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There are no clear relations between primary metallization and structure. Typical protore is found more than 1,000 feet from any known porphyry mass of considerable size. Permeability of the rock mass and an abundant supply of active solutions were probably more essential to metallization than any other combination of factors. Permiability was due largely to the minute fissuring.

Deposition of protore probably followed closely the intrusion of the granite porphyry, but no known facts are available to fix this event in geologic time. It is reasonable to assume that the granite porphyry was intruded in Laramide time, certainly after deposition of the Mississippian and Pennsylvanian limestones and before eruption of the dacite.

The early stages of the enrichment must have been very slow. Under normal conditions the pyritized rock would be brought within reach of supergene solutions only after erosional removal of the overlying rock. The sulphides first reached probably were sparsely disseminated, and oxidation proceeded only here and there where conditions were especially favorable. As successively deeper portions were attacked, chemical activity would increase, and downward movement and concentration of copper would be in full progress.

Oxidizing solutions first attacked pyrite and chalcopyrite. Increasing quantities of chalcocite were deposited lower down at the expense of pyrite and chalcopyrite, and, as erosion progressed, this chalcocite came into the zone of oxidation. A stage must have been reached in which chalcocite and not pyrite was the object of attack of the descending atmospheric waters. When this stage is reached the process slows down so that if the erosional rate remains the same or is accelerated, it may overtake enrichment and attack rock that contains copper carbonate and silicate formed above the chalcocite.

The process of enrichment is potentially a cyclic operation, but many complicating factors, such as rate of erosion, depth to underground water, climate, topography, and country rock influence it.

Reference

Ransome, F. L., The Copper Deposits of Ray and Miami, Arizona, U.S. Geol. Survey Prof. Paper 115, 1919.

Clifton-Morenci District[38]

By

B. S. Butler and Eldred D. Wilson

Introduction

The following general description of the Clifton-Morenci district is summarized from Dr. Lindgren's classic report,[39] published in 1905, and the more detailed description of the Morenci open-pit mine is mainly from the records of the Phelps Dodge Corporation. The writers are particularly indebted to W. C. Lawson, Chief Engineer, for information.

In 1901 and 1902, when Dr. Lindgren studied the district, the mining of the low-grade ore in the monzonite porphyry of Copper Mountain was already well advanced. The low-grade ore then mined was much richer than the disseminated ore later so extensively mined in the Southwest but was of the same general type. Its successful exploitation at Morenci pointed the way to the development of other great disseminated deposits.

Dr. Lindgren's report was the first detailed description of a disseminated copper deposit, though of a somewhat specialized type, and it, too, pointed the way to the development of the disseminated deposits.

In the third of a century since the publication of Professional Paper 43, advancement in the mining and metallurgy of copper ores has steadily lowered the grade that can be profitably mined until material then of no value has risen to large value. Such is true of part of the mineralized area of Morenci that is now being developed into one of the largest copper mines of the state. Thus, the Morenci district, which was first in the utilization of disseminated copper ores, is now developing the latest mine in this type of deposit.

The main purpose of the present paper is to show the relation of this disseminated deposit to the other deposits of the district and to give a brief description of the geology of the district.

History

Some of the important events of the district with dates follow:

1872. Discovery by the Metcalf brothers.
1873. Sale of important claims to the Lesinskys.
      Organization of Longfellow Copper Company by Lesinskys and building of adobe furnace.
1875. Detroit Copper Company organized.
1882. Sale of Longfellow Company to Arizona Copper Company.
1887. Phelps, Dodge, & Company acquire interest in Detroit Copper Company.
1893. Discovery of low-grade sulphide ores of Copper Mountain.
1899. Organization of Shannon Copper Company.
1919. Purchase of Shannon Copper Company by Arizona Copper Company.
1921. Purchase of Arizona Copper Company by Phelps, Dodge, & Company.
1937. Beginning of Morenci open-pit operations.

Rocks

The oldest rock of the district is pre-Cambrian granite. Resting on the granite is the Cambrian (Coronado) quartzite, 200 feet

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[38] Paper obtained for, and originally presented at, the regional meeting of the A.I.M.&M.E. held at Tucson, Arizona, November 1-5, 1938.

[39] Waldemar Lindgren, *The Copper Deposits of the Clifton-Morenci District, Arizona* (U.S. Geol. Survey Professional Paper 43, 1905).

thick, followed by the Ordovician (Longfellow) limestone, 380 feet; the Devonian (Morenci) shale, 175 feet; and the Carboniferous (Modoc) limestone, 170 feet.

Unconformably on the Paleozoic rocks are a few hundred feet of Cretaceous shale and sandstone.

The Cretaceous and earlier rocks are intruded by a stocklike body, porphyritic in texture and ranging in composition from granite through monzonite to diorite. Extending from the stock into the surrounding rocks are dikes, sills, and laccoliths. Following a period of erosion that removed the cover from the intrusive bodies and exposed the copper deposits to oxidation, the area was buried beneath volcanic flows, breccias, and tuffs, ranging in composition from basalt to rhyolite.

Following the outpouring of volcanic material, the lower areas were buried by coarse, poorly assorted gravels (the Gila conglomerate) deposited by streams from the higher ground. In the Clifton area the Gila conglomerate has been rather deeply trenched and redeposited as bench and stream gravels.

Structure

The region doubtless had a complex structural history in pre-Cambrian time, but the pre-Cambrian rock is largely granite and reveals little of its early structural history.

From Cambrian time to the close of Cretaceous, the area alternated between erosion and deposition, the result of broad uplift and depression, but with no pronounced folding or faulting recognized.

At or near the close of Cretaceous, stresses developed that fractured the rocks in a generally northeast-southwest direction. Into this fracture zone magma rose to form the porphyry stock and associated dikes, sills, and laccoliths.

Along the contact of the porphyry stock with the sedimentary rocks, large and small masses of the earlier rocks were engulfed in the porphyry (Pl. XVI).

Stresses of the type that produced the breaks along which the magma rose continued after its solidification and produced a series of prominent northeasterly striking fissures in the porphyry. Such stresses doubtless caused continued movement on the earlier breaks and opened new breaks in the older rocks. These are the mineralized fissures that strike from north to east, with a prevailing direction of about N. 35 degrees E.

Associated with the northeasterly fissures are less persistent breaks that seem without rhyme or reason. If mapped in detail, they would doubtless fall into definite systems. These fractures broke the rocks, especially the porphyry, into small fragments bounded on all sides by fissures (Pl. XVII).

Some of the more prominent northeast fissures, including the Humboldt and the Wellington in Copper Mountain, and fissures in the open-pit area are shown on Plate XVI.

Especially prominent near Morenci are northwesterly striking

Plate XVII.—View of shattered monzonite porphyry, fifth underground level, open-pit area. (Photograph, courtesy Phelps Dodge Corporation.)

faults that determine the location of some of the principal gulches. These faults are later than the mineralization of the northeast fissures and associated breaks and even later than the enrichment of the veins by oxidation processes but earlier than outpouring of the lavas. It seems probable, however, that these breaks were initiated before the intrusion of the monzonite porphyry.

Ore Deposits

The primary mineralization was probably all at essentially one time, closely following the intrusion and solidification of the porphyry and the fissuring of it and the older rocks.

The deposits may be separated into three main groups: (1) those that replaced sedimentary rocks, (2) those that formed in fissures and as disseminations in the monzonite porphyry, and (3) fault-fissure veins of the Coronado type.

Deposits Replacing Sedimentary Rocks

The early operations were largely on oxidized ores of deposits that replaced sedimentary rocks. The primary ores consisted of pyrite, chalcopyrite, and sphalerite in a gangue that contained abundant silicates of which garnet and epidote are most abundant. These minerals replaced favorable strata of the limestone with material of low copper content. The ore resulted from the oxidation of this material with the change of the copper minerals from sulphides to carbonates and oxides and with an enrichment in copper.

The Longfellow Mine at Morenci is of this type as are numerous other deposits at both Morenci and Metcalf. Production from this type of deposit has been worth several million dollars.

Fissures and Disseminations in Monzonite Porphyry

Due to the barren outcrops of the veins in porphyry which had been leached to a depth of some 200 feet, the deposits in the monzonite porphyry remained undiscovered for several years after the development of the deposits in the limestones. The early operations were confined to the larger veins, but as it became possible to treat lower grade material, more and more of the wall rock was mined. Lindgren[40] wrote in 1905:

> On both sides of these seams extends a mass of sericitized porphyry, of varying width, containing little seams and grains of chalcocite. To this ore there are no well-defined walls, but they gradually fade out into material too lean to constitute ore. Could two percent ore be made payable, the width of the ore bodies would be much increased.

When it became profitable not only to treat 2-per-cent ore but material of much lower grade, the width of the ore bodies was so extended that it became practicable to take all the material between fissures and to mine the lode zones as one ore body.

Professor Lindgren[41] describes the vein of Copper Mountain as follows:

> The most important vein system is that which, under the general name of the Humboldt vein, extends from northeast to southwest through Copper Mountain at Morenci. The outcrops of this vein are practically barren, but at a depth of 200 feet the deposit becomes productive and contains chalcocite associated with pyrite. There are usually one or more central seams of massive chalcocite, some of which are fairly persistent. These seams are ordinarily adjoined by decomposed porphyry, now chiefly consisting of sericite and quartz, together with pyrite and chalcocite. These extensive impregnations of the country rock are rarely confined to distinct walls, but gradually fade into the surrounding porphyry. That these deposits are genetically connected with fissure veins, however, cannot be doubted. In lower levels the ore is apt to change to pyrite and chalcopyrite.

This, as a general description, applies equally well to the more recently developed deposits, including the open-pit mine.

Characteristic features.—The lode systems have a general northeast trend. Mineralization is strong in the main fissures and extends into the smaller associated fissures. The primary mineralization, as shown in the deep levels, is quartz, pyrite, chalcopyrite, and sphalerite veins with most veins rich in pyrite. Outcrops over the ore are largely leached of both iron and copper. Ore croppings are light buff in color as contrasted with the deep red and brownish red tones common in mineralized porphyry that does not contain ore.

[40] *Op. cit.*

[41] *Op. cit.*

Below the leached cap rock, which has a maximum thickness of 500 feet, the ore consists of secondary chalcocite that has replaced pyrite extensively in the rich ore and decreasingly with increased depth or decreased permeability of the rock.

Development usually stops where the copper content falls below the commercial grade, though the copper may still be present in part as secondary chalcocite. There are, therefore, no very definite data on the copper content of the primary mineralization, but it is low and the ore represents a relatively large addition of copper from the leached zone.

The present water table is below the ore that has been enriched, and the irregular lower surface of the ore indicates that it has not been controlled by a water table. Much of the enrichment was accomplished before the burial of the area by lavas, and the water table may then have had a very different relation to enriched ore. Since erosion of the lava from above the deposits, the enrichment process has been renewed.

Coronado Vein

The Coronado vein occurs as a cementation of breccia on the Coronado fault which strikes east-northeastward and has thrown Coronado quartzite against pre-Cambrian granite. A diabase dike was intruded into this fault before movement had ceased and before mineralization. The primary mineralization was similar to that of the fissures in the monzonite porphyry, but alteration resulted in the formation of a zone of oxidized ores and one of secondary sulphide ores. This contrasts with the deposits in limestone which were mostly oxidized ores and those in the monzonite porphyry which were mostly sulphide ores. The difference is probably due to the different types of rock in the different deposits. The reactive limestone yielded oxidized deposits, the relatively inert monzonite porphyry yielded secondary chalcocite, and the intermediate rocks of the Coronado vein yielded both.

The Morenci Open-Pit Mine

Location.—The Morenci open-pit mine is on the southwest side of Chase Creek and north of the area that has been most productive in the past—namely, the Copper Mountain-Longfellow area (Pl. XVI).

The ore body, as now defined, has a maximum length of 4,400 feet and a maximum width of 2,800 feet.

Rocks.—The mine is entirely within the quartz monzonite porphyry body, though there are some blocks of mineralized quartzite engulfed in the porphyry within the mine. The monzonite is highly altered throughout the mineralized area. No detailed study of the alteration of this area has been attempted, but it is clearly the same in all essentials as that of the Copper Mountain area described by Lindgren,[42] and by Reber.[43] Typically, it consists of sericitization together with the introduction of pyrite and chalcopyrite.

Structure.—The most striking feature of structure is the fissuring. In most faces, fissures seemingly without definite order or pattern break the rocks into small angular fragments (Pl. XVII). A mapping of the more prominent fissures, however, indicates very definite directions.

Different parts of the ore body have been developed by different methods. Some of the earliest openings followed the more prominent fissures for hundreds of feet. Later, areas were developed by underground openings laid out in a rectangular pattern, and the latest developments were by core drill. The conspicuous fractures in the underground openings are shown on the Company maps. No attempt at a statistical compilation of direction has been made, and it is difficult to evaluate the strength of the fissures from the records. A general inspection of the maps, however, gives the impression that fully three fourths of the mapped fissures strike within the northeast quadrant and that those within this quadrant are predominantly about northeast.

In the part of the mine early developed along the most prominent fissures, the northeast direction is particularly conspicuous. Some strike nearly north. The fissures for a part of the fifth level are shown on the plan map of the ore body (Pl. XVIII). Similar fissures are doubtless present in other parts of the ore body, but the data for plotting them are not now available. The fissures that were sufficiently prominent to induce vein prospecting are widely spread, 300 to 400 feet apart, but between them are networks of smaller fissures that, as already stated, break the whole body of the rock into small fragments.

Ore body.—It may be noted that the greatest dimension of the ore body is in the direction of the strike of the more prominent fissures—namely, northeast.

Lindgren has shown that the disseminated deposits of the Copper Mountain area are unquestionably associated with the northeast fissures of that area. It seems equally evident that the disseminated deposits of the open-pit mine are associated with northeast fissures.

In the estimation of ore reserves, assay maps were prepared of all openings. As these maps clearly show, drifts that follow northeast fissures have much higher average copper content than openings laid out on a rectangular pattern, or those that do not follow fissures.

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[42] Waldemar Lindgren, *Op. cit.*

[43] L. E. Reber, Jr., "Mineralization at Clifton-Morenci," *Econ. Geol.*, XI (1916), 528-73.

No attempt has been made to ascertain the copper content of fissure drifts, but they evidently average two to three times that of the average of the ore body. If the fissures alone were sampled instead of the whole width of the fissure drift, the average would be much higher.

The concentration in the larger fissures is so evident that in estimating copper content of the ore body, the fissure drifts were not included.

The mineralized body, in common with other disseminated deposits, can be separated into three parts or zones: (1) the upper or surface zone, (2) the ore zone, and (3) the lean sulphide zone.

1. The upper or surface zone consists of iron-stained, silicified, and sericitized monzonite. Over the ore body this is generally of light buff color with darker red to brown streaks along the fissures in contrast with much higher colored red and brown capping of the rocks surrounding the ore body.

The copper content of the capping rock as a whole is not shown on the assay plans, but the few recorded assays and the visible features of the rock indicate that, near the surface, the removal of the copper has been nearly complete.

The oxidized capping has a maximum thickness of 500 feet, with an average of 216 feet. In general, it is thickest under hills and thinnest under valleys.

In places, the lower part of the oxidized zone contains considerable copper so that there is not everywhere a sharp change in copper content between the oxidized zone and the sulphide zone.

2. The ore zone lies beneath the oxidized zone. Its blue-gray color contrasts sharply with the buff capping rock. At closer range, the network of fissures becomes prominent (Pl. XVII). Examination shows the fissures to be composed mainly of quartz and pyrite, the latter coated and replaced to varying degrees by chalcocite.

The thickness of the ore body is irregular, but over much of the area is 500 to 700 feet (Pls. XIX and XX). There is a general pitch of the ore zone eastward in the direction of greatest elongation. The bottom of the ore to the east is some 200 feet lower than to the west. The same in general holds for the top of the ore, and both roughly correspond with the slope of the present erosion surface.

There are no sharp boundaries to the ore either laterally or in depth. The boundaries as shown are based on expectation of profitable extraction. In depth, however, many drill holes show a rather sharp drop from near 1 per cent to ½ per cent or less. As most drill holes were stopped when the copper fell to ½ per cent, there is no general record of the copper content of the underlying material. Some holes, carried 200 feet or more below the ore, indicate that the unenriched material contains less, perhaps considerably less, than ½ per cent copper. In this material the copper is probably in chalcopyrite.

The zone of secondary enrichment, when formed, before the outpouring of the later lavas, may have had some definite relation to a water table, but neither the top nor the bottom of the secondary enriched zone is now determined by a water table.

The Phelps Dodge Corporation prospectus covering the issue of convertible 3½ per cent debenture bonds, in regard to the Morenci open-pit ore reserve, estimates 284,000,000 tons of ore assaying 1.030 per cent copper. The ore carries small and relatively unimportant amounts of gold and silver. The ore available for extraction on the basis of the pit lay-out now contemplated for this program is estimated at 230,000,000 tons carrying 1.06 per cent copper.

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Ray District[44]

Introduction

Ray is about 17 miles south of Miami on Mineral Creek, between the Dripping Spring Range on the east and the Tortilla Mountains on the west.

The latest and most complete report on the Ray district is by Dr. F. L. Ransome.[45] Since the time of Dr. Ransome's report, underground development has further revealed the extent of faulting and the structural relationships.

The present paper gives a general description of the geology largely summarized from Ransome's reports, together with new data regarding the structural features of the ore body. These new data, together with Figure 7, are taken from an unpublished manuscript by C. Leroy Hoyt.[46]

History and Production

1873. Mineral Creek district organized prior to this time by silver prospectors.

[44] Paper compiled for the regional meeting of the A.I.M.&M.E. held at Tucson, Arizona, November 1-5, 1938.

[45] F. L. Ransome, *Copper Deposits of Ray and Miami, Arizona* (U.S. Geol. Survey Prof. Paper 115, 1919); *Description of the Ray Quadrangle* (U.S. Geol. Survey Folio 217, 1923).

[46] Engineer, Nevada Consolidated Copper Company.

1880. Location and prospecting of claims. Mineral Creek Mining Company builds a five stamp mill.

1883. Ray Copper Company organized with a capital of $5,000,000.

1898. Small-scale operations at Ray Mine.

1899. Ray Mine acquired by Ray Copper Mines, Ltd., capitalized at £260,000. Building of 250 ton mill at Kelvin and blocking out of ore at mine. This company failed because of inadequate sampling.

1907. Ray Consolidated Copper Company organized by D. C. Jackling and others to acquire and work the ground formerly held by the Ray Copper Mines, Ltd. Arizona Hercules Copper Mining Company and Kelvin-Calumet Mining Company begin operations.

1909. The existence of about 50,000,000 tons of ore is ascertained. Ray Central Copper Mining Company succeeds Kelvin-Calumet Mining Company.

1910. Louis S. Cates becomes Superintendent of Mines and develops mining system whereby Ray later became the first copper mine in the world to produce 8,000 tons or more of ore per day by caving methods.[47]

1911. Production starts from mines of Ray Consolidated Copper Company after construction of mill at Hayden.

1924. Ray Consolidated and Chino companies merge.

1926. Nevada Consolidated absorbs Ray and Chino.

Production of the Ray mines to the end of 1931 has been recorded[48] as follows:

TABLE 4.

	Copper (pounds)	Gold (value)	Silver (value)	Total value
Ray, 1911-31	1,156,000,000	$280,000	$150,000	$198,500,000
Ray Hercules, 1918-23	8,000,000	....	....	1,500,000
Total	1,164,000,000	$280,000	$150,000	$200,000,000

Rocks[49]

The oldest rocks in the region are the Pinal schist, which consists mainly of metamorphosed siliceous sediments and various granitic intrusive rocks. All these rocks are of older pre-Cambrian age. Resting on the eroded surface of the old crystalline rocks are Apache group beds (Pl. III) aggregating from 1,200 to 1,300 feet in thickness, apparently in conformable sequence and supposed to be younger pre-Cambrian. More than two thirds of this thickness is represented by two quartzite formations; the remaining beds include shale, dolomitic limestone, and conglomerate. Great masses of diabase of uncertain age (p. 15) intrude the

[47] A. B. Parsons, *The Porphyry Coppers* (A.I.M. and M.E., 1923).

[48] M. J. Elsing and R. E. S. Heineman, *Arizona Metal Production* (Univ. of Ariz., Ariz. Bureau of Mines Bull. 140, 1936), p. 99.

[49] Description largely from Ransome, *op. cit.*