bearing rocks has been found on many prospect dumps on the lower southeast slopes of Jacque and Tucker Mountains, and molybdenite-bearing quartz veinlets one-quarter inch thick cut the bluish-gray quartzites on Tucker Mountain. In the upper D and G tunnel on Jacque Mountain, already referred to, disseminated molybdenite grains occur in the garnetized rock and also in quartzite. The molybdenite deposits found in the mapped area have proved to be of insufficient size or grade to exploit.

Besides these more typical high-temperature minerals, which are commonly found in contact metamorphic deposits, the high-temperature deposits in the Kokomo district contain disseminated pyrite. Pyrite associated with pyrrhotite also forms massive replacement bodies in the limestones, discussed below, but the disseminated pyrite appears to be free from pyrrhotite, and tentatively is considered a part of the high-temperature assemblage of minerals. Although pyrite forms disseminated grains and bunches in the sedimentary rocks it occurs profusely in the porphyry masses both as disseminated grains and in discontinuous veinlets. On the northern end of Tucker Mountain and adjacent parts of Jacque and Union Mountains both the sedimentary rocks and igneous rock masses have been locally so thoroughly impregnated with pyrite that it is difficult to distinguish the rock types. The outcrop here is weathered and thereby forms a huge mass of rock stained yellow to buff by the iron oxide formed by oxidation of the disseminated pyrite.

Replacement Deposits

By A. H. Koschmann, F. G. Wells, and James W. Odell

The replacement deposits, which are the most productive in the district, occur in the limestone beds of the middle unit of the Pennsylvanian and Permian (?) sedimentary rocks. Some of the underground workings near the head of Kokomo Gulch may be in limestone beds in the lower unit of these rocks, but as these workings are inaccessible not much is known as to their extent or their output of ore.

The largest deposits, which lie southwest of Searle Gulch between the valley of Tenmile Creek and the Little Chief fault on the south end of Elk Ridge, have replaced beds in the Robinson limestone and the upper bed of the White Quail limestone, but small ore bodies have also been explored in the Jacque Mountain limestone on the east side of Searle Gulch. The Robinson limestone has been the chief ore horizon in the Robinson, Felicia Grace, New York, Champion, and Wheel of Fortune mines and probably in the Eldorado and East mines. The White Quail limestone is the chief horizon in the White Quail, Colonel Sellers, Wilfley, Kimberly, Breene, and Delaware mines on the south end of Elk Ridge, and in the Snowbank, Lucky Strike, Washington, Michigan, and Uthoff mines on the east slope of East Sheep Mountain. No underground information is available on any of the deposits in the Jacque Mountain limestone and very little on the deposits in the Robinson limestone. The only accessible mines in the district are the Wilfley and Kimberly on the southeast slope of Elk Ridge, and the Lucky Strike, Washington (through Lucky Strike workings) and Uthoff mines on the southeast slope of East Sheep Mountain, all in the White Quail limestone. The description of the ore bodies that follows is therefore based in part on the earlier report by Emmons,[59] in part on incomplete underground studies of the accessible mines by Koschmann and Odell, and on the field and office studies by Wells.

The replacement deposits lie to either side of vertical fissures—some of them fault fissures—that trend chiefly from N. 50° to N. 60° E. As the beds dip northeastward the ore shoots pitch to the northeast. In the Robinson mine the fractures which presumably admitted the ore-bearing solutions can be readily distinguished in the roof of the ore body. They are generally situated at about the middle of the shoot, but are not continuous throughout its length.

[59]Op. cit., pp. 4-6, 1898.

They probably consist of a series of fractures having one general direction, arranged more or less en echelon. Some of these fractures are lined with pyrite and, in the No. 1 ore shoot of the Robinson mine which is in the main limestone bed, the vertical ore-lined fracture was traced upward 80 to 100 feet to the upper limestone bed. Ore-bearing solutions appear to have migrated along the intersection of the fissures and limestone beds and thence laterally, replacing the more favorably constituted beds.

The ore bodies are irregular in size and shape. They range from a few feet to 300 feet and more in width, and some have been mined down the dip for more than 2,000 feet, as in the Robinson mine. Although some limestone beds as much as 30 feet thick have been entirely replaced by sulfides, the sulfide deposits rarely exceed 10 feet in thickness. The solutions apparently spread along the contact of the limestone with overlying layers of impervious shale or porphyry; and as replacement has generally extended from the top of the limestone downward, the base of the ore body is locally irregular. The roof of the ore bodies is clearly defined at the top of the limestone bed. Above the ore bodies in the Robinson limestone is a roof streak, 1 to 2 feet thick, of fine-grained highly micaceous sandstone impregnated with marcasite, or white iron as it is called by the miners. A relatively high proportion of the micaceous material consists of sericite that has been formed by replacement of an originally feldspathic sandstone. In places a thin seam of black shale, studded here and there with lumps of pyrite, forms the barren roof above the ore deposits in the White Quail limestone.

The lateral transition from ore to unmineralized limestone is sharp. In the Robinson mine the mineralization is, in places, defined laterally by fault planes or fissures that parallel the central fissure, but the margins of the ore bodies in the mines in the White Quail limestone, where seen, show no barriers which might have restricted the circulation laterally, nor have faults been found at such places which might have cut off the ore. According to Emmons[60] in the White Quail limestone in the Quail group of mines the margin of the ore bodies grades in a short distance from solid sulfide through quartz impregnated with sulfides to barren jasperoid, and thence into what the miners call "short lime" to limestone. In places the quartz and jasperoid zones are absent. Apparently mineralization advanced from transecting channels along the strata or impervious contacts, and all available mineralizing constituents were deposited along the interface between unreplaced limestone and ore, thus precluding any deposition far in advance of such fronts.

In mineral composition the replacement deposits are aggregates of sulfides, being composed of pyrite, pyrrhotite, marcasite, marmatite (black sphalerite), galena, and chalcopyrite, with a small proportion of gangue. The relative abundance of the ore minerals varies widely both in the same deposit and from one deposit to another, and locally the deposits are zoned or banded. On the basis of composition they can be classified as (1) pyrrhotite ore, (2) pyrite ore, and (3) mixed sulfide ore. Classes (1) and (2) are not at present of commercial interest.

The pyrrhotite ore consists of massive pyrrhotite with fine-grained intergrown pyrite. Pyrite locally is also concentrated in pockets or lenses. Marmatite (black sphalerite) where found at all is sparsely disseminated, and occurs most commonly at the base or margins of the pyrrhotite bodies. Galena is rare. Chalcopyrite, though invariably present, is scarce; it nowhere forms more than 1 percent of the ore and in places it is visible only under the microscope. It occurs in the pyrrhotite and commonly as numerous dots and blebs in the marmatite. In such ore marcasite is commonly present, in the majority of places as a supergene mineral.

The pyrite ore consists essentially of coarsely crystalline pyrite and some marcasite, with a fine-grained, brown-

[60]Op. cit., p. 5, 1898.

ish-white carbonate. Marmatite is locally a minor constituent of this ore, but pyrrhotite is sparse.

The mixed sulfide ores are coarsely crystalline aggregates of pyrite, marmatite, and galena, all more or less argentiferous and accompanied by accessory marcasite and a little gangue. In most of the ore the sulfides are mingled irregularly, but in some places the ore is broadly banded, and locally galena is concentrated in pockets or lenses. Because of the high lead content of ore mined before 1895 it seems probable that shoots rich in galena were common in the ore bodies just below the oxidized zone in the Robinson and White Quail mines. According to Emmons,[61] ore from the White Quail group of mines, when concentrated 6 to 1, contained about 62 percent lead, only 3 or 4 percent zinc, and 23 ounces of silver to the ton.

Quartz is the most abundant gangue mineral, and carbonates, chief among which is siderite, are second in abundance. Calcite, also, is locally present, and Emmons[62] reported a little barite in the White Quail mine and barite, rhodochrosite, and rhodonite in the Robinson mine.

Veins

The veins of the district comprise two types: (1) metalliferous veins, and (2) carbonate veins. Locally carbonate veins form the medial portion of metalliferous veins, clearly establishing that the carbonate veins formed later than the metalliferous veins. The carbonate veins mark the final, low-temperature stage of mineral deposition in the district.

Metalliferous Veins

The only large metalliferous vein deposit of economic importance is the one exploited in the Queen of the West and adjoining mines on the southeast slope of Jacque Mountain. According to Emmons[63] the ore occurs in a series of

[61] Op. cit., p. 5, 1898.
[62] Op. cit., pp. 4-5, 1898
[63] Op. cit., pp. 5-6, 1898.

parallel fissures and closely spaced faults of slight displacement, which cross alternating layers of sandstone and porphyry at right angles. The fissures strike N. 60° to 70° E., which is about the same as the prevailing regional trend of the larger faults. In mineral composition the metalliferous veins are similar to the replacement deposits. In the veins the minerals that formed toward the end of metallization are somewhat more abundant than the earlier formed minerals. The reverse is true in the replacement bodies. The unaltered vein ore that was mined was mostly galena, sphalerite, and pyrite but contained sulfides of silver; the gangue was chiefly calcite and unaltered country rock. In the main or central vein there was found a vein 1 to 2 feet thick of crystalline calcite with curved faces which is evidently the filling of an open fissure formed subsequently to ore deposition. The most productive portion of these veins was the oxidized ore, which extended 200 to 300 feet below the surface. It consisted of iron-stained quartzose material with seams or veins or barite as well as the secondardy ore minerals.

Other veins with the same general strike and dip as the Queen of the West veins are scattered throughout the district, many of them in association with premineral faults along some of which postmineral movement has taken place. Lumps of sulfide, largely of galena, are found in the comminuted kaolinized rock in the veins. Although this galena has been involved in the movement along the faults, much of it may have been deposited in pre-existing fault fissures. It is coarse grained and relatively free from other sulfide minerals.

Small vein deposits were also found in fissures leading from the replacement deposits in the Robinson and other limestones. Along these fissures in the overlying sandstone, there were small deposits of siliceous pyritic ore, which according to the late Mr. Jesse F. McDonald,[64] of Leadville contained neither galena nor sphalerite, but the value of the

[64]Oral communication.

silver content was high. Although the output from metalliferous veins has been relatively small they may serve as guides to possible ore in adjacent limestone beds.

Carbonate Veins

Besides the carbonate veins found underground in the Queen of the West group of mines, three large but barren carbonate veins are exposed on Tucker Mountain, one of which has been explored by the Boston Cooney mine, now inaccessible. They strike approximately N. 15° to 40° E. and, judging from the effects of topography on their trace, dip steeply northwestward. They are 12 to 20 feet thick and from 750 to 2,000 feet long. The two shorter veins are in the sedimentary rocks, but the longest one also cuts the porphyritic quartz monzonite. Like those in the Queen of the West mine they consist of coarse calcite with curved crystal faces. In the porphyritic quartz monzonite the vein carries inclusions of monzonitic gangue and a little quartz. Neither in the outcrop nor on prospect dumps were sulfides found associated with the carbonate.

Surficial Alteration of the Ores

The early production of the Kokomo district, as in neighboring mining districts, notably Leadville, consisted of oxidized ores. The oxidization, solution, and consequent removal of zinc and iron sulfides from the primary mixed sulfide ore produced a high grade residual ore rich in the precious metals and lead. As these metals were easily recovered from this type of ore they played an important part in the early mining development.

This process of alteration consists of the oxidization of the sulfides in the zone above the water table to sulfates and transfer of the soluble metal compounds either downward or lateraly to a position below the water table, where reducing conditions exist. Here the sulfates of some of the metals are reduced and the metals redeposited as sulfides. In the Kokomo district the minerals were attacked in the following order: first, pyrrhotite and marcasite; then sphalerite, pyrite, and chalcopyrite; manganiferous siderite; finally galena and the contained silver minerals. The greater part of the iron is dissolved, but owing to the tendency of ferrous sulfate to oxidize and hydrolize in the presence of oxygen, much of the iron is precipitated as ferric hydroxide and remains in the oxide zone. Manganese behaves similarly, but its solution is delayed until the ore has been partially impoverished in the reducing sulfide minerals. Thus, most of it is probably fixed in the oxide zone, which is thereby relatively enriched in manganese. Zinc sulfate is highly soluble and though the zinc can be deposited in the form of carbonate, as at Leadville, once in solution it is usually completely removed from the ore body. As lead sulfate is only slightly soluble, galena is not attacked until most of the more soluble sulfides have been oxidized. Sulfuric acid concentration is then low and the proportion of carbon dioxide is relatively high. Under these conditions most of the lead sulfate derived from the oxidation of galena is quickly changed to carbonate and deposited nearby. The oxidization of the silver minerals or minerals containing silver, such as galena, evidently took place at a late stage probably because minerals of this metal were so well protected by the enveloping minerals. The first oxidization product of silver-bearing minerals, silver sulfate, is relatively soluble, but where the silver came in contact with dissolved halides, horn silver, which is highly insoluble, was precipitated. Such silver sulfate as escaped reaction with chlorides was carried downward to the lower part of the oxidized zone and redeposited as native silver and secondary argentite (silver sulfide). Gold is difficultly soluble and rarely travels far. In the absence of specific data, it is safe to assume that the gold content of the ores at Kokomo was originally small and has undergone little change in the process of surficial alteration of these ores.

In general, oxidization and solution have largely or completely removed the zinc, and much of the iron, and have effected a relative increase of lead and silver. Where oxidation has been carried to an advanced stage, as in the upper levels of the Robinson mine, a porous powdery mass remains consisting of hydrous oxides of iron and manganese and manganese and silica containing cerussite and a little chloride of silver. This product, called gossan, is ocher, red or black.

Copper and silver are usualy redeposited as sulfides below the water table level. Though only a fraction of a percent of copper is present in the ores at Kokomo, some apparently supergene chalcopyrite has been observed. The common supergene copper sulfide, chalcocite, has not been recognized, nor was supergene silver sulfide, argentite, observed in the specimens available, but some supergene enrichment in silver has probably taken place below the water table for Emmons[65] has noted that "singular variations occur in the silver contents on either side of the small strike faults; as for example, from 28 ounces on one side, to 7 ounces on the other, which would seem to indicate a transportation of silver since the second period of faulting."

The character and extent of oxidation and redeposition of ores are influenced by the mineral composition of the primary ore, by their texture, by the position of the ground water table, by the amount of recent and glacial erosion of the region, by the recency of any differential uplift, and by the climatic history. Of these factors only the amount of recent glacial erosion is of practical significance to the miner and requires discussion here. In some parts of the district the ore bodies are oxidized to considerable depth, whereas in other parts unoxidized or only slightly oxidized ores are found at the grass roots. In the Robinson mine the ore bodies were oxidized to the level of the Robinson Flat, whereas the ore in the Lucky Strike and Michigan mines nearby is unoxidized even at the surface. The oxidized ore in the Snowbank mines was shallow and such ore did not extend deeply in the White Quail group of mines. On Jacque

[65]Op. cit., p. 5, 1898.

Mountain the ores in the Free America and Wintergreen mines are but a little oxidized, whereas the ore in the Queen of the West is oxidized to a depth of about 300 feet. Although the depth of oxidation undoubtedly varied from place to place in the district according to factors locally prevailing, there is no reason to believe that the process of oxidation extended several hundred feet below the surface in some places but was non-existent in others. The observed differences in the depth limits of the oxidized ores cannot therefore be due solely to differences in the original depth of oxidation, but must have been brought about largely by removal of oxidized ore by erosion. It is known that on the lower slopes in Tenmile Valley and Searle Gulch glacial action has locally scoured off 200 to 300 feet of material, and the absence of a blanket of oxidized ore in some areas is therefore ascribed to glacial scouring.

Genesis and History of Original Ores

The occurrence of the mineral deposits in the district in all classes of rocks implies their derivation from solutions that permeated the district after emplacement of the intrusive rocks. From the post-intrusive age of the mineral deposits it is inferred that they mark the end phase of the igneous cycle though there is no tangible evidence regarding their source.

The fact that some intrusive bodies are mineralized might be construed as showing a close genetic relation of the ore solutions and the intrusive rocks. It is clear, however, that the mineralizing solutions did not emanate from the exposed rocks for the great majority of the intrusive rocks as well as the enclosing sedimentary rocks, both above and below the sills, are free from effects of mineralization. This is true even of the larger sills, and where these are most numerous as in Searle Gulch. The location of the high-temperature mineral deposits, centering on Tucker Mountain, coincides with the eruptive center indicated by the chonolith and monozonite stocks, and the mineralizing solutions may have emanated from the same deep source as the intrusive rocks. The chonolith and stocks, as shown on page 75, were intruded along zones of weakness, and the mineralizing solutions apparently worked their way towards the surface along the same general major structural zones, probably after a period of fracturing. From these primary deep-seated channels the solutions spread into subsidiary connecting channels and laterally along the contacts, planes of stratification, and minor structures.

The wide differences in character of the mineral deposits and their field relations imply that they were deposited in several stages according to temperature and the complex solubility relations of the constituent minerals. Obviously the temperature gradient is not a simple function of the distance from the source and the overlying cover but is modified by variations in permeability of the enclosing rocks or, in other words, by the rate of flow of the solutions along major channels of the escaping solutions. The temperature gradient may be further complicated by changes in circulation brought about by the development of new faults or channels of circulation during the period of metallization or by the obstruction of old channels by previous deposits.

The general restriction of the high-temperature deposits to the northern part of the area, with its center on Tucker Mountain, and their absence in the area of the principal ore deposits implies either that the channels of access from the points of origin were restricted or the solutions were spent before reaching outlying areas. The absence of intermediate or low-temperature deposits in the areas of the high-temperature deposits favors the conclusion that the early fissuring was restricted to Tucker Mountain and the immediately adjacent area.

Subsequent to the deposition of the high-temperature deposits recurrent deformation over an area of wider radius produced new faults and fissures and afforded access channels to the later hydrothermal solutions, which were somewhat lower in temperature than the earlier solutions which effected the high-temperature deposits. These solutions of intermediate temperature were especially rich in the constituents forming the principal ore deposits. The distribution of such deposits in a narrow zone adjoining Tenmile Valley suggests that they were controlled by a concealed major fault or zone of weakness in Tenmile Valley. A major fault of northeast trend is known to occur in Tenmile Valley beteween the New York and Tenmile shafts and it seems plausible that the ore solutions were derived from a deep source and migrated along this structure from which the solutions spread along subsidiary structures. Except for the replacement bodies in the limestones, deposits formed at intermediate temperatures, though widely scattered. are small and commercialy unimportant. Either the supply of ore solutions in other parts of the area was small or the channels were too numerous and tight and the solutions were thus too widely and ineffectively spread to form large ore bodies. The presence of large commercial ore bodies in the outlying areas seems unlikely.

Data are insufficient to explain the close association of the principal ore bodies with the Robinson limestone and the upper bed of the White Quail limestone. In view of the large stratigraphic spread between these limestone beds and contrariwise the juxtaposition of unreplaced limestone beds with the ore-bearing limestones, it cannot be argued that the unreplaced beds were not accessible to the mineralizing solutions, for faults cut both. Selective replacement of the Robinson and the White Quail limestones must therefore be a result of favorable texture and composition.

The final stage of mineralization is represented by the carbonate veins, which are low-temperature deposits. Their restricted distribution on Tucker and Jacque Mountains suggests that deformation which preceded their deposition was slight. That some old fissures were reopened is illustrated by the composite veins in the Queen of the West mine, but a few new ones also were formed. They gave access to the final hydrothermal solutions which had cooled to a relatively low temperature. These veins have proven to be barren of ore and are of no commercial interest.