THE GEOLOGIC FEATURES OF THE OCCURRENCE OF COPPER IN NORTH AMERICA

By F. L. Ransome
California Institute of Technology, Pasadena, California

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Balch Graduate School of the Geological Sciences
California Institute of Technology
Pasadena, California

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Introduction

Copper is of such widespread natural occurrence in North America and there are so few metal-mining districts that have not contributed to its production that it is obviously necessary in any brief general treatment of the geology of the copper deposits of the continent to restrict the discussion to the districts in which copper is the dominant metallic product. Otherwise the summary would be unreasonably long.

The copper deposits of North America may be classified in various ways—with respect to form, genesis, geologic age, distribution, and distinctive features of character or occurrence. On the whole, an areal grouping will probably be most satisfactory. To some extent this will coincide with a classification based on the form or character of the deposits, but there will be notable exceptions. Classification, after all, is merely a human expedient for systematizing description and for facilitating studies of origin. It is essentially artificial and sets up class distinctions, the legality of which, at least so far as ore deposits are concerned, Nature does not recognize.

The present paper discusses the geology of the copper deposits of North America in accordance with the following general grouping:

1. Copper deposits of the Appalachian belt.
2. Copper deposits of the pre-Cambrian Canadian Shield.
3. Copper deposits of the Lake Superior region.
4. Copper deposits of Butte, Montana.
5. Copper deposits of the southwestern United States and northern Mexico.
6. Copper deposits of the Pacific coast north of Mexico.

Copper deposits of the Appalachian belt

The term "Appalachian belt" is here used to designate the chain of mountains along the Atlantic seaboard, extending from Alabama into Newfoundland, which came into existence in consequence of the folding and faulting that culminated in Permian time. This unit, corresponding in part to the Appalachian Mountains of today, is less extensive than the Appalachian region of Keith (1, pp. 330–332), which, as a structural entity, he regards as extending far westward into eastern Arizona, including the Ozark dome and the Arbuckle and Ouachita Mountains.

Within the United States the Appalachian province, from central Alabama to southern New York, is generally divisible into four longitudinally coextensive units. These, from east to west, are (1) the Piedmont Plateau, composed mainly of pre-Cambrian or early Paleozoic metamorphic rocks, including gneisses, extensively invaded, in Permian time, by granite and other igneous rocks; (2) the Appalachian Mountains, of which the dominant structural and geomorphic feature is the great compound Blue Ridge geanticline, composed of rocks similar to those of the Piedmont Plateau, but with a larger proportion of relatively unmetamorphosed early Paleozoic sediments; (3) the Appalachian Valley, eroded along a belt from 40 to 125 miles wide, of closely folded Paleozoic sedimentary rocks, mainly calcareous; and (4) the Appalachian (Cumberland) Plateau, which, from its eastern escarpment, overlooking the Appalachian Valley, slopes gently westward in general conformity with the inclination of the underlying Paleozoic beds.

Although the Appalachian belt is one of the world's classic examples of folded structure, faulting, both normal and thrust, has played a large part in its tectonic development (1, 2).

The Appalachian copper deposits, except those at Ducktown, Tennessee, are of slight present economic importance, and there is little chance of improvement in this respect in the next few decades. The relative insignificance of these deposits industrially may be seen from the following statements. The entire output of copper in the United States in 1931 was 1,042,711,178 pounds. Of this, 21,911,638 pounds was given by the United States Bureau of Mines as "undistributed." This included the undivulged production from Tennessee. In 1928 the total production from Tennessee, mainly or entirely from Ducktown, was 16,374,261 pounds. If it is assumed that the output from Ducktown in 1931 was roughly 16,000,000 pounds, this would leave about 6,000,000 pounds from all undesignated sources, inclusive of the Appalachian mines other than those at Ducktown.

The most comprehensive general account of these deposits has been given by Weed (3), who divides them into six types, as follows:

1. Ducktown type. Pyrite lenses and veins in crystalline schists. Occurs at Ely, Vermont; Ore Knob, North Carolina; southwest Virginia; Ducktown, Tennessee; Milan, New Hampshire; Davis, Massachusetts; and Stonehill, Alabama.

2. Copper quartz-vein type. Quartz veins containing metallic sulphides. (*a*) Virgilina variety; quartz veins with glance and bornite; occurs at Copper Knob (Gap Creek), North Carolina. (*b*) Gold Hill variety; silicified schists, containing chalcopyrite and pyrite, with ore shoots of quartz and chalcopyrite; occurs in veins of North Carolina and Virginia gold belt. (*c*) Seminole variety; zone of pyritized schists, carrying local shoots of high-grade ores.

3. Carolinian type. Bands of amphibolite traversing mica schists and carrying chalcopyrite and pyrite disseminated through the rock or gathered in bunches or, more commonly, deposited in the gray gneiss alongside. Occurs at Elk Knob, Way-ye-hutta, and Peach Bottom, North Carolina, and at New Haven, Connecticut.

4. New Jersey type. Impregnated shale and sandstone adjacent to trap masses; in part in the trap. Occurs at Somerville, Arlington, and Griggstown, New Jersey, and at Leesburg and Orange, Virginia.

5. Pahaquarry type. Devonian sandstones impregnated with copper ores; and shales, etc., of Coal Measure regions with occasional ore; not rare but insignificant in amount.

6. Blue Ridge (Catoctin) type. Bunches and joint fillings in the surficial portions of the basaltic rocks (Catoctin schist) of the Blue Ridge region.

The foregoing list is not all-inclusive and, in certain respects, is open to criticism or modification. Many of the examples cited are practically negligible economically. Attention will be given here only to a few of the more important types and localities.

Ducktown type

The Ducktown district, in which are the principal deposits of the Ducktown type, is mainly in the southeast corner of Tennessee but extends a short distance across the State boundary, into northern Georgia. It is within the Blue Ridge division of the Appalachian Mountains. The district has been fully described by Emmons and Laney (4), whose paper contains a full bibliography on the area.

The ore deposits occur in the schistose rocks of the Great Smoky formation, which are metamorphosed sediments of Lower Cambrian age. The only igneous rocks recognized in the district are dikes of gabbro, of probably late Paleozoic age. There were apparently two main epochs of folding and metamorphism—one at the end of the Ordovician period and one at the end of the Carboniferous. Less intense deformation of undetermined post-Carboniferous age represents a third epoch.

The ore bodies of Ducktown are chiefly curved tabular masses such as would result from the replacement of particular beds, after complex folding. They are chiefly faulted domes and anticlinoria, complicated by subsidiary carinate folds. The hypogene ore consists principally of pyrrhotite, pyrite, chalcopyrite, sphalerite, bornite, actinolite, calcite, pyroxene, tremolite, quartz, garnet, chlorite, specularite, and magnetite.

Various views have been advanced as to the origin of the Ducktown ore bodies. Emmons (4, p. 64) concludes that they have been formed by the replacement of lenticular bodies of limestone, after these had been folded and faulted with the Great Smoky formation, of which they are stratigraphic parts. He believes that the source of the mineralizing solutions was some deep-seated granitic mass, similar to exposures known about 12 miles away.

In the early period of development most of the copper from the Ducktown district was derived from a zone or layer of high-grade chalcocite ore, commonly from 3 to 4 feet thick. The top of this layer was roughly coincident with the underground-water table and lay about 100 feet below the highest ore outcrops. Although chalcocite enrichment probably took place during the development of the Tertiary peneplain, of which remnants are recognizable in the region, the chalcocite mined was deposited during the period of erosion that followed the uplift of that peneplain. The process of enrichment is fully discussed by Emmons in the report cited and also by Gilbert (5). In the thinness, definiteness, and regularity of the supergene chalcocite zone, the Ducktown deposits present a marked contrast to the enriched copper deposits of the arid southwestern United States, doubtless because of the relatively humid climate of Ducktown, the stability of the water table, and the presence of abundant pyrrhotite in the ore.

The copper deposits of Maine and of Milan, New Hampshire, included by Weed in the Ducktown type, should, in accordance with their description by W. H. Emmons (6), probably be regarded as a separate type. These deposits lie in a low plateau, floored by closely folded metamorphic, sedimentary, and igneous rocks, ranging in age from pre-Cambrian (?) to Devonian. The deposits occur in schists, which are in part metamorphosed siliceous shales and argillaceous sandstones (Ellsworth schist) and in part metamorphosed andesitic and rhyolitic lavas and associated clastic rocks (Castine formation). These rocks are probably pre-Cambrian. The ore bodies are chiefly more or less lenticular, veinlike masses of pyrite, with some chalcopyrite, pyrrhotite, magnetite, arsenopyrite, bornite, chalcocite, and a little sphalerite and galena. The gangue minerals are quartz, chlorite, muscovite, and biotite. The ore masses, probably of post-Cambrian and pre-Silurian age, have undergone at least a considerable part of the contortion and metamorphism that have affected the enclosing rocks, and in this respect they differ from those of Ducktown. Moreover, they appear to have been originally replacement veins along fissures and not to have replaced limestone. The shipping ore from the Milan mine, according to Emmons, carries about 2.25 percent of copper, 7.3 percent of zinc, 1.6 percent of lead, and about $1.50 in gold and as much as 2 ounces of silver to the ton. These ore deposits are not clearly related to any particular intrusive rock, although Emmons suggests that some of them may be genetically connected with granites of late Silurian or early Devonian age.

Virgilina type

Of Weed's second type (copper quartz veins), the Virgilina variety is the only one to which particular attention will here be given. The Gold Hill variety includes deposits that are as much gold veins as copper veins, and the Seminole variety is of very slight economic importance.

The best-known and probably the only economic examples of the Virgilina type are those of the district from which the name is derived. The Virgilina district extends across the line between Virginia and North Carolina, about 160 miles west of Norfolk, Virginia, near the eastern border of the Piedmont Plateau. The rocks of the district are greenstone schist and quartz-sericite schist, derived respectively from pre-Cambrian or early Paleozoic andesite and rhyolitic lavas, with associated tuffs. The tuffs of andesitic affinity grade in places into sandstones and conglomerates. These rocks are cut by intrusions of granite and gabbro. The structure, according to Laney (7), is probably that of a closely compressed syncline with axis striking north-northwest. The beds dip 70°–80° E.

The copper deposits occur as steeply dipping veins, which generally strike a little more northerly than the adjacent schists. Some of the veins are 20 feet wide and may be traced for 4 or 5 miles along their strikes. Most of them are markedly lenticular, and a banded structure is common. The vein filling is chiefly quartz, carrying bornite and chalcocite, with rarely a little chalcopyrite. Locally, epidote, calcite, and albite may be present as gangue minerals.

Laney concludes that the ores are probably related in origin to the intrusion of the granite, although the fact that they are confined to the more basic facies of the greenstone schists is referred to as indicating some genetic relationship, not definitely stated, between the copper ores and the basic schists. He regards the bornite and the greater part of the chalcocite as of contemporaneous, hypogene deposition. The deepest mines at the time of Laney's study were less than 500 feet deep, and probably there has not since been any notable amount of work done below that depth.

Catoctin type

The native copper deposits of the Catoctin type are of no economic importance but are of considerable interest with respect to genesis. These deposits are distributed along the Blue Ridge region of the Appalachians from southern Pennsylvania into Virginia. They lie generally between the folded Cambrian and Ordovician sediments on the west and areas of Cambrian quartzite and Triassic rocks on the east. The contacts between the copper-bearing rocks and the Paleozoic rocks on the west are in part due to thrust faulting; the contacts on the east are in part due to normal faulting.

The copper-bearing rocks are pre-Cambrian basaltic lavas which have been altered to greenstones and in part to schists. In some places, as in South Mountain, Pennsylvania, the basic lavas are associated with metarhyolites. Augite and olivine are still recognizable in some of the ancient basalt, but there has generally been an extensive development of chlorite, epidote, and secondary quartz. The basic flows, of which two have been recognized, are strongly folded and are cut by thrust faults with low dips to the east. Joints are numerous, and the copper is generally associated with zones of vertical sheeting.

Native copper is the characteristic ore mineral, in places accompanied by cuprite and by the usual carbonates due to oxidation. There are no well-defined veins. The copper occurs disseminated through zones of jointing and epidotization. The deepest exploration, by shafts, is about 300 feet.

Some deposits of the same type are reported to occur in the Piedmont Plateau, in Virginia.

Most geologists who have studied these deposits have concluded that the copper was derived from the basic lavas themselves. Weed regarded the process of concentration as essentially superficial—a consequence of weathering. Watson (8), however, has more recently suggested that, although the copper was derived from the lavas, it was extracted and concentrated as native copper by hot, hypogene solutions in pre-Cambrian time. He accounts for the deposition as native metal by suggesting that the sulphur in the ore-bearing solutions was oxidized by the ferric iron in the epidote, thus appealing to a process similar to that advanced to account for the native-copper deposits of Michigan and Bolivia. The explanation offered by Watson, however, appears to be scarcely consistent with the contemporaneous deposition of copper and epidote, which is apparently indicated by the published descriptions of these interesting though noneconomic deposits.

New Jersey type

The deposit near Bristol, Connecticut, on which the most recent publication is that of Bateman (9), is notable rather for the mineralogic specimens of chalcocite which it has yielded than for its output of copper. It would appear to fall most nearly into the New Jersey type of copper deposit—impregnated Triassic shale and sandstone near trap masses (10). The mine was worked as early as 1837 but has been idle since 1895. According to information gathered by Bateman, the ore occurs partly within a strong fault along which Triassic sandstone on the southeast has been dropped against schist of supposedly Ordovician or Silurian age on the northwest. The copper sulphides, mainly bornite and chalcocite, apparently occurred as irregular veins in the fault zone and as veinlets and disseminated particles in certain of the Triassic sandstone beds adjacent to the fault, in the hanging wall. Bateman concludes that the chalcocite and bornite are hypogene, that the deposition took place during the Triassic, and that it probably was genetically connected with the intrusion of the trap during that period.

In southeastern Quebec the Appalachian Mountains are represented by two systems of anticlinal ridges from 20 to 25 miles apart, which, together with the intervening valley and adjacent territory on both sides, are composed of closely folded, more or less schistose sedimentary and igneous rocks of pre-Cambrian and early Paleozoic age. Most of the copper deposits occur within or close to the two main belts of schistosity.

In Nova Scotia are unimportant deposits of Triassic age similar to those in New Jersey (11).

Summary

From the foregoing outline it appears that the Appalachian copper deposits, although for the most part of slight economic importance, are of diverse character and of considerable scientific interest. The principal periods of deposition seem to have been in early Paleozoic and Triassic time. The deposits of the Catoctin type, according to divergent views of origin, may be as old as the pre-Cambrian or as young as the Quaternary. Although the copper deposition was presumably associated in some manner with igneous activity, the relation is neither direct nor obvious. The details of the connection between igneous intrusion and copper-ore deposition have, in this region, been matters of inference or conjecture rather than of demonstration, and, for the ores of the Catoctin and New Jersey types, the parts played by hypogene and supergene processes are still in question.

Copper deposits of the pre-Cambrian Canadian Shield

The term "Canadian Shield" is a familiar designation for the great U-shaped area of pre-Cambrian rocks which stretches northward from the vicinity of the Great Lakes, on both sides of Hudson Bay, into the Arctic regions. It is in general a lake-dotted peneplain of low relief but attains altitudes of at least 5,000 feet along the northern coast of Labrador.

The rocks composing the Shield fall into two main divisions. The older division is also of dual character, being composed of an older series, the Keewatin, consisting mainly of ancient lavas, largely basic, with a minor proportion of sedimentary rocks, and a younger series, the Timiskaming, consisting of sedimentary rocks. Overlying the older division (Ontarian of Lawson) with great unconformity is the Huronian system of sedimentary rocks.

In addition to these rocks, the region contains enormous areas of granite and granite gneiss, with associated intrusive rocks. According to Lawson (12), these fall mainly into two groups—those intruded at the end of Keewatin time (Laurentian revolution) and those intruded at the end of the Huronian (Algonkian revolution). The Laurentian intrusions have, so far as known, obliterated the original base of the Keewatin.

Occurrences of copper ore are known at many widely scattered localities over the Canadian Shield, but only three groups are of sufficient economic importance to demand attention in the present review. These are the nickel-copper deposits of Sudbury, the copper deposits of Rouyn, and the deposits of the Schist Lake area of Manitoba and Saskatchewan.

Nickel-copper deposits of Sudbury

The nickel-copper deposits of Sudbury are in the Province of Ontario, about 35 miles north of Georgian Bay, Lake Huron. These unique and highly important deposits, the world's chief source of nickel, are described elsewhere in this volume. It must suffice here to recall that the dominant geologic feature of the district is a spoon-shaped intrusive sheet of "nickel eruptive" which has an elliptical outcrop about 37 miles long and 17 miles in its shorter diameter. The average thickness of the sheet has been estimated at about a mile. The sheet is mainly composed of what has generally been termed "norite," but this changes upward, by gradation or otherwise, into what has commonly been designated "micropegmatite." The norite rests, so far as is observable, on an ancient complex of granites and gneisses (of Laurentian age in part), schists, metamorphosed sediments (Sudbury series), and various acidic and basic eruptives. At least a part of the granite and granite gneiss of this complex is regarded by some geologists as having been intruded after the norite. Within the spoon, in synclinal attitude, are sedimentary rocks, probably of Animikie age, with a total maximum thickness estimated as between 9,000 and 10,000 feet.

The copper-nickel ores occur near the base of the norite, largely within that rock but partly in the underlying rocks. They consist essentially of pyrrhotite, pentlandite, chalcopyrite, pyrite, and small quantities of magnetite. The general order of deposition has been magnetite, pyrrhotite, pentlandite, and chalcopyrite, with pyrite not definitely placed in the sequence.

The origin of these deposits has been earnestly discussed, and the literature relating to them is voluminous (13, 14, 15, 16, 17, 18, 19, 20, 21). The evidence, variously interpreted by different investigators, appears to indicate that the Sudbury deposits are high-temperature metasomatic replacement deposits and that their constituents came from the norite magma. Their age is pre-Cambrian.

Rouyn district

The town of Rouyn is in western Quebec, about 30 miles south-southeast of Lake Abitibi and 24 miles east of the Ontario boundary. It lies a little east of the middle point of a line drawn from the southern tip of Hudson Bay (James Bay) to the north shore of Georgian Bay, Lake Huron.

The Rouyn district shows the major twofold division of pre-Cambrian rocks characteristic of the Canadian Shield, with the two divisions separated by a profound unconformity. The older group comprises the Keewatin, composed of ancient lavas of great diversity, ranging from basalt to rhyolite, with some metamorphosed sediments, overlain, with probable unconformity, by the Timiskaming sedimentary series. Above the major unconformity of the region come the Huronian and later sediments. Intrusive rocks of many kinds, but predominantly granitic and granodioritic, cut the Timiskaming and older rocks (22).

The copper deposits occur in the Keewatin rocks. The ore bodies are irregular masses, of stout or rotund form, to which the terms "lens" and "lenticular" are only roughly applicable. They consist commonly of pyrite and pyrrhotite, with a varying proportion of chalcopyrite. Some also contain sphalerite and magnetite. The proportions of these minerals vary greatly in different deposits. Moreover, some are virtually solid sulphide masses, whereas others are merely country rock carrying disseminated sulphides in uneconomic quantity. They range from those of very small size to great masses several hundred feet long and 200 feet wide.

Economically the deposits may be divided into two classes—those which consist chiefly of iron sulphides and those which contain industrial quantities of copper and zinc sulphides. This grouping, according to Cooke, James, and Mawdsley (22), corresponds also to a difference in age, the copper and zinc sulphides having been introduced after the deposition of the iron sulphides, although there is some late-stage pyrite.

The rocks in which the sulphide bodies occur are all siliceous lavas (rhyolites and dacites) or corresponding pyroclastic rocks and tuffs. They have been extensively silicified and chloritized near the sulphide masses. This alteration, there is some evidence to indicate, was effected mainly by the solutions that deposited copper and zinc sulphides rather than by those that deposited principally iron sulphides. The chalcopyrite apparently followed closely upon chloritization and replaced the chlorite.

The Rouyn copper deposits were formed by progressive hydrothermal replacement at sites rendered favorable by the character of the rock and the presence of fissures. The depositing solutions were hypogene and, in addition to the metals and sulphur, carried large quantities of silica and magnesia. Pyrite and pyrrhotite were deposited first, followed by chalcopyrite and sphalerite. Cooke, James, and Mawdsley regard the ore-depositing solutions as unquestionably of magmatic origin and are inclined to relate the iron-bearing solutions to the magma that supplied the various bodies of soda-rich syenite porphyry, of post-Timiskaming age, present in the district. Whether the copper-bearing solutions emanated from the same magma is a question that they do not undertake to answer.

The principal copper mine of the district is the Horne.

Schist Lake region

Of the deposits of the Schist Lake region in Manitoba and Saskatchewan, two, the Mandy and the Flin Flon, are of present outstanding importance. The Mandy mine is on the west shore of the northwest arm of Schist Lake, about 70 miles north of The Pas and 400 miles northwest of Winnipeg, close to the western boundary of Manitoba. The Flin Flon mine, on the lake of the same name, is about 4 miles north of the Mandy. These deposits have been described by various writers, among whom may be mentioned Spurr (23), Bruce (24), and Hanson (25).

The Manitoba deposits occur in pre-Cambrian rocks, near the western border of the Canadian Shield. The old rocks, the Amisk series, consisting of lavas, tuffs, agglomerates, and derived schists, are probably the equivalent of the Keewatin farther east. They are succeeded by gneisses and pre-Cambrian sedimentary rocks, but the copper deposits are confined to the Amisk volcanics. There appear to have been two periods of granitic intrusion—an earlier, represented by the Cliff Lake granite porphyry, following the deposition or eruption of the prototypes of the Kisseynew gneisses, which overlie the Amisk volcanics, and a later, represented by the Kaminis granite, of which the intrusion, as great batholiths, apparently marked the end of the pre-Cambrian (Algoman revolution).

The ore bodies of the region are lenticular veins and masses in the Amisk volcanics. Two general classes have been distinguished by Hanson—those consisting chiefly of pyrite, chalcopyrite, and sphalerite and those consisting chiefly of pyrrhotite. The deposits of economic importance up to the present time belong to the first class. All represent mineralization along sheared or brecciated zones in the more or less schistose volcanic rocks.

The Mandy ore body is an irregular lens 225 feet long and as much as 40 feet wide, with relatively narrow, veinlike projections from its ends. It strikes with the enclosing chlorite schists and greenstones, a little west of north, and dips 75°–80° E. It consists of nearly pure pyrite near the walls but encloses a nuclear mass of banded sphalerite and chalcopyrite. It is believed by both Bruce and Hanson that an original hydrothermal replacement of the schist by pyrite was followed by successive fracturing and deposition of sphalerite and chalcopyrite, the final deposit being mainly chalcopyrite. Arsenopyrite and galena are also reported in the ore. Bruce believes that the source of the ore-bearing solutions was the magma of the younger or Kaminis granite. Hanson favors a similar granitic source but is not definite as to the age of the granite. Spurr, in accordance with his well-known views, regards the Mandy ore body as formed by a series of intrusions of "plastic sulphides" (23, p. 116).

At the Flin Flon mine the ore occurs in the same rocks as the Mandy ore body but is less complex in internal structure and in the distribution of the sulphides. It is also of lower grade. It is reported to contain about 18,000,000 tons of ore carrying 1.71 percent of copper and 3.45 percent of zinc. The ore replaces the greenstone along a great shear zone. It has been explored for a length of over 2,500 feet at the surface and is known to be 1,000 feet long at a depth of 900 feet. It extends to a depth of at least 2,500 feet and is 75 feet in maximum width. It strikes northwesterly with the schists and dips 60°–70° NE. The ore at Flin Flon is chiefly pyrite, with sphalerite, chalcopyrite, and some magnetite. The only gangue material consists of small blebs of quartz and inclusions of country rock. Virtually all geologists who have studied the Flin Flon deposit, including Spurr, consider it as having been formed by hydrothermal replacement of the sheared schist. The opinions recorded as to the source of the depositing solutions of the Mandy ore body apply also at Flin Flon.

Other deposits

Smaller pyritic deposits, more or less resembling those of Manitoba and occurring in various parts of the Canadian Shield, are briefly described by Hanson in the paper cited, and similar but undeveloped and low-grade deposits in the Manitoba-Saskatchewan region are mentioned by Spurr (23, p. 123).

About 50 miles northeast of the Flin Flon deposit, in northern Manitoba, is the Sherritt-Gordon copper-zinc deposit (26). This is a more or less lenticular mass of pyrrhotite, chalcopyrite or chalmersite, sphalerite, and marcasite, with a gangue of quartz, amphibole, chlorite, garnet, biotite, and scapolite, formed by the replacement of folded gneiss (Kisseynew gneisses). The copper-zinc deposition is supposed to have been genetically connected with granitic intrusions in the gneiss.

Still farther north, on the Coppermine River, between Great Bear Lake and Coronation Gulf, are deposits of chalcocite and native copper in pre-Cambrian amygdaloidal basalts. According to Gilbert (27), although native copper is widely disseminated through the basalts, it is probably not present in economic quantity. The more promising deposits are veins carrying chalcocite, with a little bornite and chalcopyrite. Gilbert, while recognizing the possibility of some genetic connection between the basaltic magma and the vein deposits, concludes that there is no direct relation between these deposits and the visible amygdaloidal flows.

The Canadian Shield is an area in which ore bodies are not easily found, and it is probable that in that vast region there are still many masses of copper ore which have not been discovered.

Copper deposits of the Lake Superior region

Although deposits of native copper are known elsewhere on the globe, those of northern Michigan are unique, among deposits of this type, for their size and productivity. They have yielded, since 1845, more than 7,500,000,000 pounds of copper. As these deposits are practically confined to a single district, that of the Keweenaw Peninsula, which is adequately described elsewhere in this volume, they will be accorded much briefer treatment in the present paper than is commensurate with their scientific interest and economic importance. The information presented has been drawn chiefly from the most recent comprehensive report on the district, that by Butler and Burbank and their collaborators (28).

The outstanding geologic features of the Keweenaw Peninsula are a thick series of basic lava flows, reddish felsitic conglomerates, and sandstones, which strike generally in a northeasterly direction and dip northwest. These rocks, constituting the Keweenawan series, of pre-Cambrian (Algonkian) age, have been upthrust from the northwest over Upper Cambrian sandstone. The basaltic flows, in part amygdaloidal, are some thousands of feet in total thickness and are interbedded with the conglomerates. The upper part of the series is mainly sandstone. Intrusive rocks, in relatively small volume, are found in the Keweenawan series. They have been classed as gabbro, quartz porphyry and felsite, and basic dikes.

The copper occurs at various horizons in the Keweenawan series, chiefly in the amygdaloidal or brecciated tops of the basalt flows and in certain of the felsitic conglomerates. To a minor extent it also occurs in fissures that cut through the basalts and conglomerates. With the native copper are present, in much smaller but significant quantities, chalcocite, bornite, and various arsenides of copper. A characteristic assemblage of gangue minerals is associated with these ore minerals. Chlorite, feldspar, epidote, and pumpellyite were formed generally in advance of the copper deposition, which was accompanied by the formation of quartz, calcite, prehnite, and datolite. Laumontite, analcite, and some other minerals are younger than the copper.

Various opinions have been advanced to explain the origin of these remarkable deposits. These are fully reviewed by Butler and his associates, who conclude that the deposition was effected by hypogene solutions that emanated possibly from the magma of the Duluth gabbro and rose along the Keweenaw fault, which limits the Keweenawan series on the southeast. These solutions carried sulphur and in most districts would have deposited sulphide ores. The reduction to native copper, involving oxidation of the sulphur, they believe, was brought about by the oxygen of the ferric iron present in the conglomerates and particularly in the permeable tops and bottoms of the lava flows. Their theory, which is presented here in bare outline, is very fully developed in the report cited and is supported by such an array of facts that those who may not be ready to consider the problem closed must nevertheless accept their results until further, equally thorough and able study affords a reasonable basis for dissent.

In connection with the native-copper deposits of the Keweenaw Peninsula, it is of interest to note the occurrence on Susie Island, near the northwest shore of Lake Superior, of the economically unimportant veins of copper sulphides in calcite and quartz, described by Schwartz (29). Here, on the opposite limb of the syncline occupied by the western arm of Lake Superior, hypogene solutions deposited bornite, chalcocite, chalcopyrite, and pyrite, in contrast with the predominant native copper of the southeast limb of the same syncline.

Copper deposits of Butte, Montana

The region of the northern Rocky Mountains, in Montana and adjacent States to the south and west, is characterized by the widespread distribution of the Belt series of Algonkian sediments, overlain unconformably by Paleozoic rocks of Cambrian, Devonian, and Carboniferous age, which in turn are succeeded unconformably, in some localities, by Jurassic and Cretaceous sediments. These rocks have been vigorously folded and are cut by many faults, some of which are overthrusts of great magnitude.

The period of major deformation that appears to have ended the Cretaceous sedimentation was accompanied by the extensive intrusion of domelike masses of magma, which solidified as granite, diorite, and intermediate types. The age of these intrusive masses has not in all cases been determined. The largest of them, the batholith that contains the Butte copper deposits, which is exposed for a length of some 65 miles and a width of 15 miles, was believed by Weed to be of Miocene age (30, p. 29), but it is more probably late Cretaceous to Eocene (31).

The copper veins of Butte, which since the beginning of production, about 1868, have produced over 9,000,000,000 pounds of copper, occur in the quartz monzonite of the Boulder batholith, near its western margin, in a region of north-south block faulting on a large scale.

As the Butte district is elsewhere described in this volume, the present account is compressed to extreme brevity.

The fissures of the district have been divided by Sales (32) into seven classes, as follows:

1. Anaconda or east-west system. Ore-bearing.
2. Blue or southeast-northwest system. Ore-bearing.
3. Mountain View faults. Not ore-bearing.
4. Steward or southwest-northeast system. Ore-bearing.
5. Rarus fault. Not ore-bearing, except of ore dragged in from earlier fissures.
6. Middle faults. Not ore-bearing.
7. Continental fault. Not ore-bearing.

According to Weed and Sales, the fissures were formed at different periods and have the age relations indicated by the order of the foregoing list, the Anaconda fissures being the oldest. Ray (33), however, maintains that all the ore-bearing fissures were formed at the same time, although subsequent faulting and supergene enrichment have affected the northwest and northeast veins more strongly than the east-west veins. I concur in this opinion.

The Butte copper veins were formed by the filling of fissures, accompanied by considerable replacement of crushed quartz monzonite. They consist essentially of quartz, pyrite, chalcocite, bornite, and enargite, with smaller quantities of rhodochrosite, covellite, chalcopyrite, tetrahedrite, and tennantite. Supergene chalcocite has been an important source of copper above a depth of 1,200 feet, but the chalcocite below that depth is mainly hypogene. The Butte veins constitute a remarkably intricate complex, in which the splitting up of certain veins into brushlike aggregations of smaller veins, the so-called "horsetails," is one of the most extraordinary features.

In the Butte district the essentially copper-bearing veins, so far as outcrops are concerned, are limited to a relatively small area adjacent to the city of Butte, and this area is enclosed by a zone of predominantly zinc-lead-silver veins. Deep development has tended to show that this distinction is less indicative of two different sets of veins than of an upward and outward zoning from a deep-seated center of mineralization. In other words, sufficiently deep development on the stronger fissures of the zinc-lead-silver zone would probably reach the copper zone.

Geologists are generally in agreement that the Butte ores emanated from the magma which in part solidified as the Boulder batholith and that consequently they are of early to middle Tertiary age.

In connection with the description of the Butte deposits, inasmuch as both occur in the northern Rocky Mountain region of the United States, may be mentioned the copper deposits of the Encampment district, Wyoming, described by Spencer (34). These economically rather unimportant deposits occur (*a*) in pre-Cambrian rocks as the result of concentration of chalcopyrite in certain layers of hornblende schist before or during regional metamorphism; (*b*) as the result of contact-metasomatic replacement of hornblende schist by chalcopyrite; and (*c*) as deposits of chalcopyrite in fissured or fractured quartzite interbedded with the schist. The deposits are probably of pre-Cambrian age, although those in quartzite may possibly be younger.

Copper deposits also occur in the Belt series in the Bitterroot Mountains of northern Idaho and western Montana, but these are not of great present importance and cannot be described here.

Copper deposits of the southwestern United States and northern Mexico

The copper deposits of the vast region extending from Utah into Mexico and from the southern Rocky Mountains and Great Plains on the east to the Sierra Nevada and Gulf of California on the west occur under so great a variety of geologic conditions and are so diverse in character that it is difficult or impossible to characterize them briefly as a whole.

The region is one in which pre-Cambrian and Paleozoic rocks are most prominently displayed, although in Mexico sediments of Mesozoic age are abundant. Marine Tertiary sediments are generally lacking, but Tertiary intrusive and effusive igneous rocks are widespread, and to the intrusive rocks of probable Tertiary age is largely, though by no means exclusively, to be ascribed the deposition of the copper ores.

Although folded structure is by no means absent in this region, the larger and more conspicuous structural features, of later than pre-Cambrian origin, are the result of faulting. The relatively undisturbed post-Archean rocks of the Colorado Plateau contain no large deposits (35), but some copper ores, related to fissuring, have been mined at various localities in that region (36).

Of the copper deposits having obvious genetic relationship with the intrusive porphyry masses, the disseminated ores, or so-called "porphyry copper ores," constitute at present the most characteristic and productive type of the region. Among them may be mentioned those of Bingham, Utah; Ely, Nevada; Santa Rita (Chino) and Tyrone, New Mexico; Morenci, Bisbee (in part), Miami, Ray, Ajo, and Bagdad, Arizona; and Cananea (in part), Mexico. In practically none of the districts is the copper confined to the disseminated type of deposit, but in all but Bisbee and perhaps Cananea this type is now the principal source of the copper produced.

The characteristic feature of these deposits is the dissemination of the copper-bearing minerals through parts of the intrusive porphyry mass itself or through the adjacent rock into which the porphyry is intrusive, in the form of isolated crystalline specks or as small veinlets. The most common copper mineral is chalcocite, formed by the supergene enrichment of low-grade rock, or protore, containing disseminated pyrite and chalcopyrite. The deposits, consequently, are not of great vertical range but are limited downward by the depth to which solutions derived from the surface have been able to penetrate during the present or some earlier stage of erosion. The foregoing general statements require amplification or qualification with respect to particular districts, as will presently appear. As the principal districts yielding disseminated copper ores are individually described elsewhere in this volume, only such general outline of each will here be presented as may suffice to show wherein they conform to or depart from a common type.

Bingham

In the Bingham district, Utah (37, 38, 39), quartzites and limestones of Carboniferous age, with an aggregate thickness of about 10,000 feet, were invaded at some not definitely determinable post-Carboniferous time by irregular masses of quartz monzonite and quartz monzonite porphyry.

The copper ores occur as lenticular or irregular pyrometasomatic bodies in limestone and as disseminated deposits in the quartz monzonite. The massive replacement bodies were first worked, but these, now largely exhausted, have been in later years far surpassed in importance by the great body of disseminated ore worked by the Utah Copper Co. Both types of deposit are genetically related to the monzonitic intrusions.

The disseminated copper ore, of which there is about 514,000,000 tons averaging 1.15 percent of copper, occurs in the quartz monzonite as scattered crystal particles and small veinlets of chalcopyrite and bornite, in part altered to supergene chalcocite.

Ely

At Ely, Nevada (40), sedimentary rocks ranging in age from Ordovician to Carboniferous and comprising limestone, quartzite, and shale have been invaded by monzonite and monzonite porphyry. The intrusion has been doubtfully assigned to Jurassic time. There were later eruptions of late Tertiary rhyolitic rocks. The principal ore bodies, which are of the disseminated type, occur in the monzonite and have been formed by chalcocitic enrichment of pyrite-chalcopyrite protore. There has also been considerable mineralization of the limestones, but relatively little sulphide ore has been found in these rocks. The ore deposits at Ely are believed to be genetically connected with the intrusion of the monzonite. Supergene enrichment may have been in operation for a long period, possibly beginning before the eruption of the Pliocene lavas.

Santa Rita

In the Santa Rita district, New Mexico, sedimentary rocks, chiefly calcareous or dolomitic and ranging in age from Cambrian to Cretaceous, were intruded by a granodiorite porphyry stock which metamorphosed and mineralized the adjacent limestones and, after extensive fracturing, was itself mineralized in the part now exposed to view. Disseminated pyrite and chalcopyrite in the intrusive stock were enriched by supergene processes, with the development of chalcocite, and to this enrichment the value of the ore body is almost entirely due. The intrusion and hypogene mineralization probably occurred in Tertiary time, and oxidation and enrichment, probably interrupted for a time by the eruption of Tertiary lavas, have continued to the present day.

Tyrone

At Tyrone, New Mexico (41), the regional geologic relations are in general the same as at Santa Rita, but the intrusive rock, here classed as quartz monzonite porphyry, is enclosed in pre-Cambrian granite, which does not come to the surface at Santa Rita. The ore bodies occur both in the granite and in the monzonite porphyry and are of very irregular form. The controlling factors in the localization of the original protore, chiefly pyrite with a little chalcopyrite, and in its subsequent chalcocitic enrichment were zones of fracturing and brecciation. The source of the mineralization, according to Paige, was the quartz monzonite magma. The time of intrusion has been doubtfully identified as late Cretaceous. Enrichment, as at Santa Rita, was probably interrupted for a time by the eruption of Tertiary lavas.

Morenci

At Morenci, Arizona (42, 43), pre-Cambrian crystalline rocks, mainly granite and schist, are unconformably overlain by about 3,000 feet of Paleozoic sediments, comprising Upper Cambrian quartzite, Ordovician limestone, Devonian shale and limestone, and Carboniferous limestone. These, in turn, are unconformably overlain by Cretaceous shale and sandstone, and the entire district was in Tertiary time buried under lava flows.

In late Cretaceous or early Tertiary time the region was elevated, faulted, and invaded by intrusive masses of granitic, quartz monzonitic, and dioritic porphyries. Renewed faulting was followed by ore deposition by solutions that, according to Lindgren, probably emanated from the porphyry magma. Contact-metasomatic deposits, hydrothermal fissure fillings, and disseminated deposits in porphyry are all represented, but deposits of the first two types are mostly exhausted, and the future of the district depends upon the disseminated deposits, estimated to contain about 25,000,000 tons of approximately 2 percent ore. This ore has been formed by supergene chalcocitic enrichment of a protore consisting essentially of pyrite and chalcopyrite, disseminated through the porphyry near and between fissure zones. The district has yielded nearly 2,000,000,000 pounds of copper since 1873.

Bisbee

At Bisbee, Arizona, pre-Cambrian granite and schist are unconformably overlain by Paleozoic sediments ranging in age from Cambrian to Permian. The basal formation, as at Morenci, is a quartzite, but the succeeding beds are mainly limestones. All these rocks were folded and faulted and were intruded by granite porphyry. Subsequently, after long erosion, the older rocks were buried under a thick series of Lower Cretaceous (Comanche) beds. Subsequent faulting, with some folding, was followed by erosion, which reexposed the pre-Cretaceous rocks in part. Some difference of opinion exists as to the age of the granite porphyry intrusion. I believe (44) that it occurred in post-Carboniferous but pre-Cretaceous time. Tenney (45), however, maintains that the granite porphyry is of early Tertiary age.

The copper deposits of Bisbee are predominantly metasomatic replacement deposits in limestone, particularly in the Devonian and Mississippian limestones, though the enclosing calcareous beds suffered generally rather slight contact-metasomatic alteration. The deposits are clearly related to contacts between porphyry and limestone and to zones of fissuring and constitute a cupriferous halo around the principal porphyry stock, on its western and southern sides. The hypogene replacement bodies consist essentially of pyrite and chalcopyrite, with less widely distributed bornite, sphalerite, and galena. Oxidation extends to a maximum depth of 2,200 feet, or 1,200 feet below water level. Bonillas (46) and I believe that this deep oxidation is related to the development of the pre-Cretaceous peneplain, which was later tilted, but Tenney (47), in conformity with his view of Tertiary mineralization, naturally rejects this explanation. Chalcocitic enrichment connected with this deep oxidation played a highly important part in the supergene concentration of the large, high-grade ore bodies, now nearly exhausted, which were the mainstay of Bisbee copper production in the last two decades of the nineteenth century.

The bodies of disseminated ore, which were of later exploitation and which in the Bisbee district are of subordinate importance, occur in the main porphyry stock of Sacramento Hill and in the brecciated and silicified limestones at its margin. They owe their value to supergene chalcocitic enrichment of a low-grade pyrite-chalcopyrite protore.

Miami

In the Miami district, Arizona (48), the fundamental rocks are of pre-Cambrian age and comprise schists and various intrusive rocks ranging from quartz diorite to granite. Unconformably overlying these rocks are sediments which include quartzite and limestone of early Cambrian or Algonkian age, succeeded by quartzite and limestone of Cambrian, Devonian, and Carboniferous time. The Paleozoic and older rocks are cut by various intrusive masses, including granite, quartz monzonite, and diabase, whose age is not definitely determinable. The region was subjected to long erosion, followed, in Tertiary time, by the eruption of thick and extensive flows of dacite. Probably at or near the end of the Tertiary period the rocks of the region were intensely faulted. Vigorous erosion and the deposition of thick detrital valley deposits characterized the Quaternary period.

The disseminated copper deposits occur on the northern margin of a large intrusive mass of sodic granite, partly in porphyritic facies of the granite but mainly in the adjacent schist. The sulphide ore is principally a chalcocitically enriched protore which consisted originally of scattered crystals and small stringers of pyrite and chalcopyrite, with associated quartz, in minutely fractured, sericitized schist and porphyry. At one time rock containing less than about 1.3 percent of copper was classed as protore, but of late years the Miami Copper Co. has mined some chalcopyritic ore containing as little as 0.6 percent of copper. The supergene enrichment of the Miami ore is believed to have been effected mostly in Tertiary time, before eruption of the dacite flows and before the vigorous faulting that followed that eruption. The hypogene mineralization was probably connected genetically with the intrusion of the granite (Schultze granite), which probably occurred in early Tertiary time, although the evidence upon which this conclusion is based is far from conclusive.

The reserves of disseminated copper ore at Miami were originally estimated at 143,282,419 tons, and the production to date has been about 3,000,000,000 pounds of copper.

Ray

In the Ray district, Arizona (48), the general geologic conditions are similar to those at Miami, but the intrusive masses to which the ore deposition was genetically related are quartz monzonite porphyry, of doubtfully early Tertiary age. The ore is almost wholly in schist. The protore is similar mineralogically to that of Miami, although generally of rather lower grade. The total reserves were estimated in 1916 at 93,373,226 tons, with an average tenor of 2.03 percent of copper. The production to date has been about 1,100,000,000 pounds of copper.

Ajo

In the Ajo district, Arizona (49), a superficially small mass of quartz monzonite, probably a lopolith, is intrusive into pre-Cambrian granite and into rhyolitic and andesitic flows of presumably Tertiary age. The ore body, of the disseminated type, is almost entirely in the monzonite. The disseminated sulphides are chiefly chalcopyrite and bornite, with very little pyrite. Probably as a consequence of the scarcity of pyrite, there has been very little supergene enrichment, and the oxidized ore is of nearly the same tenor as the hypogene sulphides. In this respect the Ajo deposit differs notably from the other large disseminated copper deposits of the southwestern United States. The total production has been about 800,000,000 pounds of copper.

Cananea

At Cananea, Sonora, Mexico (50, 51, 52), pre-Cambrian granite is unconformably overlain by Cambrian quartzite and by limestones that are in part as young as Carboniferous. These rocks have been cut by nine kinds of intrusive rocks, ranging from granite to gabbro, and have been in part buried, perhapsat one time completely so, by lava flows and tuffs. All the igneous rocks except the pre-Cambrian granite were believed by Emmons to have been differentiates from a single magma reservoir and have been assumed to be of Tertiary age.

The ore deposits were believed by Emmons to be genetically connected with the Henrietta diorite porphyry, which, as mapped, was regarded by him as actually a complex of intrusives and volcanic rocks (in part tuffs), and to a less extent with the intrusion of the Elisa "quartz porphyry" and of the Cuitaca granodiorite. Later work has tended to show, however, that the Henrietta "diorite" consists mainly of volcanic material (51).

The copper deposits include contact-metasomatic deposits in limestone, nearly vertical pipes or "chimneys" in igneous rocks, and the supergenely enriched chalcocitic deposits of Capote Basin. These last have supplied the greater part of the production but are now practically exhausted.

The Capote Basin deposits occur in much fractured fault blocks, chiefly in Henrietta diorite porphyry and Elisa quartz porphyry. The original disseminated protore, consisting of pyrite, chalcopyrite, and a little sphalerite in much sericitized and silicified porphyry, was, above depths ranging from 300 to 1,000 feet, so greatly enriched by supergene chalcocite as to render it somewhat doubtful whether the resulting ore bodies should be classed as disseminated deposits.

Summary of disseminated deposits

From the foregoing necessarily brief descriptions it appears that the disseminated copper deposits of the southwestern United States and northern Mexico are all within or closely associated with masses of intrusive rock of generally less than batholithic proportions. In composition these rocks range from granite to diorite, but the greater number are quartz monzonite or granodiorite. Commonly it is the porphyritic rather than the granular facies of these rocks which is most closely associated with the ore. The geologic age of these intrusive masses is rarely determinable with certainty. Those of Morenci cut Cretaceous sediments and are older than the Tertiary lavas. The granite porphyry at Bisbee is according to one view post-Carboniferous but pre-Cretaceous; according to another, it is probably Tertiary. In other districts the age is more or less conjectural. Those who favor the view that most of the copper deposits of the Southwest, except those of pre-Cambrian age, originated in a single period of mineralization are naturally predisposed to regard the intrusions as all of early Tertiary age. The protore is generally of rather simple mineralogic character—usually pyrite and chalcopyrite with abundant sericite and secondary quartz. Sphalerite and molybdenite are almost invariably present in small quantity. Bornite is rare, except at Ajo, where, with chalcopyrite, it is abundant. All the deposits, except Ajo, owe their economic importance mainly to supergene chalcocitic enrichment, although locally some of the hypogene material may be classed as ore. At Santa Rita, Tyrone, Morenci, Miami, and Ray evidence has been found to indicate that oxidation and supergene enrichment began before the eruption of the Tertiary lavas.

Other types

To copper deposits of other types in the southwestern region only brief attention can here be given, a few of the more outstanding examples being cited.

Of pre-Cambrian pyritic replacement deposits in schists, Jerome, Arizona (53, 54, 55, 56, 57), affords the most noteworthy illustrations. The basal rocks of the district are crystalline schists, in large part metamorphosed rhyolites and rhyolitic porphyries. These are intruded by a stock of rather basic diorite. These rocks after prolonged erosion were covered by Paleozoic sediments and, after a second epoch of erosion, by Tertiary basaltic flows. Faulting has occurred at various times, and some of the displacements are large. The economically important hypogene ore bodies are confined to the pre-Cambrian rocks.

The district contains two ore bodies of outstanding size and productivity—namely, that of the United Verde mine and that of the United Verde Extension mine. The ore bodies of the United Verde, chiefly chalcopyrite, occur as lenticular masses, in which the copper is distributed through a great pipelike body of quartz, pyrite, sphalerite (marmatite), and very subordinate quantities of other sulphides. This pipe, which lies in an embayment of the diorite, with that rock as the hanging wall, has been mined to a depth of more than 3,000 feet. To a large extent the quartz and sulphides have replaced the previously chloritized schistose rhyolitic rocks into which the diorite is intrusive. The United Verde Extension ore body lies east of the United Verde ore body, on the opposite or hanging-wall side of the great Verde fault. It was not exposed at the surface, being covered by about 850 feet of nearly horizontal Paleozoic beds and Tertiary basalt. The Extension ore body is similar in form and geologic environment to the United Verde ore body but differs from it in two significant respects. It is definitely cut off, at a depth of about 2,000 feet, by the Verde fault, and it was largely converted to supergene chalcocite before the deposition of the Paleozoic beds that now cover it. After a careful study for the United Verde Extension Mining Co., I reached the conclusion that this ore body was originally the upper part of the United Verde ore body; that it was sheared off and relatively downthrown 2,400 feet on the Verde fault in pre-Cambrian time; and that it reached its present relative position by a further throw of 1,600 feet, on the same fault, in Tertiary or Quaternary time.

The total production of the United Verde mine has been nearly 1,900,000,000 pounds of copper, with over 20,000,000 ounces of silver and 400,000 ounces of gold. The United Verde Extension mine has yielded about 600,000,000 pounds of copper, with a proportionate quantity of silver and gold.

Deposits of generally similar type, but smaller and of lower grade than those at Jerome, have been mined in the Bigbug district, a few miles southeast of Prescott, Arizona.

Of metasomatic replacement deposits in limestone, genetically connected with the group of granitic and monzonitic intrusives referred to in the account of the disseminated deposits, those at Bisbee have been most productive, although noteworthy examples are found in the Morenci, Globe, and Christmas districts, Arizona. The Bisbee deposits are described more fully elsewhere in this volume. Deposits in limestone of more decidedly contact-metamorphic type occur at San Pedro and other localities, New Mexico; at Silver Bell, Twin Buttes, and Washington, Arizona; and at Cananea, Mexico.

Deposits essentially of vein type, usually with walls that have been considerably replaced, have also contributed a notable quantity of copper to the production of the southwestern United States. Of this group, the Old Dominion mine, at Globe, and the Magma mine, near Superior, Arizona, stand in the first rank. The mineralization that produced these ore bodies is generally ascribed to the same magmatic source as that to which the disseminated ore deposits of the region are due.

Brief mention must be accorded, also, to the interesting deposits of columnar or pipelike form exemplified by the Pilares deposit, near Nacozari, and the

Duluth-Cananea and Colorada deposits, near Cananea, all in Mexico. The Pilares deposit (58, 59, 60) is essentially a nearly vertical, somewhat flattened cylinder of chalcopyrite ore, in rocks described as latite breccia, andesite breccia, and monzonite. The plug is composed of the same rocks as those which enclose it but shows clear evidence of subsidence. The occurrence of the ore around the margin of the plug and as more or less isolated bodies within it is clearly conditioned by fracturing and faulting. Various hypotheses of origin have been advanced, but these are largely conjectural.

The latest deposit to be discovered at Cananea, the Colorada, found by drilling in 1926, is a remarkable mass of bornite, chalcopyrite, chalcocite, and quartz in the general form of an inverted hollow cone which terminates at a depth of about 1,300 feet. The mass occurs at the contact of a body of Elisa quartz porphyry with Henrietta diorite porphyry.

The unique deposits near Santa Rosalia, Baja California (61), occur as four main mineralized argillaceous beds, interstratified with tuffs and conglomerates of Pliocene age. The most abundant sulphide is chalcocite, associated with covellite, bornite, chalcopyrite, and a very little pyrite. In the higher beds the sulphides have been largely oxidized, and nearly every known oxidized compound of copper is represented, as well as native copper and some rare lead-copper minerals such as boleite and cumengite.

According to Touwaide, the copper was extracted from the pyroxenes of the tuffs by connate waters and was precipitated in the clayey layers, chiefly as chalcocite and native copper. The deposits accordingly were formed long after the intrusion of the Coast Range batholith and have no direct genetic connection with that event.

It is worthy of note, although the deposit has not been economically developed, that native copper and chalcocite are widely distributed through a thick series of basaltic or andesitic amygdaloidal lava flows in the Comobabi Mountains of southwestern Arizona. The copper minerals occur chiefly in the amygdules, associated with quartz and epidote. The lavas have been tilted and truncated by erosion and are probably pre-Tertiary. They are cut by felsitic dikes, which are also mineralized to some extent with copper.

Copper deposits of the Pacific coast north of Mexico

California

In California the outstanding geologic feature to which most of the copper deposits are clearly related was the intrusion of the Sierra Nevada batholith, consisting mainly of granodiorite, in early Cretaceous time. This batholith is probably connected, under the lavas of the Cascade Range of Oregon and Washington, with the Coast Range batholith of British Columbia and Alaska, which is structurally more complex than the Sierra Nevada mass and represents successive intrusions that apparently began in Jurassic time, or slightly earlier than in California. Most of the metalliferous deposits of the Pacific coast, except those of mercury, appear to be genetically connected with the intrusion of the various plutonic rocks, ranging from granite to gabbro, which make up the Sierra

Nevada and Coast Range batholith and, consequently, to be of late Jurassic or early Cretaceous age. They occur in belts of metamorphic rocks adjacent to the intrusive mass, in roof pendants, and, to a much less extent, in the marginal portions of the batholith itself (62).

At Copperopolis, Calaveras County, California (63), copper has been produced from lenticular bodies of chalcopyrite and pyrite in greenstone schist (meta-andesite) of probable Jurassic age. The deposition of the ore was supposedly a consequence of the intrusion of the Sierra Nevada batholith. According to Reid, the copper deposition was slightly earlier than the formation of the gold quartz veins of the adjacent Mother Lode belt.

Smaller deposits, generally similar to those at Copperopolis, occur elsewhere along the western base of the Sierra Nevada and also in British Columbia.

The Engels copper deposits, in Plumas County, California (64), are high-temperature deposits consisting chiefly of bornite, chalcopyrite, magnetite, and ilmenite in pneumatolytically altered gabbro, quartz diorite, andesite, and other rocks. They occur at and near the contacts of roof pendants in the gabbro and younger quartz diorite. The region was apparently an area of magmatic differentiation, and it is not clear which of the differentiated submagmas was the cause of the mineralization. In a broad sense, the ores are genetically related to the intrusion of the Sierra Nevada batholith.

In Shasta County, California (65, 66), large bodies of pyrite, with some chalcopyrite, occur as replacement masses in rhyolite porphyry. They have yielded much copper since their development in 1895 but are now largely exhausted or of too low grade to be profitable. The porphyry is intrusive into closely folded slates and schists of Devonian and Carboniferous age, and the intrusion was slightly earlier than that of an associated quartz diorite which is probably equivalent to the granodiorite of the Sierra Nevada batholith. Graton regards the ore as having been deposited by replacement in zones of shearing and brecciation by solutions emanating from the magma, which solidified as rhyolite (alaskite) porphyry. This is equivalent to relating their deposition, in a broad sense, with the intrusion of the Sierra Nevada batholith.

British Columbia

The copper deposits worked by the Britannia mines, east of Howe Sound and north of Vancouver, British Columbia (67, 68), are among the most productive in Canada, with an annual production of about 30,000,000 pounds of copper and a total since 1904 of about 250,000,000 pounds. The ore bodies, consisting chiefly of pyrite, chalcopyrite, and quartz, locally with sphalerite, barite, anhydrite, and rare galena, occur as large replacement veins in a great shear zone. The rock replaced is a greenish mottled schist which has been formed by the shearing and metamorphism of porphyry sills composed originally of dacite and quartz latite. The entire mass of metamorphic rocks, of which the sills are a part and which consists largely of originally volcanic material of probable Mesozoic age, has been irregularly invaded, supposedly in Jurassic time, by the granodioritic intrusives of the Coast Range batholith. This mass is probably a great roof pendant in the batholith, from which, it is believed, were derived the hydrothermal solutions that deposited the ores.

In the same general region copper deposits associated with hematite, magnetite, and molybdenite occur within the batholith itself and have been interpreted as having been deposited at higher temperature than the ores in the Britannia shear zone (68, p. 119).

The Tyee deposit, at Mount Sicker, southern Vancouver Island, formerly productive, resembles in some respects the Britannia ore bodies.

The ores of the Rossland district, British Columbia (69), although most valuable for their gold, are generally so cupriferous as to deserve mention among the copper deposits. The ores most characteristic of the district consist mainly of pyrrhotite and chalcopyrite with a subordinate gangue of altered country rock. They occur along zones of fissuring and shearing and to a large extent represent replacement of the rock adjacent to or between the fissures. The geologic relations are complex, but the ore bodies occur chiefly in "augite porphyrite" of supposed Carboniferous age, which has been extensively invaded by monzonitic facies of the Coast Range batholith, the intrusion of which is tentatively dated as late Jurassic. The mineralization was probably a late manifestation of the batholithic intrusion.

The Boundary district, adjacent to Phoenix, British Columbia, which 20 years ago was the leading producer of copper in Canada, has been described by Le Roy (70). The rocks comprise the Knob Hill group, consisting of clastic rocks of igneous origin, porphyries, and subordinate sedimentary rocks, overlain by the Atwood series of metamorphosed limestones and argillites, of supposed Carboniferous age. These have all been tentatively classed as Paleozoic. The Tertiary is represented by the Kettle River formation and the Midway volcanic group.

The ore bodies, consisting essentially of disseminated chalcopyrite, pyrite, and hematite, associated with magnetite, epidote, garnet, quartz, calcite, and chlorite, occur as metasomatic replacement deposits in the Brooklyn limestone of the Atwood series. The mineralogy of the ores indicates contact-metamorphic action, but they are not obviously related to any visible intrusive mass. They are supposed by LeRoy, however, to represent emanations from the magma of the Coast Range batholith.

At Allenby (Copper) Mountain, about 13 miles south of Princeton, in the Similkameen district, British Columbia, a stock of monzonite is intrusive into Paleozoic sediments, and both rocks are cut by innumerable dikes of various kinds. Copper ores occur at the contact between the monzonite and sediments and as lenses in fracture zones. The ores in the fracture zones, which apparently are the more valuable, contain pyrite, chalcopyrite, arsenopyrite, and magnetite. They are reported to average between 1.5 and 2.0 percent of copper, with a little gold and silver (11, p. 170).

At Anyox, on Portland Canal, British Columbia (11, p. 172) deposits which for many years have yielded about 30,000,000 pounds of copper annually occur in a belt of schists and metamorphosed sediments enclosed in the granodioritic rocks of the Coast Range batholith. The ore bodies are large and consist chiefly of pyrite, pyrrhotite, chalcopyrite, sphalerite, magnetite, and arsenopyrite. They appear to resemble in many respects the deposits of northern Manitoba.

Alaska

The remarkable copper deposits near Kennecott, Alaska, have been well described by Bateman and McLaughlin (71). The principal ore bodies are fissure veins, massive replacement bodies, and stockworks, in the thick Upper Triassic Chitistone limestone, which overlies the altered basaltic flows of the Triassic Nikolai greenstone. The most abundant ore mineral is chalcocite, which forms over 95 percent of the ore. Associated with the chalcocite are covellite, enargite, bornite, chalcopyrite, luzonite, tennantite, pyrite, sphalerite, and galena, listed in the order of decreasing abundance.

The fissures are believed by Bateman and McLaughlin to be the result of tension in the limestone produced by synclinal folding. The copper is regarded as having been derived from the underlying greenstones, which themselves contain small and scattered deposits of copper ore. The transporting agent is believed to have been meteoric water which was heated in its passage through the greenstones, possibly as a result of heat from a magmatic source. The heated water gathered the copper from the greenstones and carried it upward to the places favorable for deposition, in the limestone. The chalcocite and associated sulphides are considered to be hypogene.

The copper deposits of Copper Mountain and the Kasaan Peninsula, Prince of Wales Island, Alaska, described by Wright (72), are principally pyrometasomatic contact deposits which are obviously related in genesis to the intrusion of the Coast Range batholith. They occur in limestone, chiefly of Devonian age.

Classification of the deposits

From the facts presented in the foregoing review it is clear that copper deposition in North America was not confined to any particular geologic age or ages, although the exact period within which many of the deposits were formed remains in doubt. That the important copper deposits of Jerome, Arizona, are pre-Cambrian is highly probable, and that they are pre-Devonian is certain. The Lake Superior ores are definitely pre-Cambrian, and it is probable, though not certain, that the copper ores of the Canadian Shield are also older than Cambrian. Here probably also belong the copper deposits of Encampment, Wyoming.

The Ducktown deposits occur in Lower Cambrian rocks but are regarded by Emmons and Laney as being of late Paleozoic age, that being the time of the youngest granitic intrusives of the region. The metamorphosed deposits of Maine and New Hampshire, according to Emmons, are post-Cambrian and pre-Silurian. The Virgilina deposits are considered by Laney to be probably late Paleozoic, for the same reason as the Ducktown deposits. Deposits of the New Jersey type, including that of Bristol, are obviously Triassic or younger. The Butte veins are probably of early to middle Tertiary age.

The Bingham Canyon ores are post-Carboniferous and may be Tertiary. At Ely, Nevada, the mineralization was post-Carboniferous and, according to Spencer, probably late Jurassic. At Santa Rita the ores are post-Cretaceous and rather probably Tertiary. At Tyrone a late Cretaceous age is doubtfully assigned to the ores by Paige. At Morenci Lindgren showed that the ores are younger than certain Cretaceous beds and older than supposedly Tertiary lavas. He regarded them, therefore, as late Cretaceous or early Tertiary. At Globe, Miami, Ray, Superior, and Ajo, the age relations of the ore are uncertain. Such general evidence as is available is indicative of a Tertiary age for these deposits. At Bisbee I considered the ores to be post-Carboniferous and pre-Comanche, but others have since suggested a Tertiary age for these deposits. The ores of Cananea are post-Carboniferous and have been assigned, without entirely satisfactory evidence, to the Tertiary. Those of Pilares, are presumably, though not demonstrably, also Tertiary. The Boleo deposits, in Baja California, according to Touwaide, are Pliocene. In California, British Columbia, and Alaska the copper deposits, inasmuch as most of them are apparently consequences of the intrusion of the Pacific coast batholith, are commonly regarded as of late Jurassic or early Cretaceous age. The exceptional deposits at Kennecott are definitely later than Upper Triassic and may be of the same general age as those more closely related to the batholith.

Although the deposition of copper ores was thus not restricted to any one geologic period, even in a single region, in general the process has closely followed or accompanied the major orogenic and igneous manifestations in the various provinces. Thus, in the Appalachian region the more important deposits are probably of late Paleozoic age, although some are recorded as pre-Silurian. In the Canadian Shield, which has suffered little deformation since the beginning of the Cambrian, the copper ores are mainly pre-Cambrian. In the Rocky Mountain region such copper deposits as occur appear to range in age from pre-Cambrian to Tertiary. The outstanding deposits at Butte may possibly be related to the Laramide revolution, although they appear to be somewhat later. Those of the Basin and Range province, in the southwestern United States, are in part pre-Cambrian, in part possibly Mesozoic, but the greater number are connected in origin with monzonitic intrusions referable, with various degrees of probability, to early Tertiary time, when marine sedimentation was ended by uplift. The deposits of the Pacific coast, from California to Alaska, are genetically connected, for the most part, with the batholithic intrusions of late Jurassic or early Cretaceous time. The Boleo deposits, of supposed Pliocene age, stand by themselves. Of possible late origin, also, are some of the deposits in the "red beds" of younger Paleozoic or older Mesozoic age in the Colorado Plateau region and in New Mexico.

With respect to general form, it appears that the copper deposits of the Canadian Shield and the pre-Cambrian deposits elsewhere are predominantly lenticular replacement masses in schistose rocks, related to zones of shearing. Deposits of the disseminated sulphide type are practically confined to the relatively arid Basin and Range province, where conditions of climate and underground-water table have been favorable to the process of supergene enrichment, to which most of them owe their economic value. In this region also occur most of the great metasomatic replacement deposits in limestone, which are due to the concurrent circumstances that the Paleozoic beds are largely calcareous and have been invaded at many localities by monzonitic masses. Typical vein deposits, except at Butte, have not contributed largely to the total output of copper in North America, although in Arizona some individual mines, such as the Old Dominion and Magma, have been operated with great success on deposits of this form.

As regards mineralogic character, the native-copper ores of the Lake Superior region stand practically alone, although there are some points of similarity between them and the economically unimportant ores of the Catoctin type in the Appalachians, the undeveloped deposits of the Comobabi Mountains, Arizona, and those of the Coppermine River, District of Mackenzie, Canada.

In the pre-Cambrian deposits and those of Paleozoic age the principal hypogene copper mineral is chalcopyrite, often found associated with pyrrhotite, pyrite, and sphalerite and, less commonly, with magnetite and marcasite.

The mineralogic combination of pyrite, enargite, bornite, and hypogene chalcocite found in the Butte veins is probably unique among the large copper deposits of North America. At Butte these minerals may be associated also with chalcopyrite, tetrahedrite, tennantite, and covellite.

The disseminated copper deposits of the southwestern United States are generally simple mineralogically. The common sulphides are pyrite and chalcopyrite. Molybdenite, in relatively small quantity, is almost invariably present. Sphalerite may be a minor constituent of the protore but is never conspicuous, and galena is rare. Bornite is not common, except at Ajo and Bisbee, although it occurs in the Bingham Canyon ore. Chalcocite, the principal mineral in the zone of enrichment, is invariably supergene. In the metasomatic replacement deposits in limestone, in the same region, the common hypogene ore is an aggregate of pyrite and chalcopyrite, with gradations into practically pure chalcopyrite. Bornite may be an abundant constituent of some ore bodies, as at Bisbee, and sphalerite and galena may be locally present. Tennantite is rare but has been noted at Bisbee.

The association of hypogene chalcocite and bornite has been noted by Laney in the Virgilina district and by Bateman at the Bristol mine, on the Atlantic seaboard. A similar association on a larger scale is shown in the vein of the Magma mine, in the Superior district, Arizona. Here the hypogene ore consists of chalcopyrite, bornite, and chalcocite, with smaller quantities of tennantite, sphalerite, and galena. A very little enargite serves to link the Magma ore mineralogically with the Butte veins.

Genetically most of the economically important copper deposits of North America are related to intrusive igneous rocks, although the relation is not invariably as definite as might be desired for a positive statement. For example, it is not certain whether the copper deposits at Jerome, Arizona, are consequent upon the intrusion of the regionally extensive Bradshaw granite or that of a local mass of basic diorite. Again, the copper of the native copper deposits of the Lake Superior region is thought by Butler and Burbank to have originated in the magma of the Duluth gabbro, but proof of this relationship is not available. On the other hand, the connection between the disseminated copper deposits of the southwestern United States and the intrusion of monzonitic or granitic masses is beyond question. The same may be said of the many deposits that occur on the margins of the granodioritic Pacific coast batholith.

Among the large deposits that cannot be closely linked to igneous intrusion may be mentioned the Kennecott deposit in Alaska and the Boleo deposit in Baja California. Here also belong the chalcocite deposits in the "red beds" and other sedimentary rocks in the southwestern United States. Copper is readily transportable as sulphate in surface waters and may be deposited not only as chrysocolla and carbonates but also, under some circumstances, as sulphides, particularly as chalcocite. Such hypogene deposits, however, are of minor economic importance.

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