is noteworthy, however, that according to the Stokes equation for the formation of chalcocite from pyrite by neutral cuprous sulphate, sulphuric acid is abundantly generated by the actual process of chalcocitization.

There remains to be considered the bornite, concerning which, so far as relates to the question of its hypogene or supergene origin, the available evidence is admittedly inconclusive. If it is hypogene, then its formation was separated from that of the other hypogene sulphides by fissuring, deposition of the quartz gangue, and renewed fissuring. If it is supergene, it was formed directly in advance of the chalcocite by the same sulphate solutions that generated that mineral. Although the bottom of the bornite has not been reached, the ore with abundant bornite grades in some directions into leaner material and clearly represents local concentration in the lode. This concentration is suggestive of supergene origin. The bornite is more abundant in the lower part than in the upper part of the ore body, and this fact gives additional force to the suggestion. Finally, the apparent occurrence of the rich ore in two shoots each related to one of the two zones of juxtaposition of the quartzite with the dike accords best with the view that the bornite was formed by descending solutions. The quartzite, it is to be observed, is the principal water-bearing stratum, and just above it, at the base of the Devonian limestone, occur lenticular layers of copper-bearing sulphides which in their oxidized and leached form will be referred to presently in connection with the Lake Superior & Arizona mine. It is not unlikely that the solutions which found their way along the quartzite carried copper dissolved from some of these lenticular bodies and added their burden of this metal to that carried by waters which moved more directly downward through the dike. If a mingling of solutions, such as is here suggested, was an important factor in the localization of the ore shoots, evidently the vertical range of each ore body must have depended to some extent on the hydrostatic relations of the water in the dike to the water in the quartzite and on the relation of surface

[1] Op. cit., p. 38.

supply to deep drainage. It is entirely possible that, as the mine becomes more extensive, the ore in the two shoots may be found to merge in places across the interval which has been found unproductive in the present workings. As yet too little is known to permit the laying of heavy stress on the supposed distinctness of the two ore shoots seen in 1912. Furthermore, present conditions do not justify the assumption that the formation of chalcocite and other sulphides took place only below water level. It is probable that oxidation and the water level that limits it have advanced downward on the chalcocite zone and that the chalcocite has itself been oxidized in part, dissolved, and reprecipitated. Two essential conditions for important sulphide enrichment appear to be the absence of free oxygen in the zone of deposition and the existence of deep drainage. These conditions may exist above the water level, and the depth to which deposition may extend below that level would seem to depend largely on a deep and slow movement of the underground water sufficient to remove the solution which has lost its copper and to bring fresh supplies of that metal down from above.

On the whole the evidence now available is believed to indicate that the high-grade ore of the Queen mine is the product of downward sulphide enrichment.

OCCURRENCE OF ORE IN THE LAKE SUPERIOR & ARIZONA MINE.

At several horizons within about 20 feet of its base the Devonian limestone has been brecciated along bedding planes, and this brecciation is associated in surface exposures with considerable limonite, manganese oxide, and some quartz and hematite. In places this brecciated material is irregularly veined with malachite and chrysocolla. Near the mouth of the Carlton tunnel this ferruginous layer is about 4 feet thick and about 20 feet above the base of the Devonian. What apparently is the same rusty layer is visible for considerable distances along the mountain side both north and south of Queen Creek. Underground workings, however, show that the brecciation is not everywhere at the same stratigraphic horizon, and some of the brecciated masses are lenticular. Although some bunches of oxidized copper ore have been found in the brecciated layers, most of these have a porous character and appear to have been leached of their copper. Whether this has been carried down the dip and concentrated in workable bodies of ore below the level of the Carlton tunnel is a question that the present workings do not satisfactorily answer. The conditions at the Queen mine indicate that in this district the possibility of enrichment to a considerable depth below the water level should be fully considered.

ORE BODY OF THE SILVER KING MINE.

The Silver King mine was well described by W. P. Blake[1] 30 years ago, but his original publication is not readily accessible. Accordingly, although the present paper is concerned mainly with the copper deposits, and although the old mine, being full of water, could not be reexamined, a brief descriptive summary of the conditions under which the ore occurred will perhaps be of sufficient interest to warrant its inclusion here.

The eruptive mass which incloses the ore is a quartz diorite porphyry or closely related rock. It presents some rather noticeable variations, which Blake distinguished as "porphyry," "sienite," and "granite," although they appear to be merely facies of one intrusive body which is probably of Mesozoic age.

The ore body formerly cropped out at the top of a little hill about 75 feet high, composed of much-altered yellowish-brown to greenish-gray porphyry. Stoping was carried to the surface and a crater-like pit from 100 to 125 feet in diameter marks the site of the former outcrop. Here and there in the porphyry walls of the pit may be found small veinlets of rich, partly oxidized silver ore, but, so far as can be seen from the surface, the ore body was not part of a vein, and there is nothing to suggest that it was determined by the intersection of two or more persistent fissures. It apparently was a compact plexus of veinlets inclosed in comparatively unfissured porphyry.

Blake's description and the maps of underground workings show that the ore body was a stockwork about 130 feet in maximum diameter, with a general dip of 70° W. The stockwork was disposed about an irregular core or axis of milk-white quartz, containing some bunches of rich ore but as a whole comparatively barren. This material is abundant and conspicuous in the mine dump and evidently constituted at times the bulk of the waste. The ore consisted of altered porphyry traversed in all directions by innumerable veinlets carrying stromeyerite, tetrahedrite, galena, sphalerite, chalcopyrite, and pyrite in a gangue of quartz with some barite. The minerals named were noted in 1912 on the dump, but Blake lists and describes also native silver, argentite, bornite, calcite, and siderite. Bornite, chalcopyrite, and pyrite are said to have been comparatively rare. Blake makes the interesting observation that stromeyerite and highly argentiferous tetrahedrite with more or less argentite were the most important constitutents of the ore on the upper levels, whereas argentiferous sphalerite had become the principal ore mineral on the seventh level. Native silver, associated with stromeyerite and sphalerite, was abundant on that level, according to the same

[1] Description of the Silver King mine of Arizona, New Haven, 1883, 48 pp., with illustrations.

observer. He also describes the metallic minerals as occurring generally along the medial plane of the veinlets, a characteristic that is verifiable in specimens collected on the dumps in 1912. Apparently the deposit was not deeply oxidized and veinlets seen in the open pit in 1912 showed sulphides present with cerargyrite, malachite, and azurite. Blake notes also native copper, cuprite, " oxides and carbonates of lead and possibly embolite, the chlorobromide of silver; also the argentite, in pure black lumps."

From the fact that water is now flowing from the collar of the No. 2 shaft the original water level was probably close to the surface. The quantity of water pumped to keep the mine clear near its maximum development in 1887 was 10,941 gallons a day.[1] Blake states that at the time of his visit (1882 or 1883), when the mine was 714 feet deep, only 2,000 gallons a day was pumped, all of which entered the mine at the first or 114-foot level.

In the early stages of development, before there was a railroad in Arizona, some rich ore was shipped under great disadvantages. Blake states that some of this carefully sorted ore averaged $1,000 a ton, and as late as 1887 the superintendent, Mr. Arthur Macy, reported assays up to 447 ounces of silver to the ton in ore consisting chiefly of tetrahedrite. Subsequently two 20-stamp mills were built at Pinal, 5 miles from the mine. Some idea of the character of the ore during a rather late stage in the activity of the mine is obtainable from the company's report for 1887, wherein it is stated that mill No. 1, employing wet crushing and concentration, treated 2,698.75 tons of ore with an average content of 21.08 ounces of silver to the ton. The product was 577,813 tons of first-class concentrates averaging 834,135 ounces of silver to the ton and 31 per cent of lead. Of the total silver contents, 53.95 per cent was native silver. In addition the mill turned out 1,261.55 tons of second-class concentrates carrying 31.77 ounces of silver to the ton, chiefly combined in zinc blende and galena. Mill No. 2, in which chloridizing, roasting, and pan amalgamation were employed, treated 4,840.08 tons of first-class ore, averaging 32.47 ounces of silver to the ton of roasted pulp, 1,913.51 tons of second-class concentrates, and 3,875.34 tons of old tailings with an average content of 12 ounces of silver to the ton. The superintendent states that whereas previously the ore treated in this mill had carried 50 per cent of its silver in native condition, the proportion for the year covered by the report had fallen so notably and the bullion, notwithstanding an extraction of over 96 per cent of the total silver, had become so base that he had stopped this method of treatment and was experimenting with an old lixiviation plant previously used.

[1] Report of the Silver King Mining Co. for 1887, San Francisco, 1888.

Various explanations are given locally for the failure of this interesting deposit below the 800-foot level, some stating that the ore body was faulted, some that the ore changed in character and grade. The latter is probably true. The worked-out part of the deposit appears to have been a striking example of deep downward enrichment. If so, the time may come when the old mine will be reopened and its low-grade hypogene ore utilized.

COPPER DEPOSITS OF THE WHITE MESA DISTRICT, ARIZONA.

By James M. Hill.

GENERAL FEATURES OF THE DISTRICT.

Location.—The White Mesa mining district, sometimes called the Keams district, is in the Navajo Indian Reservation, Arizona, 100.2 miles N. 9° E. of Flagstaff and 34.8 miles N. 10° W. of Tuba City, as measured on the Land Office map of Arizona issued in 1909. It lies in unsurveyed territory but is approximately in T. 37 N., Rs. 9 and 10 E., Gila and Salt River meridian. It covers an area about 5 miles east and west by 3 miles north and south, though some claims not visited by the writer are located about 3 miles west-northwest of the main group.

Roads and transportation.—To reach the district the main Lees Ferry road is followed north from Flagstaff to a tank about 10 miles north of Willow Springs and 18 miles northwest of Tuba City, at the base of Echo Cliffs. From this point a rough road ascends the cliffs and reaches the surface of the lower mesa through a gap in the ridge at its western edge. The road then turns almost due north. The distance from Flagstaff to the claims by road is between 135 and 140 miles and is increased a few miles if a detour is made to Tuba City. For at least two-thirds of the distance the roads are fair, but in the remaining third it is necessary to go through deep sand that makes heavy freighting well-nigh impossible. The trip from Flagstaff to the claims by team occupies from 6 to 10 days, and the cost of freighting small lots is probably about 3 cents a pound, or $60 a ton. It is possible for an automobile to go from Flagstaff as far as the tank at the base of Echo Cliffs, about 18 miles from the deposits, in less than a day.

Topography.—The district is on a low divide that runs east and west for a number of miles across the relatively level plateau extending from Echo Cliffs to the Colorado River canyon at an elevation of approximately 6,250 feet. Between the cliffs and the main claims of the district the level of the plateau, which in this paper is called the lower mesa, is broken by small hills and shallow drainage lines marked by low cliffs. Five miles south of the district there is a bowl-shaped depression about 75 feet below the general level.

The east-west divide has an average elevation of 6,400 feet, though at least two points attain a height of 6,500 feet. These two peaks are marked by United States land monuments 1 and 2 and are about in accord with the highest mesa at the extreme east end of the mineralized area.

The middle mesa, 6,400 feet in altitude, is much dissected, as a consequence of which it is irregular in detail and marked by numerous high and low cliffs and by benches at various elevations.

General geology.—The Lees Ferry road at the base of Echo Cliffs passes over red, purple, and bluish-green shales and thin-bedded impure limestones and is probably near the top of this series, for as soon as the ascent of the cliffs is begun massive dark-red sandstone appears which continues nearly to the base of the hills on either side of the gap through which the road passes upon the lower mesa. This sandstone is 400 to 500 feet thick and is composed of rather massive members which exhibit some cross-bedding. The red sandstone forms the floor of the south end of the lower mesa.

Above this red sandstone lie strongly cross-bedded, light-colored, very friable sandstones, that stand up as low hills and cliffs at least 270 feet high. The hills are the remnants of the lower part of a series that is exposed at the summit of Echo Cliffs, where it shows at least 350 feet of white, buff, and light-red sandstones without fossils, and is everywhere marked by intricate cross-bedding. In these sandstones the sand grains, though fine, are distinct. They are set in a white, pink, or buff-colored matrix which weathers very rapidly, leaving the heavy sand that covers so much of the area. The matrix is essentially clay, in which there is some very finely comminuted quartz. To recapitulate, the stratigraphic series of the mesa, beginning from the top, is about as follows:

White to buff friable sandstones, very strongly cross-bedded, forming the higher hills on which the copper claims are located. This is probably to be correlated with the lower portion of the La Plata sandstone (Jurassic) of southwestern Colorado and southeastern Utah.

Red sandstones, rather massive, with thin conglomerate lenses near central and upper portions. Forms lower part of Echo Cliffs. Probably to be correlated with the Dolores formation (Triassic) of southwestern Colorado and southeastern Utah.

Green, purple, and red shales, thin bedded and containing some beds of conglomeratic limestones, exposed under Echo Cliffs along the Lees Ferry road. Permian (?).

Structure.—On White Mesa the light-colored sandstones lie flat, apparently being undisturbed by either tilting or faulting. They are so strongly cross-bedded that local observations for dip and strike give widely varying results, though the true bedding is essentially horizontal. The only openings are joint planes, some of which seem to have had an influence on the deposition of the ores.

At Echo Cliffs the massive red sandstone and underlying shales have an apparent dip of about 20° ENE. This dip appears to be localized along the cliffs, for near the rim of the lower mesa the red and white sandstones are practically flat.

ORE DEPOSITS.

The copper ores found in this region are chrysocolla and malachite, locally, with a very minor quantity of azurite. Chrysocolla is by far the most widely distributed copper mineral, occurring as a greenish-blue cement to the sandstone. Malachite, the next in abundance, is in places associated with very dark brown hematite and forms small irregular masses in the chrysocolla ore. In a very few places it occurs alone. These two minerals may be said to constitute the ore, as the azurite is very scarce. The specific gravity of the ore is about 2.61, and a ton of it occupies about 12⅓ cubic feet.

The ores occur in the lower middle portion of the white cross-bedded sandstone as rather small, very irregular bodies of blue color, distinct from the barren rock into which they grade. In a few places there are veinlike forms having lateral and vertical dimensions longer than their width, but even in these the margins are not sharply defined, there being a gradation between ore and rock. In some places the ore occurs on either side of small open crevices that appear more like joint planes than fissures, but the largest number of ore bodies occur as small bunches in the sandstone in which there are no apparent openings.

On close inspection the greenish-blue color is seen to be due to the color of the matrix of the sandstone; in other words, the ore minerals have replaced the original cementing material of the sandstone—an impure clay probably containing a large amount of kaolinite. The quartz grains themselves have not been attacked, though in one slide of the ore some of the grains are seen to be cracked, and chrysocolla has been deposited in the openings.

Where hematite occurs it replaces the matrix of the sandstone in the same manner as the copper silicate.

The ore bodies occur through a vertical range of 250 feet. The lowest deposits noted are on the Nestor claim, at an elevation of about 6,250 feet, and the highest on the Butte Valley claim, on the rim of the upper mesa at an elevation of 6,500 feet.

ECONOMIC CONDITIONS.

Water.—On the road from Flagstaff to the prospects water has to be carried by the freight teams, as there are only five places where it can be obtained, as follows:

1. At the Halfway House there is a natural tank in the bottom of the canyon, about 600 feet east of the road.
2. An artificial tank 1½ miles southwest of the new bridge over the Little Colorado contains water most of the year.
3. Willow Springs.
4. At the point where the road to the claims leaves the Lees Ferry road there is a cement tank about a small seep.
5. Five miles south of the claims and about 1 mile west of the road there are two wells which give a small but continuous supply of water.

No water has been found nearer to the deposits than the two wells last mentioned. Because of the extreme porosity of the sandstone it will be impossible to develop water tanks in the district unless they are entirely lined with cement, which would make the cost almost prohibitive.

It might be possible to obtain water by deep wells, though a 212-foot shaft has encountered none. Probably to reach water the wells would have to go down to the underlying limestone, a distance of 700 to 800 feet.

Development.—Nothing in the way of real mining has been done in the district. There are prospect holes in many places, usually in groups of four to eight pits in a small area around the most promising exposure of ore on each of the claims. These pits are usually 4 by 6 feet in cross section and average from 2½ to 10 feet in depth. Open cuts are numerous in the faces of low benches showing ore, and there are a number of trenches from 2 to 6 feet deep where that method of prospecting was most available. There are some short tunnels, but in only one of these was any considerable amount of ore uncovered. Several shallow shafts have also been put down in ore; the deepest of them is about 30 feet.

Work of this kind, while it discloses the ore on and near the surface, does nothing to determine whether there is any at greater depth.

Quantity of ore.—It is very difficult to make any fair estimate of the amount of ore in these deposits, because of their extreme irregularity and the impossibility of telling in advance of actual development work where ore will be encountered or where an ore body will give out.

The size of the ore bodies exposed by the present development is extremely diverse, ranging from 1 cubic foot up to 10,000 cubic feet, but most of the bodies so far demonstrated contain from 100 to 200 cubic feet of ore.

Value of the ore.—The value of the ore bodies is extremely variable, depending on the degree of replacement. Some bodies are of a very faint bluish-green color, and samples taken from them carry from 0.5 to 3 per cent of copper. The larger part of the ore shown by the cuts is a rather deep greenish-blue material which assays between 5 and 8 per cent of copper. Ore of this class contains small amounts of dark-green malachite-bearing material, with some hematite which is of higher grade. A sample of this ore from the Pais-Lee-Chee claim assayed 14 per cent of copper, and it is possible that by picking even higher assays might be obtained.

Other considerations.—Mining costs would be rather low if it were not for the high cost of supplies. The ore can hardly be smelted, on account of its extremely siliceous character. Certainly it can not be smelted on the ground, because of the lack of flux. It is probably more amenable to leaching. Any leaching process, however, requires abundant water, which has not yet been developed on the ground and which would in all probability be very expensive to obtain. Under present conditions these ores can not be profitably worked, but it is possible that with better transportation a small quantity of copper could be won from the deposits.

SURVEY PUBLICATIONS ON COPPER.

The following list includes the principal publications on copper by the United States Geological Survey or by members of its staff. In addition to the publications cited below, certain of the folios of the Geologic Atlas of the United States contain discussions of copper resources. This list does not include publications on Alaska, a list of which is given in Bulletin 542, the annual report on progress of the Survey's investigations in Alaska for 1912.

The Government publications, except those to which a price is affixed, can be obtained free by applying to the Director, U. S. Geological Survey, Washington, D. C. The priced publications may be purchased from the Superintendent of Documents, Government Printing Office, Washington, D. C. The publications marked "Exhausted" are not available for distribution but may be seen at the larger libraries of the country.

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