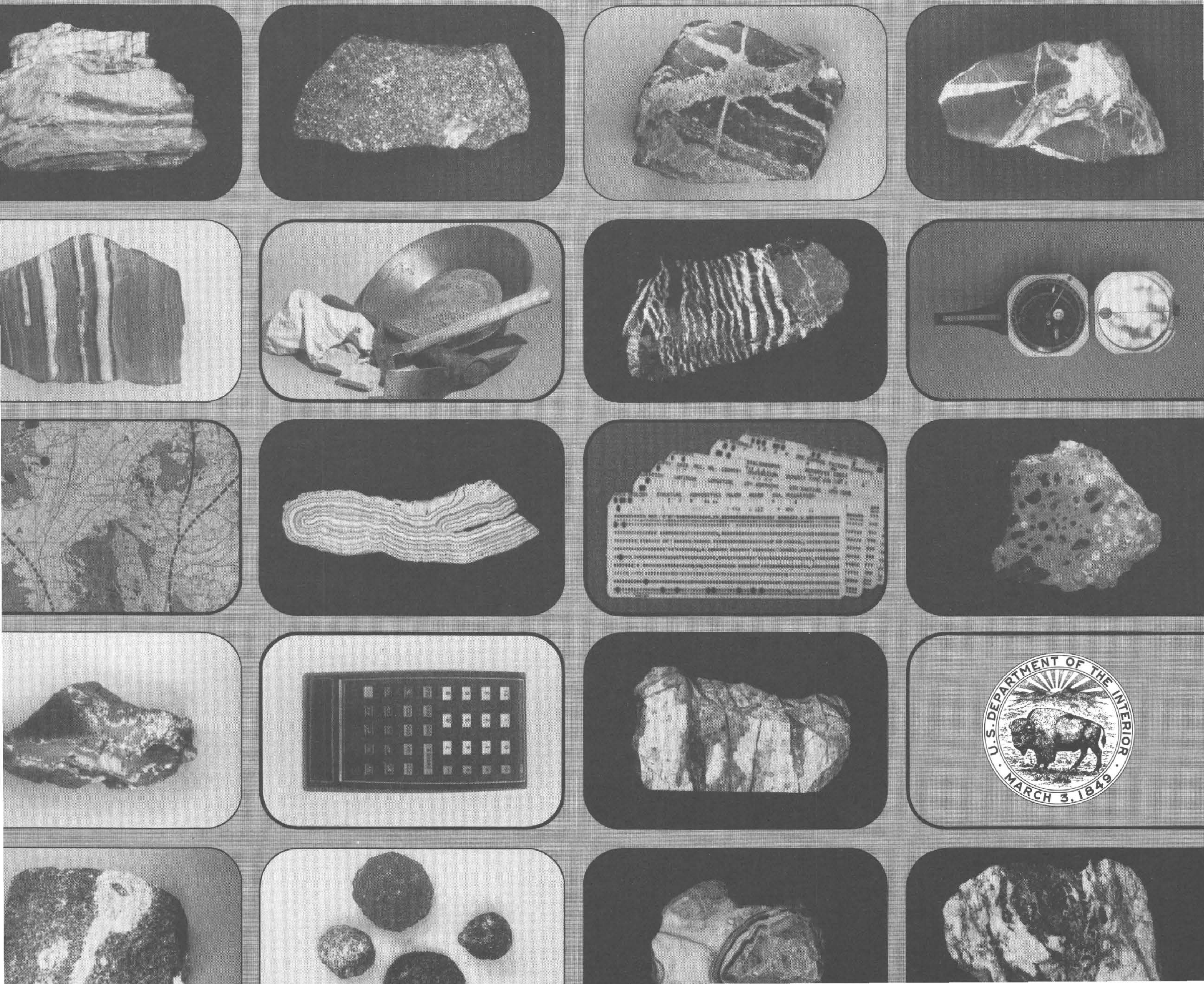
Copper Deposits in Sedimentary and Volcanogenic Rocks

GEOLOGICAL SURVEY PROFESSIONAL PAPER 907–C



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Copper Deposits in Sedimentary and Volcanogenic Rocks

By ELIZABETH B. TOURTELOT *and* JAMES D. VINE

GEOLOGY AND RESOURCES OF COPPER DEPOSITS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 907-C

A geologic appraisal of low-temperature copper deposits formed by syngenetic, diagenetic, and epigenetic processes

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APPRAISAL OF MINERAL RESOURCES

Continuing appraisal of the mineral resources of the United States is conducted by the U.S. Geological Survey in accordance with the provisions of the Mining and Minerals Policy Act of 1970 (Public Law 91-631, Dec. 31, 1970). Total resources for purposes of these appraisal estimates include currently minable resources (*reserves*) as well as those resources not yet discovered or not currently profitable to mine.

The mining of mineral deposits, once discovered, depends on geologic, economic, and technologic factors; however, identification of many deposits yet to be discovered, owing to incomplete knowledge of their distribution in the Earth's crust, depends greatly on geologic availability and man's ingenuity. Consequently, appraisal of mineral resources results in approximations, subject to constant change as known deposits are depleted, new deposits are found, new extractive technology and uses are developed, and new geologic knowledge and theories indicate new areas favorable for exploration.

This Professional Paper discusses aspects of the geology of copper as a framework for appraising resources of this commodity in the light of today's technology, economics, and geologic knowledge.

Other Geological Survey publications relating to the appraisal of resources of specific mineral commodities include the following:

Professional Paper 820—"United States Mineral Resources"
Professional Paper 926—"Geology and Resources of Vanadium Deposits"
Professional Paper 933—"Geology and Resources of Fluorine in the United States"
Professional Paper 959—"Geology and Resources of Titanium in the United States"

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COPPER DEPOSITS IN SEDIMENTARY AND VOLCANOGENIC ROCKS

By ELIZABETH B. TOURTELOT and JAMES D. VINE

ABSTRACT

Copper deposits occur in sedimentary and volcanogenic rocks within a wide variety of geologic environments where there may be little or no evidence of hydrothermal alteration. Some deposits may be hypogene and have a deep-seated source for the ore fluids, but because of rapid cooling and dilution during syngenetic deposition on the ocean floor, the resulting deposits are not associated with hydrothermal alteration. Many of these deposits are formed at or near major tectonic features on the Earth's crust, including plate boundaries, rift valleys, and island arcs. The resulting ore bodies may be stratabound and either massive or disseminated.

Other deposits form in rocks deposited in shallow-marine, deltaic, and nonmarine environments by the movement and reaction of interstratal brines whose metal content is derived from buried sedimentary and volcanic rocks. Some of the world's largest copper deposits were probably formed in this manner. This process we regard as diagenetic, but some would regard it as syngenetic, if the ore metals are derived from disseminated metal in the host-rock sequence, and others would regard the process as epigenetic, if there is demonstrable evidence of ore cutting across bedding. Because the oxidation associated with diagenetic red beds releases copper to ground-water solutions, red rocks and copper deposits are commonly associated. However, the ultimate size, shape, and mineral zoning of a deposit result from local conditions at the site of deposition—a logjam in fluvial channel sandstone may result in an irregular tabular body of limited size; a petroleum-water interface in an oil pool may result in a copper deposit limited by the size and shape of the petroleum reservoir; a persistent thin bed of black shale may result in a copper deposit the size and shape of that single bed.

The process of supergene enrichment has been largely overlooked in descriptions of copper deposits in sedimentary rocks. However, supergene processes may be involved during erosion of any primary ore body and its ultimate displacement and redeposition as a secondary deposit. Bleached sandstone at the surface may indicate significant ore deposits near the water table.

INTRODUCTION

Copper is one of the earliest discovered and most widely used metals. However, our knowledge of the distribution and origin of economically workable deposits is incomplete and fragmentary despite long familiarity with the metal. This report will examine the great variety of copper deposits in sedimentary rocks and discuss the similarities and differences between deposits. To facilitate and clarify discussion, some words commonly used in economic geology are redefined here and other terms are intentionally avoided because their meaning has become blurred through the years. The main thrust of this paper is to explain the occurrence and genesis of sedimentary copper deposits, therefore resource and reserve data are not tabulated in this report. The reader interested in precise reserve data is referred to McMahon (1965), Kinkel and Peterson (1962), Cox and others (1973), and Pélissonnier and Michel (1972).

Concepts of genesis definitely influence exploration for and development of copper deposits; the size, shape, and tenor of an ore deposit are controlled by its mode of formation. In developing a mine, the geologist needs to know whether a deposit is likely to be large or small, spotty or persistent, whether it is associated with a ground-water table or a petroleum-brine interface, and whether the primary control of the deposit is lithologic, stratigraphic, or structural. The size and primary controls of a deposit are influenced by its genesis—Is it syngenetic, diagenetic, or epigenetic? Is it supergene or hypogene? What are the permeabilities of the associated strata? Are the associated strata marine or nonmarine? What is the structural setting of the associated rocks—Are they related to a plate margin or a stable craton? The answers to all of these questions are important in suggesting new prospecting areas as well as in developing known mineralized areas. Therefore this paper will emphasize theories of genesis and consider these many factors that influence ore deposits.

ACKNOWLEDGMENTS

We have benefited greatly from discussions with our colleagues, who generously shared their knowledge of the various copper deposits of the world. While the opinions expressed here are our own, we deeply appreciate the helpful suggestions, references, and criticisms received during the writing of this report. We also thank Richard B. Taylor and Louise Hedricks for their help in preparing the photographs and photomicrographs used in this report.

CONCEPTS OF GENESIS

Development of concepts of genesis during the nineteenth and twentieth centuries (see Stanton, 1972, p. 7–35, for a concise history of genetic theories) culminated in the domination of the epigenetic hydrothermal hypothesis for the origin of most major ore deposits. Although the veins at Butte, Mont., and Cornwall, England, are classic localities of hydrothermal ore deposition, the modern concept of a hydrothermal deposit is best illustrated by porphyry copper deposits. In a porphyry copper deposit, mineralization is irrefutably related to magmatic intrusion; concentric zones of hydrothermal alteration center in the upper part of the intrusion and extend outward into country rock (Lowell and Guilbert, 1970, fig. 3; Sillitoe, 1973). The igneous body is generally regarded as the source of heat, metals, and volatile constituents responsible for alteration and mineralization. Ore minerals are precipitated in veins or disseminated grains in a porous or chemically reactive rock by a decrease in temperature and pressure and a loss of volatiles. This hydrothermal-magmatic hypothesis has served well in the exploration and development of many major mining districts throughout western North and South America (Sawkins, 1972; Sillitoe, 1972b, c). However, recent oxygen isotope studies, such as those described by Taylor (1973, 1974), show that a large proportion of meteoric water is involved in the processes of alteration and mineralization of some hydrothermal deposits. This raises the question of whether the other constituents of porphyry copper deposits and of other epigenetic hydrothermal ore deposits are derived from the magma or whether they are leached from intruded country rock, or more simply, which constituents originate where and in what proportions? The answer to this question may suggest new exploration targets. Many ore deposits, among them some of the world's largest, show no relation to igneous intrusion and no hydrothermal alteration of country rock. They cannot be explained by conventional hydrothermal theories.

The epigenetic-hydrothermal hypotheses have tended to dominate discussions of the genesis of ore deposits until recently. This predominance occurred even though a leading advocate of the hydrothermal hypothesis, Waldemar Lindgren (1933), included several chapters in his textbook "Mineral Deposits" on nonhydrothermal types of ore deposits, including one entitled, "Deposits Formed by Concentration of Substances Contained in the Surrounding Rocks by Means of Circulating Waters." This is essentially what older workers called "lateral secretion," but the term and concept have been so discredited that they are now rarely used. Instead, we have people writing in the following terms, "The * * * orebody is a massive hydrothermal cupriferous pyrite deposit, averaging 4 percent copper. It is of some interest in that hydrothermal wallrock alteration is almost entirely absent * * *" (John, 1963, p. 107).

A period of uranium exploration, mostly by small independent companies or petroleum companies, beginning in the early 1950's and still active, employed petroleum geologists for uranium exploration—individuals who had no personal commitment to the hydrothermal hypothesis but who were familiar with concepts of migration of fluids and diagenesis in sedimentary rocks. The success of the application of concepts developed by petroleum geologists to the search for uranium in sedimentary rocks suggests that the same concepts might be equally useful in the search for other metals that are mobile under conditions of low temperature and pressure, including copper.

DEFINITION OF TERMS

Many copper deposits in sedimentary rocks show no evidence of hydrothermal alteration. If the deposits have lateral persistence and are concordant with the stratification of other sedimentary rocks, they are generally called stratiform. If they are confined to specific stratigraphic horizons on a large scale but are discordant on a small scale, or if they gradually cut across local bedding planes, they are generally called stratabound. (These definitions, modified slightly, are from Stanton, 1972, p. 541.) In some districts stratiform deposits occur at several different horizons and in other districts stratabound deposits may occur in rocks of several different lithologies. One of our problems is to find unifying themes among the great variety of deposits that exist in sedimentary rocks. (See Dunham, 1969, for further discussion.)

In this paper the terms "stratiform" and "stratabound" will be used for copper deposits in sedimentary rocks, instead of "red-bed" copper deposit. Red-bed copper deposit implies that the copper deposits in sedimentary rocks are in intimate association with red-colored rocks. Because this is not always so, the term "red-bed type" has been stretched in many instances to the point that it is meaningless. For clarity, the other terms that we will be using frequently are defined:

Syngenetic.—Minerals deposited or formed simultaneously with the enclosing sediment.

Diagenetic.—Postdepositional formation of new minerals by equilibrium reactions between the original sedimentary rock constituents, both detrital and chemical, and interstitial fluids and gases from within the sequence. By implication, the elements making up the new minerals were present in the sedimentary sequence at the time of deposition.

Epigenetic.—Postdepositional formation of new minerals, especially ore minerals, by chemical reactions between the original sedimentary rock constituents and solutions from an external source. Historically the term has implied hydrothermal solutions of magmatic origin, but in recent years it has been extended to ground waters of meteoric origin, which might have been introduced into aquifers after tectonic uplift and truncation.

Hypogene.—Describes ascending solutions, generally in the form of volcanic exhalations or hydrothermal waters. May produce syngenetic deposits on the sea floor or epigenetic deposits in preexisting rock.

Supergene.—Describes descending solutions, generally meteoric waters entering ground water systems. Applied most frequently to the oxidative destruction of a preexisting ore body and the formation of an enriched mineralized zone at greater depth, but it could be applied to the mobilization of disseminated ore minerals and redeposition of an ore body.

Diplogenetic.—A term proposed by Lovering (1963) for mineral deposits whose elements are in part syngenetic and in part epigenetic. A possible example is the White Pine copper deposit in Ontonagon County, Mich., where several authors, including White and Wright (1966) and Ensign and others (1968), have suggested that the iron in preexisting pyrite was replaced by copper from copper-bearing solutions.

Hydrothermal.—Means hot water. It can be either deeply circulating ground water in an area of high temperature gradient or water with components of juvenile water from igneous activity.

Tons.—All tonnages in this report are in metric tons. Most of the figures quoted are rounded and (or) estimates and the percent difference between short tons, metric tons, and long tons is less than the margin of error.

GEOCHEMISTRY

Copper is not included within the crystal structure of common rock-forming minerals; it most commonly occurs as minute grains of chalcopyrite in crystalline rocks (Goldschmidt, 1954, p. 182). Turekian and Wedepohl (1961, table 2) estimated that granitic rocks contain an average of 10-30 ppm copper and that basaltic rocks contain an average of 87 ppm. Some mafic rocks are reported to contain as much as 1,000 ppm copper (Dunham, 1972). Samples of biotite separated from felsic intrusive rock associated with porphyry copper deposits contain as much as 1 percent copper (Lovering, 1972, p. D11), probably as minute sulfide inclusions.

In the zone of oxidation and weathering, copper sulfide minerals are unstable, releasing copper ions which are carried in solution with any of the common anions, such as carbonate, sulfate, or chloride (chloride probably being the most effective under many conditions). In sedimentary environments, copper tends to stay in solution where oxygen amounts are sufficient to maintain a positive Eh and a low pH exists. At a pH greater than 6.3, the copper combines with carbonate or sulfate to form compounds of low solubility, which are then transported as suspended material (Strakhov, 1961). Very early in the evolution of the Earth's atmosphere, before free oxygen began to accumulate as a result of photosynthesis (Cloud, 1971), copper sulfides, like other heavy minerals, were probably stable enough to be transported and deposited in placer deposits. In later Precambrian time enough free oxygen existed to oxidize the copper sulfides, but a high concentration of CO_2 in the atmosphere caused a low pH of river water (Strakhov, 1962) and copper remained in solution much longer and traveled farther than it does today. Evolution of the Precambrian atmosphere may be an important factor in the occurrence of major copper deposits in association with sedimentary rocks of middle to late Precambrian age. Some Precambrian iron deposits, such as on the Keweenaw Peninsula of Michigan (James and others, 1968; Lougheed and Mancuso, 1973), contain evidence of Precambrian organisms and are older than the copper deposits in the same region (Ensign and others, 1968; White, 1968). Bakun, Volodin, and Krendelev (1964) have actually suggested the older "Archean" iron deposits in the Aldan shield as the source of copper found in the Precambrian Udokan copper deposit in Siberia.

Ordinarily, during the geologic cycle of weathering, transport, and sedimentation, copper is dispersed rather than concentrated. Copper carried to the sea in streams is usually dispersed throughout a very large quantity of marine sediment, although it may be adsorbed on clay minerals, organic matter, or manganese nodules, and somewhat concentrated. Manganese nodules studied by Mero (1962) contained an average of 0.8 but as much as 2.9 percent copper. For average sedimentary rocks, Turekian and Wedepohl (1961, table 2) listed the copper contents as shale, 45 ppm; sandstone, X ppm [1–9 ppm]; and limestone, 4 ppm. In black shale the mean copper content was found to be 70 ppm (Vine and Tourtelot, 1970, p. 265–267); the higher copper content suggests some association with organic matter. Armands (1972, p. 20) found that uranium-rich Cambrian alum shales (which are generally organic-rich, too) from the Billingen area, Sweden, contain 180–190 ppm copper. Samples of pyrite separated from these shales contained five times as much copper as the enclosing shale (Armands, 1972, p. 58–62). In contrast, the Meade Peak Phosphatic Shale Member of the Phosphoria Formation of Permian age in western Wyoming and eastern Idaho, which contains local concentrations of vanadium (McKelvey and Strobell, 1955) and uranium (Sheldon, 1959) and averages about 5 percent organic carbon, contains a mean of only 100 ppm copper, although it is enriched (compared to other black shales) in chromium, lanthanum, molybdenum, yttrium, ytterbium, and zinc (Vine, 1969, p. G14; Vine and Tourtelot, 1970). The suite of elements enriched in the Meade Peak appears to represent the elements most likely to be concentrated in a marine environment by normal marine processes, and suggests that special circumstances would be required to form a purely syngenetic marine copper deposit.

PROBLEMS OF GENESIS OF COPPER DEPOSITS

It is important to consider what special circumstances might produce an economic deposit of copper in sedimentary rocks. In many cases, there are intriguing hints about factors important in the formation of deposits that we do not completely understand. We do know that no one theory of genesis will explain all ore deposits. Because we suspect that many copper deposits result from many different processes acting on sedimentary and volcanic rocks throughout their geologic history, and because many of these processes are obscured by later events and are difficult to decipher, we wish to avoid any classification scheme that carries connotations of genesis with it. In this paper, we will discuss first copper deposits forming today or recently formed, then massive sulfide deposits, and then generally older deposits starting with the youngest and concluding with the most ancient. Some discussion of genesis will be included in the deposit descriptions, and finally we will try to sum up unifying factors. The main emphasis is on stratiform and stratabound deposits of syngenetic and diagenetic origin. For this reason, discussion of vein deposits in sedimentary rocks and replacement deposits in limestones and dolomites has been omitted. The deposits discussed were selected on the basis of economic importance, and (or) the availability of information about them, and (or) their capabilities for illustrating important factors in ore formation. We hope to show the potential economic importance of stratabound copper deposits and to stimulate research and exploration for them.

COPPER DEPOSITS FORMING NOW

MODERN BOG AND LAKE DEPOSITS

COPPER FROM RUNOFF

T. S. Lovering (1927) described the occurrence and genesis of spongy masses of native copper in a peat bog in the Beartooth Mountains near Cooke City, Mont. (fig. 1). The copper occurs in thin beds of black muck, but not in the interbedded layers of sand and gravel. Several bodies of cupriferous pyrite occur in the Precambrian crystalline terrane of the surrounding mountains, and Lovering suggested that the copper is transported in solution in surface waters from the older deposits as cupric sulfate. In the bog, the biochemical action of bacteria at least partly causes the precipitation of the native copper. Near Jefferson City, Mont., (fig. 1), a similar deposit of native copper occurs in a peat bog downstream from copper-sulfide-bearing veins in the Boulder batholith (Forrester, 1942). However, there the copper is associated with limonitic bog iron which may be the precipitating agent for copper. In both of these instances, the deposits of native copper are small, but are clearly the result of weathering, transport, and deposition under surface conditions.

COPPER FROM GROUND WATER

Another copper-rich peat deposit, in southeastern New Brunswick, Canada (fig. 1), is slightly different from the two just discussed. Fraser (1961a, b) said that although the forest peat contains as much as 10 percent copper (dry weight), no copper minerals were visible in the peat. He thought that the copper is organically bound, possibly as a chelate, and furthermore, rather than being brought in by surface water, the copper probably entered the swamp in ground water that picked up copper from the underlying nonmarine Pennsylvanian sandstones known to contain disseminated cupriferous pyrite.

In the southern Ural Mountains, U.S.S.R., there is a pond that is colored blue by the large amount of copper it contains. As described by Igoshin (1966), spring waters feeding the pond, which are also blue, contain as much as 38 ppm copper as well as other metals. Geophysical and geochemical data are purported to indicate a local source of the spring water and its metals. The rocks near the spring are enriched in metals, and Igoshin interpreted that to mean that the metals are brought to the surface from depth. The geology of the area is diverse and the exact source of the metals is uncertain.

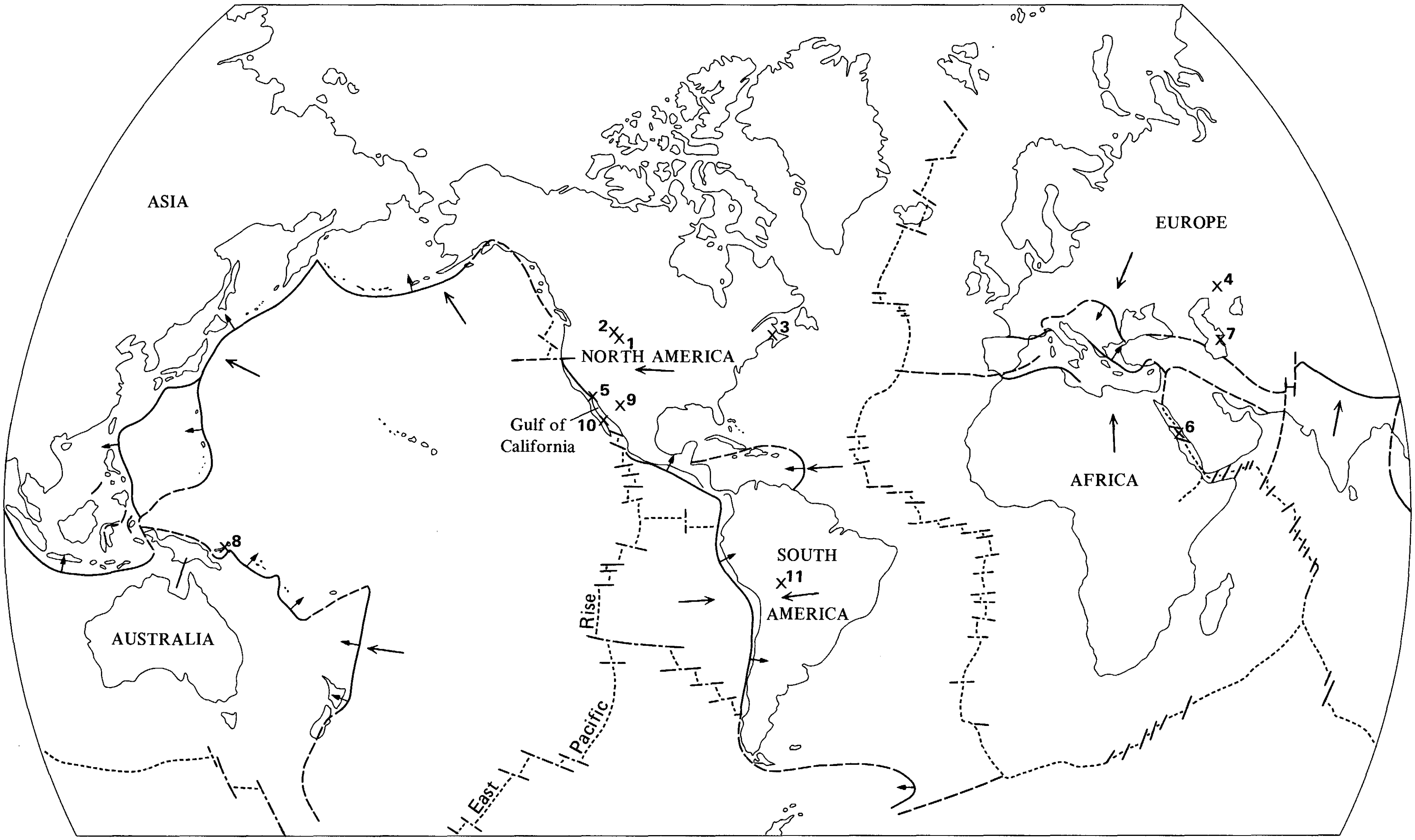
These examples of copper-rich bogs and lakes reflect the mobility of copper in the zone of weathering and in any porous rock with oxidizing ground water flow. Conversely, they also illustrate ways in which copper can accumulate, and they may be analogous to some ancient copper deposits.

DEPOSITS FROM COPPER-RICH BRINES

Besides surface waters or meteroic ground waters enriched in copper from the leaching of older copper deposits or copper-rich sedimentary rocks, other copper-rich brines are known that involve varying proportions of meteoric, connate, metamorphic, and magmatic waters. Brines enriched in metals have been discovered and studied along the East Pacific Rise (Corliss and others, 1972; Dymond and others, 1972; Bostrom and Peterson, 1966). Corliss (1971) suggested that the brines along mid-oceanic ridges become enriched in several elements in the following way—as the basalts that have been extruded along the ridges cool, they develop contraction cracks, and the chloride complexes in seawater mobilize the elements as seawater moves in and through these cracks. Moore and Calk (1971) identified microscopic spherules of iron, copper, and nickel sulfides in the glassy margins of pillow basalts. They suggested that the constituents in the sulfides are derived by diffusion from the cooling basalt.

SALTON SEA

The East Pacific Rise continues northward from the Pacific Ocean into the Gulf of California and then inland under the Imperial Valley of California. A well drilled for geothermal power near the Salton Sea (fig. 1) tapped a saline brine with an extremely high heavy-metal content (White and others, 1963). The brine from the well deposited siliceous scale at the rate of 2–3 tons per month containing an average of 20 percent copper and as much as 6 percent silver (Skinner and others, 1967). The brine is a Na-Ca-Cl brine and contains 500 ppm Zn, 90 ppm Pb, and 6 ppm Cu, but only 15–30 ppm total sulfide (D. E. White, 1968, p. 313). White (1968) decided that the major component of the brine was from meteoric water and that the high salinity was from the dissolution of evaporites at depth. Helgeson (1968) suggested that the high salinity was, instead, the result of evaporative concentration of connate water. Heat from magmatic activity at depth caused convective circulation of the ground water which leached the metals from the enclosing sediments (Helgeson, 1968). If undisturbed, the brines might or might not eventually form an ore deposit.



EXPLANATION

Spreading centers — Transform plate margin — Consuming plate margin showing dip direction of downgoing plate — Margin of uncertain nature and (or) location — Relative plate motion

FIGURE 1.—Major lithospheric plates and Cenozoic disseminated copper deposits in the world. Base showing major lithospheric plates supplied by Philip W. Guild. See Guild (1973) for maps showing massive sulfide deposits plotted on the same base. 1, Cooke City, Mont. 2, Jefferson City, Mont. 3, New Brunswick, Canada. 4, Ural Mountains, U.S.S.R. 5, Salton Sea, Calif. 6, Red Sea, showing approximate location of Atlantis II Deep. 7, Cheleken Peninsula, U.S.S.R. 8, New Britain and the Solomon Islands. 9, Colorado Plateau, United States. 10, Boleo, Mexico. 11, Corocoro, Bolivia.

RED SEA

Although anomalously high temperatures were first suspected near the bottom of the Rea Sea in 1948, the hot dense saline waters in the deeps of the Red Sea were recognized and measured during the years 1963-65 (Brewer and others, 1965; Degens and Ross, 1969). In 1965 the sediments in these deeps were cored and the high metal content was discovered (Miller and others, 1966; Degens and Ross, 1969). Structurally, the Red Sea is similar to the Gulf of California (fig. 1); it is a rift zone and is the site of sea-floor spreading. The brine is a Na-Ca-Cl brine quite different from seawater. The metal content of the brine is much lower than that of the Salton Sea brine, but is two to four orders of magnitude greater than that of seawater (D. E. White, 1968). Most likely the brines are ground waters that have dissolved evaporites and picked up the heavy metals from sediments at depth (D. E. White, 1968; Emery and others, 1969). The sediments cored in the Atlantis II Deep in the Red Sea are highly metal rich (Ross, 1972; Ross and others, 1973; Bischoff, 1973), containing an average of 1.3 percent Cu, 3.4 percent Zn, and 29 percent Fe in the top 33 ft (10 m) (Bischoff and Manheim, 1969). At 1967 prices, Bischoff and Manheim calculated that the total value of the metals in the top 33 ft (10 m) of the Atlantis II Deep was $2.5 billion. Clearly this represents a modern syngenetic ore deposit. In the Degens and Ross (1969) volume, several authors have speculated on what might happen to this deposit in the geologic future. James (1969) pointed out that the Red Sea brines are associated with evaporites as are many of the older stratabound base-metal deposits, and that, with diagenesis, the metal-rich brines might be displaced laterally until the metals were precipitated as sulfides in some favorable host rock. Ross and others (1973) have suggested similarities in the trace element content of the black-shale facies under the Red Sea with that of the Kupferschiefer.

CHELEKEN PENINSULA

Another metal-rich brine area occurs on the Cheleken Peninsula on the southeast coast of the Caspian Sea (fig. 1). Although the structural and tectonic settings may not be analogous to those in the Salton Sea area, the brines at Cheleken have been compared to those at the Salton Sea (Lebedev, 1967a, b; Vinogradov and others, 1969). A group of wells in the Cheleken area produce iodine and bromine from 12 different aquifers in the upper 3,300 ft (1,000 m) of red beds within a thick sequence of upper Pliocene strata. Large quantities of lead, zinc, copper, and other metals are recovered from the pipes and holding tanks used for recovery of halides from the hot brines.

NEW BRITAIN AND THE SOLOMON ISLANDS

Stanton and Baas Becking (1962) observed the accumulation of sedimentary sulfides associated with geothermal activity in nearshore environments along the coasts of New Britain and the Solomon Islands (fig. 1). Ferguson and Lambert (1972) have studied this accumulation in detail in Matupi Harbour at the east end of New Britain where volcanic activity has occurred relatively recently. They concluded that the thermal exhalations represent seawater circulated through hot Quaternary volcanic rocks from which large quantities of metals have been leached and carried to the surface to be precipitated and deposited with the detrital minerals in the harbor. Although the deposits forming there today are not of ore grade, the mechanisms involved have great significance in the studies of older deposits. In this case, the thermal activity is related to an island-arc tectonic setting, and there are no evaporites or sediments to be leached, but the principles involved appear to be similar to what is happening in the Salton Sea area and the Red Sea. That is, heat from igneous activity drives the circulation of brines—formed by meteoric water leaching evaporites, or by seawater—which then leach metals from the enclosing rocks. When these brines reach the surface or some special environment, the metals they carry are precipitated.

COPPER DEPOSITS RELATED TO THE PRESENT CYCLE OF WEATHERING

The expression "supergene enrichment" generally suggests the erosion, weathering, and oxidation of a sulfide ore body and the concentration of secondary sulfides, sulfates, carbonates, and other minerals near the water table. Typically, there is a zone of enrichment, overlain by a leached zone or gossan composed of the residue from the weathered part of the ore body. The leached zone contains quartz, iron oxides, and, possibly, a kaolinitic clay—minerals that are relatively insoluble in the acid environment produced by the oxidation of sulfides. A gossan is usually conspicuous over a massive sulfide body, replacement body, or sulfide-rich veins, but a similar phenomenon may be unobtrusive where sulfide minerals are disseminated through a resistant sedimentary rock such as sandstone or a quartzite. The Nacimiento deposit near Cuba, N. Mex., to be discussed later (p. C13), may include a leached zone and a zone of supergene enrichment. The Nugget Sandstone in western Wyoming has small voids or cavities filled with limonite or dolomite (fig. 2) that may represent formerly existing sulfide minerals. Similar features were observed in outcrops of copper-bearing quartzite in the Revett Formation of Precambrian age in western Montana. Conspicuous secondary copper minerals such as azurite and malachite were not seen in either instance. Thus, a leached zone associated with copper mineralization in sandstone may be inconspicuous, but should be suspected where sandstone or quartzite contains voids or cavities filled with secondary minerals, especially in areas favorable for the occurrence of disseminated copper.

COLORADO PLATEAU

Deposits resulting from supergene processes are known in several areas of the Colorado Plateau. Except for minor

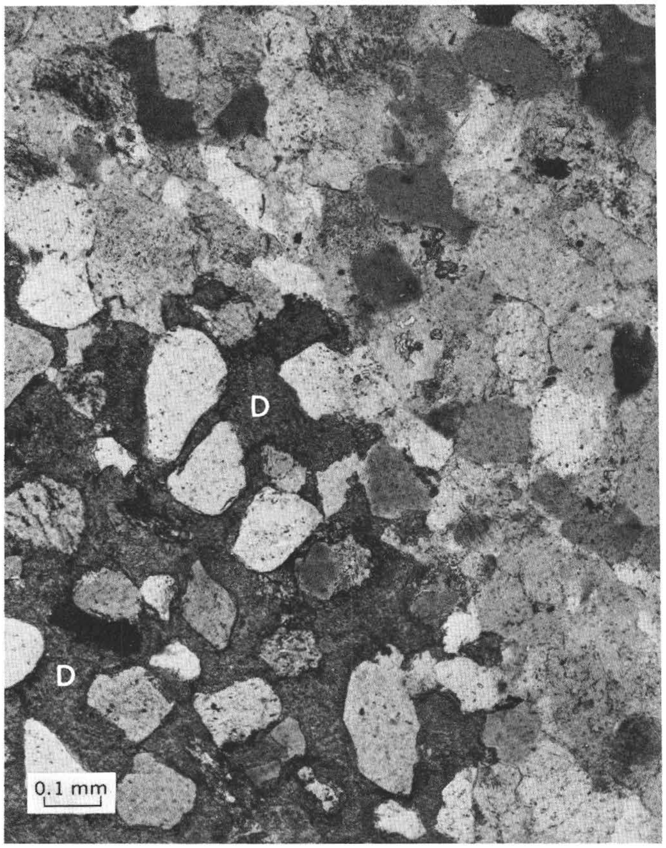


FIGURE 2.—Dolomite (D) filling of voids 1–3 mm across in Nugget Sandstone of Jurassic(?) and Triassic(?) age from Lincoln County, Wyo. Crossed polars; sample CU-28D.

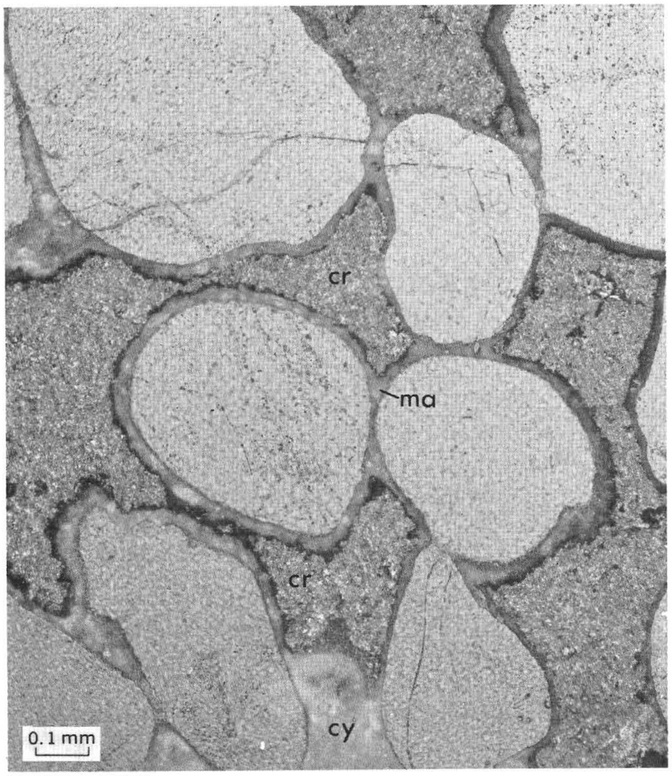


FIGURE 3.—Navajo Sandstone of Jurassic and Triassic(?) age from the Copper Mine Trading Post, Coconino County, Ariz. Sandstone cemented by malachite (ma) and with remaining pores filled with cuprite (cr) and chrysocolla (cy). Exposures by reflected light and by light transmitted through crossed polars; sample CU-11A.

occurrences of sulfide nodules or veinlets, these deposits have no known association with a primary ore body. They are characterized by colorful secondary copper minerals such as azurite, malachite, and chrysocolla at or near the surface. These secondary minerals were probably deposited by supergene processes some distance from a primary ore body that has since been completely destroyed by continued erosion. Although most of these deposits are small, they illustrate one of the processes that can form ore deposits, and there may be more as yet undiscovered large deposits of this type, similar to the Nacimiento, New Mex. deposit.

The White Mesa copper district, also known as the Copper Mine Trading Post, on the Navajo Reservation about 20 mi (32 km) south of Page, Ariz. (Mayo, 1956), probably represents such a supergene deposit. Secondary copper minerals (fig. 3) are locally disseminated in the pore spaces of the Navajo Sandstone of Jurrasic and Triassic(?) age, an eolian quartz sandstone as much as 1,500 ft (460 m) thick. Detailed geologic mapping by C. B. Read, R. D. Sample, and H. H. Sullwood, Jr. (written commun., 1943) indicated that the deposit occurs along the flank of a monoclinal fold and that the copper minerals are localized on a small scale along faults and joints, some of which are filled with chalcedony. Samples collected in 1972 show that the copper mineralization is younger than the fractures and the chalcedony. Therefore, the mineralization is probably related to the present cycle of erosion.

Secondary copper minerals also replace sandy, phosphatic limestone and dolomite (fig. 4) of the Kaibab Limestone of Permian age, located 1–2 mi (1.6–3.2 km) west of Jacob Lake Post Office, about 44 mi (71 km) by road north of the North Rim Lodge in Grand Canyon National Park. Karst topography characterizes the area, and several copper prospects are near the road that winds around the sinkholes named Jacob Lake and Lambs Lake. In addition to copper, some samples from this area contained anomalous amounts of zinc, silver, nickel, cadmium, chromium, arsenic, and antimony. Waesche (1933, 1934) described similar mineralization at the Anita mine in Kaibab Limestone on the south side of Grand Canyon and at the Grandview copper mine in a breccia zone of the Redwall Limestone of Mississippian age within the present boundary of Grand Canyon National Park. In each area, the present deposits appear to have formed by supergene processes that reworked former primary ore bodies during the present cycle of erosion, as was suggested by Jennings (1904).

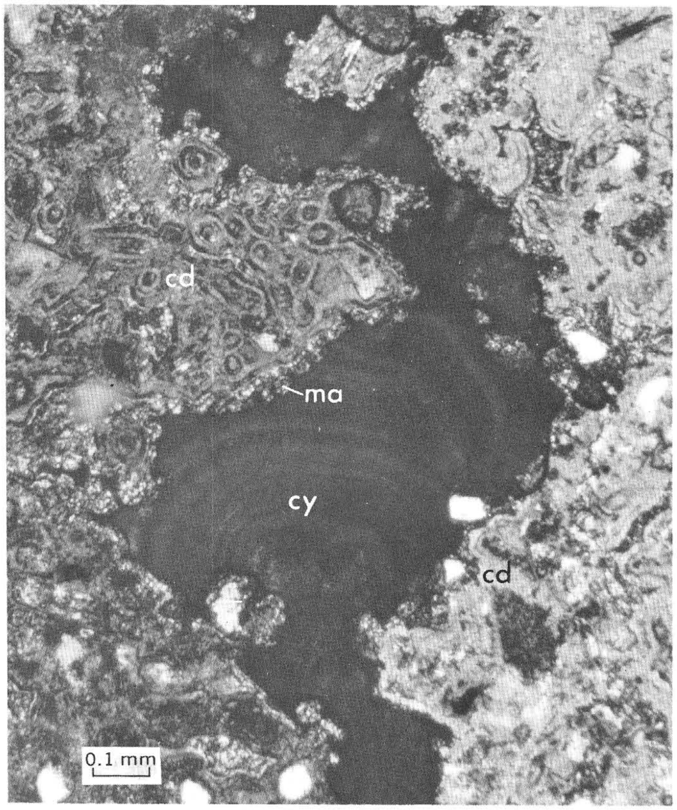


Figure 4.—Spicular limestone from the Kaibab Limestone of Permian age replaced by chalcedony (cd), malachite (ma), and chrysocolla (cy) near the sink hole at Lambs Lake, Coconino County, Ariz. Exposures by reflected light and by light transmitted through crossed polars; sample CU-15C.

In the Cumberland-Pictou lowlands of New Brunswick and Nova Scotia, Brummer (1958) has described deposits formed by supergene enrichment, which are similar to deposits of the Colorado Plateau. In Nova Scotia, the enriched zone of copper and uranium is restricted to a distance of 20–50 ft (6–15 m) down the dip of the beds, which coincides with the present position of the water table at 25–60 ft (7.6–18 m) below the surface. Chalcocite does not occur below the water table but slightly cupriferous pyrite does (Brummer, 1958, p. 322–323).

COPPER-SULFIDE DEPOSITS RELATED TO CRUSTAL-PLATE BOUNDARIES

The relationship between some stratabound copper-sulfide deposits and volcanism has been recognized for some time (Ohashi, 1919; Stanton, 1959; Watanabe, 1957; Hutchinson, 1965; Kinkel, 1966; Skripchenko, 1967; Anderson, 1969; Matsukuma and Horikoshi, 1970; see Hutchinson, 1973, for a more complete review). However, recent theories on the relationship between ore deposits and plate tectonics (Bird and Dewey, 1970; Guild, 1971, 1972a, b, 1973; Sawkins, 1972; Sillitoe, 1972a, b, c, 1973; Dunham, 1972; Dixon, 1973; Gabelman and Krusiewski, 1972; Upadhyay and Strong, 1973; Hutchinson, 1973) may further explain the existence of these deposits and may disclose a more complete pattern of occurrence for these deposits. While the ultimate cause of the deposits or source of the metals still may not be completely explained, the plate tectonic model gives us new ideas on how an ore body could be emplaced tectonically after being formed syngenetically and suggests possible exploration targets for massive copper-sulfide deposits. Data on past production and (or) reserves, taken from Laznicka and Wilson (1972), show that 18 percent of the world's copper is in copper-sulfide deposits related to volcanism.

PLATE TECTONIC THEORY REVIEWED

Massive stratabound sulfide deposits can form at the sites of either diverging or colliding plates (fig. 5). Disseminated stratabound copper deposits, in addition to forming along plate boundaries, may form at the sites of tensional rifting within plates or they may form by sedimentary and diagenetic processes within stable platform environments. A brief introduction to plate tectonics will be followed by a discussion of copper deposits in sedimentary and volcanogenic rocks whose origins appear to be closely related to the plate tectonic hypothesis.

New material is added to plate margins where plates diverge—that is, at the site of sea-floor spreading, which is often typified by a midoceanic ridge. Sulfide deposits associated with ophiolite sequences may form along spreading centers as described in detail by Sillitoe (1972a, c). The new material is gradually rafted away from the spreading center until it encounters another plate. Several authors have described the structural deformation caused by the collision of two plates (Bird and Dewey, 1970; Dewey and Bird, 1970; Warren Hamilton, 1969, 1970; Dietz and Holden, 1970; Dickinson, 1971). When two plates collide, one plate generally slides under the other along a zone of subduction (Benioff zone) and is consumed by melting at depth (Sillitoe, 1972c). If a plate carrying a continent collides with an oceanic plate, the oceanic plate, being made of denser material, is the one to subduct. Some of the upper layers of the oceanic plate, including possible ore deposits, can be added to the continental plate, producing a melange of tectonically contorted deep-sea sediments and volcanic rocks classically described as eugeosynclinal facies. Slices of the mantle may even be included. When an island arc and a continent collide, the buoyancy of the continental rocks formed in the arc prevents underthrusting of either plate (McKenzie, 1969) and so the arc is welded to the continent and breaks off from the oceanic part of the plate. The oceanic part begins to pass under the combined continent-island arc and a new Benioff zone forms on the oceanic side of the arc (Dewey and Bird, 1970). The igneous, volcanic, and sedimentary island-arc rocks, and any enclosed sulfide deposits, are further metamorphosed during the collision and welding process. In

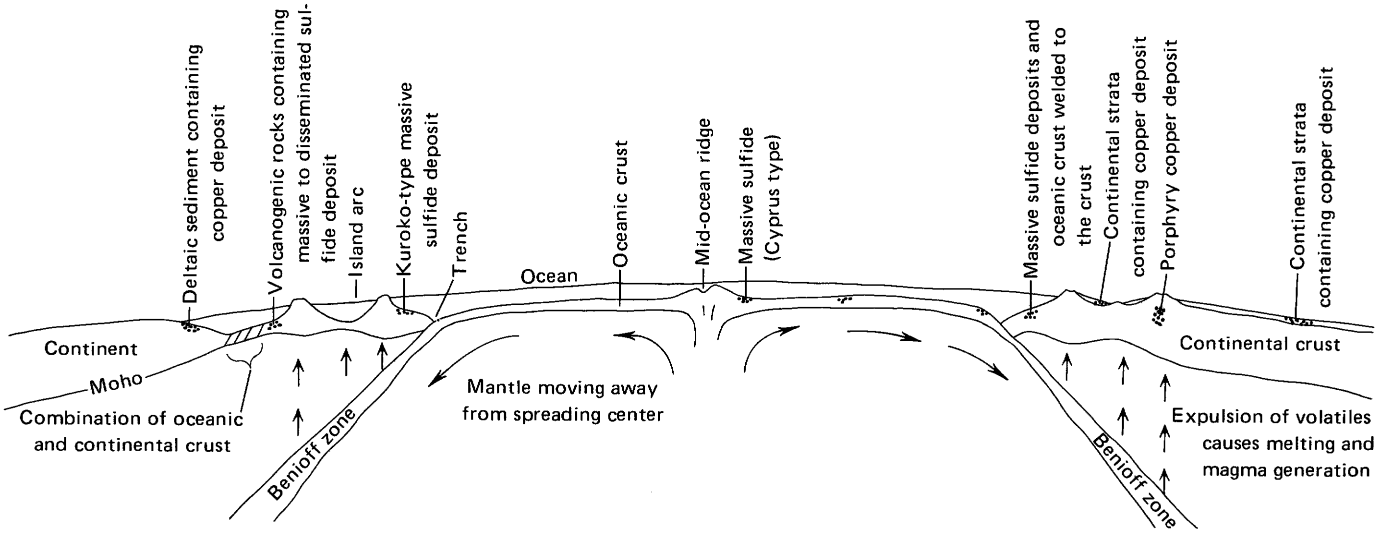


FIGURE 5.—Diagram of plate tectonic hypothesis and its relation to copper deposits. Modified from Warren Hamilton (1969), Dewey and Bird (1970), Guild (1972a, b), and Sillitoe (1972a).

either case—continent-oceanic plate collision, or continent-island arc collision—where massive sulfide deposits are present, they may be incorporated into the continental crust as part of a eugeosynclinal facies. The metamorphism that accompanies these processes may make it difficult to distinguish between those deposits that originated at a spreading center and those that formed in an island arc. Regardless of origin, eugeosynclinal facies commonly contain massive sulfide deposits, and plate boundaries are commonly the site of mineral deposits (figs. 1, 5). Guild (1973) published a map (shown in fig. 1) showing many of the massive sulfide deposits that may be associated with plate boundaries. Therefore, instead of completely cluttering his map, on figure 1 we are showing only the disseminated deposits that we discuss in some detail.

ISLAND-ARC ENVIRONMENT

Stratiform and stratabound copper deposits that occur in an island-arc environment may be massive and interbedded with calc-alkalic lavas, or they may be disseminated through rhyolitic tuff or through lagoonal facies shale and marlstone. Some of the ore deposits associated with volcanic arcs are syngenetic, formed by fumarolic activity that causes metal-rich solutions to pour out onto the ocean or lagoon floor. We have already discussed a possible modern example of this along the coasts of New Britain and the Solomon Islands (p. C6). Other deposits are epigenetic, formed by the alteration of volcanic rock and sediment as the solutions ascend to the surface. Many deposits, such as the Miocene Kuroko in Japan (Watanabe, 1957; Matsukuma and Horikoshi, 1970; Sato, 1971; L. A. Clark, 1971), may show complete gradation from epigenetic to syngenetic. The epigenetic part of the deposit may consist of pipelike alterations around ascending solutions. The syngenetic part of the deposit is represented by the sulfides precipitated with seafloor mud and volcanic ash as the metal-rich solutions reacted with seawater.

The range of deposits possible in an island-arc environment is represented by the deposits that occur in the Tasman orogenic zone of Australia, such as Rosebery (Brathwaite, 1974) and Mount Lyell in Tasmania; Mount Morgan, Queensland; and Bathhurst and Captains Flat, New South Wales (Solomon and others, 1972). Kuroko and similar deposits in Japan (L. A. Clark, 1971; Ishikawa and others, 1962) are classic examples of island-arc deposits. Other probable island-arc deposits include many of the massive sulfide deposits of Ordovician age in the Appalachian region (Heyl and Bozion, 1971), including some of the deposits in Newfoundland (Baird, 1960), Stirling, Nova Scotia (Keating, 1960), Caribou (Davis, 1972), St. Stephen, Bathhurst, Newcastle (McAllister, 1960), and Brunswick Mining and Smelting ore bodies (Stanton, 1959), all in New Brunswick, and Elizabeth, Vt. (White, 1943). Sillitoe (1972a) suggested that Rio Tinto and similar deposits in Spain and Portugal are of island-arc origin. Most likely, the deposits of the Folldal district of Norway (Waltham, 1968), some of the deposits in the Caucasus (Tvalchrelidze and Buadze, 1964), the 19th Party Congress deposit in the southern Ural Mountains (Boriskov, 1966), and Altai in Kazakhstan (Shcherba, 1971) are all examples of island-arc deposits. This is by no means a complete list of possible island-arc massive sulfide deposits.

DIVERGENT-PLATE-BOUNDARY DEPOSITS

There appear to be two types of stratiform deposits formed at the sites of spreading centers or rifting. The first type, generally a massive sulfide deposit, is that found in ophiolite sequences and described in detail by Sillitoe (1972a). The second type is disseminated. The massive sulfide deposits are generally associated with extrusive tholeiitic basalt and probably "formed initially as accumulations of brine-soaked sulphide mud in depressions on the sea floor" (Sillitoe, 1972a, p. B142). The Troodos Massif in Cyprus is the best known example of this type of deposit because it has not been greatly metamorphosed (Corliss and others, 1972; Elderfield and others, 1972; L. A. Clark, 1971; Hutchinson and Searle, 1971; Constantinou and Govett, 1973). Similar deposits are found in southeastern Turkey (Borchert, 1957), especially at Küre (Suffel and Hutchinson, 1973) and Ergani-Maden (Griffitts and others, 1972; Sirel, 1950). Other examples are Betts Cove and Tilt Cove, Newfoundland (Upadhyay and Strong, 1973); Balabac Island, Philippines (John, 1963); Mugodzhar Hills in the southern Ural Mountains (Ivanov, 1965); the Amasia-Akerin deposits in the Trans-Caucasian region (Tvalchrelidze and Buadze, 1964); West and East Shasta, Calif. (Kinkel and others, 1956), and some of the Appalachian deposits (Kinkel, 1967; Heyl and Bozion, 1971). (The preceding authors are cited for their descriptions of the deposits; they would not necessarily agree with our interpretation of genesis.) In many areas, such as the Appalachian Mountains, Scandinavia, the Ural Mountains, and the Philippines, both spreading-center and island-arc deposits may occur.

Many of the Precambrian and also many of the younger deposits are too metamorphosed for their origins to be certain. Commonly they are associated with eugeosynclinal rocks and may have been tectonically emplaced after they were formed. Also, we cannot be sure that the plate tectonic regime was the same in Precambrian time as it appears today (Burke and Dewey, 1972; Sillitoe, 1972a; Hutchinson, 1973). Therefore, this pattern cannot be used to classify many massive sulfide deposits of Precambrian age, such as Otokumpu, Finland (Peltola, 1960); Mogador (Geoffroy and Koulomzine, 1960), Mattagami (Mackay and Paterson, 1960), and Noranda (Sinclair, 1971) in Quebec; Encampment, Wyo. (Spencer, 1904); Ducktown, Tenn. (Mauger, 1972); and Jerome, Ariz. (Anderson and Nash, 1972). For many other deposits, the published descriptions are such that classification is ambiguous. Also, various advocates of the theory of the relation of plate tectonics and ore deposits may classify the same ore deposit differently. However, thinking of these deposits as essentially syngenetic rather than as replacement deposits may suggest new areas and a more systematic approach for exploration.

Thus, at the site of spreading centers or at island arcs, ore may form syngenetically—that is, the metals precipitate at the surface because of some change in Eh or pH and are deposited with the enclosing sediments—or the ore may form diagenetically or epigenetically if the metals are precipitated as the brine moves upward through already deposited sediments and tuffs. Both syngenetic and diagenetic or epigenetic components can be present in the same deposit. D. E. White (1968) pointed out that many brines are sulfur deficient in comparison to their metal contents. Sulfur may be syngenetically deposited with iron by the action of anaerobic bacteria and metals, such as copper, added later by circulating brines; together, they result in the formation of deposits termed "diplogenetic" by Lovering (1963). White (1968) and also Helgeson (1968) suggested that the metals are not necessarily a juvenile contribution of the mantle or subsurface magmas but that they may have been leached from the rocks through which the brine is flowing. Although volcanism is associated with spreading centers, periods of quiescence are observed, such as in the Red Sea and Gulf of California areas today. Therefore, the deposits formed at the sites of spreading centers are not necessarily closely associated with volcanic rocks. Many of the same factors producing an ore deposit at a spreading center can operate at the site of tensional rifting within plates. Sites of rifting are sites of high heat flow. The rifting also produces grabenlike basins that restrict circulation of water and may enhance the formation of evaporites, and thus saline brines. (For example, see Baker and others, 1972, for a detailed account of the rifting of eastern Africa.) The combination of high heat flow and saline brines can result in a mineralizing solution that can precipitate an ore deposit in a suitable environment. In fact, the high heat flow and saline brines are the most pertinent factors in producing an ore deposit.

CENOZOIC DISSEMINATED COPPER DEPOSITS

TERTIARY

BOLEO, MEXICO

The Boleo copper district adjacent to the Gulf of California in Baja California Sur, Mexico (fig. 1) appears to be an excellent example of a disseminated copper deposit related to diverging plates. Sillitoe (1972c) suggested that this deposit is related to the East Pacific Rise, and Nishihara (1957) suggested a syngenetic origin. As described by Wilson (1955), the copper ore occurs at five different horizons in soft dark beds of altered tuff in the Boleo Formation of Pliocene age. The Boleo Formation was deposited unconformably as a delta over the Comondu volcanic rocks of Miocene age. Although the district is almost mined out now, the ore mined during 1886–1947 averaged 4.8 percent copper, and about 500,000 tons of copper were produced to June 1947 (Wilson, 1955). The principal ore mineral is chalcocite; gangue minerals include montmorillonite, gypsum, calcite, chalcedony, and jasper. The ore occurs in bands, lenses, and nodules (boleos) in the tuff beds, each above a conglomerate bed. The copper deposits partly overlap the Lucifer manganese deposits (Wilson and Veytia, 1949) to the northwest. In the Boleo deposit, again there is the combination of high heat flow (the East Pacific Rise), evaporite beds (the gypsum), and reactive host rocks (the tuff beds). Interestingly, manganese deposits have also been found in the Afar depression, Ethiopia, in Miocene sediments (Bonatti and others, 1972) associated with the rifting of the Red Sea.

COROCORO, BOLIVIA

The Corocoro basin forms the western part of the Altiplano between the East and West Andes in Bolivia (fig. 1). Throughout this basin there has been extensive copper mineralization; Péllisonnier and Michel (1972, table 25) estimated that the basin contained more than 425,000 tons of copper. According to Ljunggren and Meyer (1964), the copper occurs in a thick sequence of first-cycle Tertiary sandstones and conglomerates, in a basin 31–50 mi (50–80 km) across that received sediments from mountains on both sides of the basin. The Tertiary rocks have been deformed by diapiric folds in the underlying Cretaceous evaporite sequence; evaporites also occur in the Tertiary sequence. Ljunggren and Meyer went on to say that the copper minerals always occur in sandy or conglomeratic layers, usually as elongate lenses, are always stratabound, and are generally associated with fossil plants. They recognized two types of ore bodies—one with chalcocite associated with plant material in structural lows, and the other with chalcocite or native copper in structural highs where the copper minerals replace cement in sandstones and conglomerates. The first type is regarded as syngenetic—it is lower grade (as much as a few percent chalcocite replacing fossil plant material) and is found throughout a stratigraphic interval of 16,000–26,000 ft (5,000–8,000 m). The copper probably was derived from the erosion of porphyry copper deposits in the western Andes and (or) the erosion of copper-rich basalt flows of the Altiplano. The second type of deposit is higher grade (as much as 20 percent copper) and occurs on the flanks of anticlines. The second type appears to result from dissolving the disseminated copper in ground water. The copper in the ground water is then precipitated by fossil plant remains (perhaps with the aid of reducing bacteria) or iron minerals on the flanks of anticlines.

Many copper deposits in other parts of the world may have received their copper from the erosion of porphyry copper deposits. Sillitoe (1972c) has emphasized that porphyry copper deposits are usually emplaced at very shallow depths and hence many pre-Mesozoic porphyry copper deposits have probably been eroded away (Sillitoe, 1972c, p. 190–191). Thus, eroded porphyries could be the source of anomalous copper contents in many sedimentary sequences, particularly first-cycle sandstone and conglomerate sequences. At least one such deposit, in Arizona, in basin fill associated with porphyry copper has been described by Throop and Buseck (1971). There may be others.

MESOZOIC DISSEMINATED COPPER DEPOSITS

JURASSIC(?) AND TRIASSIC(?)

WYOMING FOLD BELT

Copper deposits occur in the upper part of the Nugget Sandstone of Jurassic(?) and Triassic(?) age along much of the length of the southwestern Wyoming fold belt (fig. 6). Although mining was never systematically developed, at least several tens of thousands of tons of ore were shipped to smelters in Utah from the Griggs mine in the Lake Alice district, Lincoln County, Wyo., about 30 mi (48 km) north-northeast of Cokeville (Love and Antweiler, 1973). In their samples from the Griggs mine, Love and Antweiler (1973, p. 143) reported maximum values of 6.7 percent copper, 0.12 percent silver, and 3.2 percent zinc. Areas of copper minerals in Pennsylvanian and Triassic rocks of the fold belt were described in early reports (Veatch, 1907; Gale, 1910; Schultz, 1914), but the mineralization that occurred in the Nugget seems to be the most important. The Nugget Sandstone in this area consists of as much as 2,000 ft (600 m) of pink to white quartzose sandstone with very little matrix or cement except quartz overgrowths and a little kaolinite or calcite or dolomite. Most of the formation is crossbedded eolian sandstone that contains no fossils by which its age might be more precisely determined. Some of the upper part of the Nugget is horizontally bedded, suggesting aqueous reworking of the eolian sands, perhaps in a marine environment. The Nugget is overlain by the Gypsum Spring Member of the Twin Creek Limestone of Middle Jurassic age. The Gypsum Spring Member contains gypsum and anhydrite as well as dolomite and dolomitic siltstone (Love and Antweiler, 1973). Copper minerals occur in the upper 50 ft (15 m) of the Nugget at approximately the same stratigraphic position throughout the length of the fold belt (Love and Antweiler, 1973). About 23–24 mi (37–38.6 km) east of the Griggs mine, petroleum is produced from a fractured anticline in the Nugget at the Tip Top field, Sublette County, Wyo. (Wyoming Geological Association, 1957, p. 456–457). Samples of ore from the Griggs mine have dark-gray streaks that may represent petroleum residue (fig. 7). Thus, the copper mineralization may have followed some persistent feature such as a petroleum-water interface and the anomalously high metal contents were probably concentrated from the section of eolian sands and red beds of Jurassic and Triassic age in the area. Love and Antweiler (1973) also have pointed out the possible relation between the petroleum, the sulfate minerals of the overlying Gypsum Spring Member, and the copper mineralization.

FIGURE 6.—Areas of stratabound copper deposits in the Western United States in rocks of Mesozoic and Paleozoic ages.

TRIASSIC

CONNECTICUT VALLEY AND SOUTHEASTERN PENNSYLVANIA

The Connecticut Valley and southeastern Pennsylvania deposits of copper in arkosic sandstone and shale of the Newark Group and equivalent rocks of Triassic age have been locally mined since colonial times (Lewis, 1907; Wherry, 1908; Black, 1922; Bateman, 1923; Miller, 1924, p. 31–36; Stose, 1925; Cornwall, 1945). Some of these deposits appear to be diagenetic concentrations of disseminated copper similar to many of the deposits in nonmarine rocks of the southwestern United States. Other deposits in this area appear to be structurally controlled and genetically

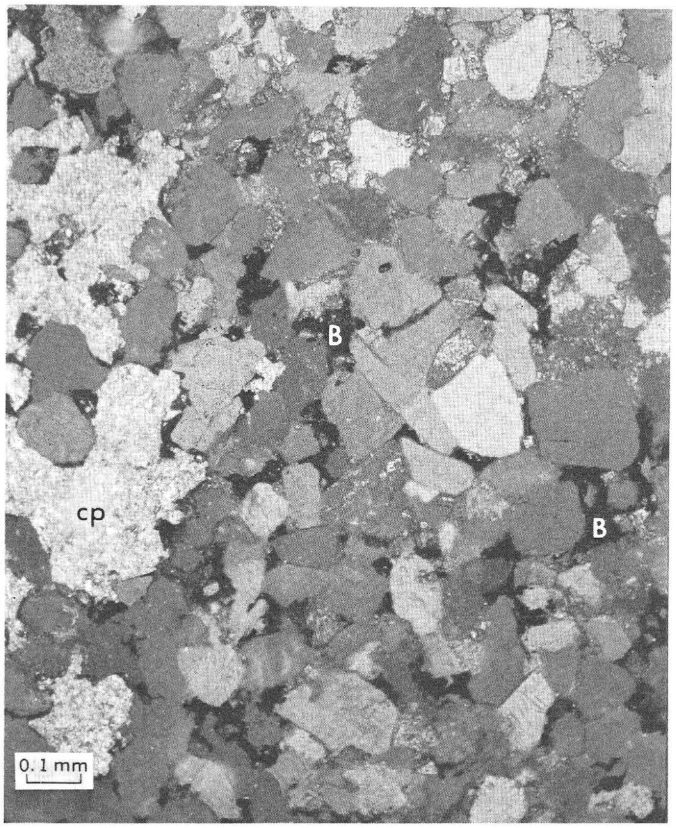


FIGURE 7.—Nugget Sandstone of Jurassic(?) and Triassic(?) age from Lincoln County, Wyo., showing chalcopyrite (cp) associated with bituminous material (B). Ore minerals may follow a fossil oil-water contact. Exposures by reflected light and by light transmitted through crossed polars; sample CU-28D.

associated with intrusive and extrusive basalt or diabase "trap rock." A map and list of 55 copper localities in southeastern Pennsylvania (Wherry, 1908) and a map of copper deposits in New Jersey (Lewis, 1907) show many deposits in a zone of low-grade metamorphism adjacent to the igneous rocks in which the sedimentary rocks are described as "baked." Other deposits, such as the Bristol mine in Connecticut as described by Bateman (1923), lie along the fault contact between Triassic sedimentary rocks and older crystalline rocks. Lewis (1907) saw both chalcopyrite and native copper in traprock and suggested that the igneous rocks were the source of the copper. In light of the modern hypotheses on the relationship between plate tectonics and metallogenic provinces (for instance, Guild, 1971, 1972a, 1973; Sillitoe, 1972a, b, c), rifting and separation of the North American plate from the European plate was accompanied by igneous activity that produced the traprock (Bird and Dewey, 1970); possibly associated volcanic exhalations formed hypogene copper deposits. Thus, the copper deposits in the Triassic basins of the eastern United States may be of different types—one type formed by ground-water concentration of disseminated copper, and one type formed by hypogene solutions comparable to the deposits now forming in the Red Sea area and in the Salton Sea-Gulf of California area.

NACIMIENTO, NEW MEXICO

In the southwestern United States, many copper deposits are found in nonmarine arkosic sandstone composed of debris shed from mountains uplifted in late Paleozoic and in early Tertiary time. (Soulé, 1956). A typical example, currently being mined, is the Nacimiento copper deposit near Cuba, N. Mex. (fig. 6) (Kaufman and others, 1972; Woodward and others, 1973, 1974). Scartaccini (1973, p. 52) reported that 11 million tons of ore assaying 0.65 percent copper had been developed for open-pit mining as of January 1973. Chalcocite, bornite, other copper minerals, and small amounts of native silver replace large fossil carbonaceous logs, as shown in figure 8, and are also disseminated through sandstone of the Agua Zarca Member of the Chinle Formation of Triassic age. The Agua Zarca is at the same stratigraphic horizon, at the base of the Chinle, as the uranium-rich conglomerate, the Shinarump Member in Utah. The Nacimiento ore body, as exposed by mining, lies at and above the water table on the west flank of the Nacimiento uplift. An erosional remnant of the Agua Zarca, consisting of sandstone that is bleached and altered to nearly pure quartz by weathering, forms Eureka Mesa. This remnant extends for several miles up the flank of the

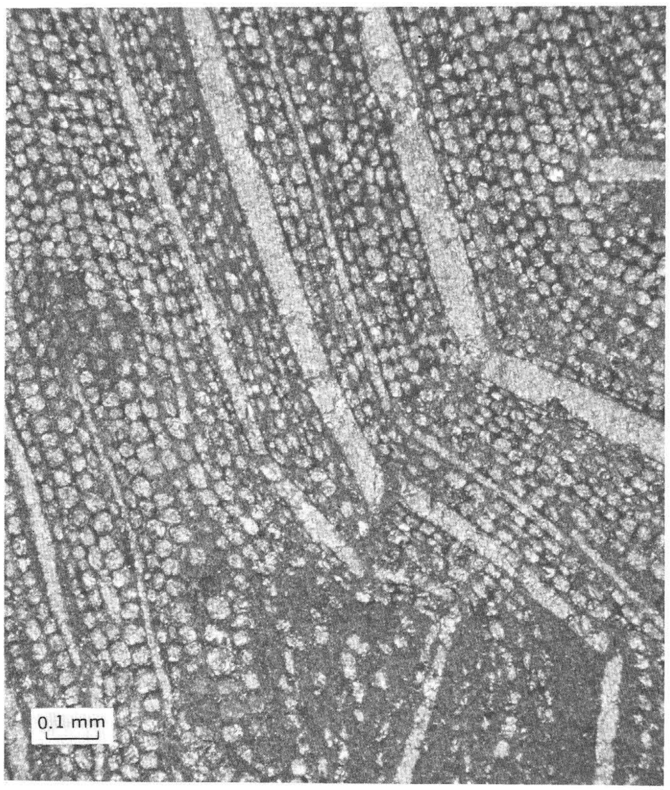


FIGURE 8.—Sulfide replacement of fossil wood from the Agua Zarca Member of the Chinle Formation, at the Nacimiento mine, Sandoval County, N. Mex. Reflected light; sample CU-10J.

mountain east of the mine. In this weathered sandstone, evidence of the former existence of fossil wood is found as empty molds, except for a few places along the cliff margin of the mesa where chalcocite-bearing fossil wood has been exposed in long-abandoned prospect pits. Small deposits of copper probably existed throughout the Agua Zarca before the area was eroded to its present level. Most of the copper present updip from the Nacimiento mine may have been flushed down to the mine area, which now represents part of a dynamic interface between oxidized and unoxidized sandstone, similar to the Wyoming roll-front type of uranium deposits. Moreover, the massive chalcocite replacements of fossil wood, as shown in figure 9, suggest a possible zone of supergene enrichment similar in occurrence and mode of origin to the zones of supergene enrichment associated with various hydrothermal porphyry, vein, and replacement deposits. At the Nacimiento mine, bleached and altered quartz sandstone overlies the main ore body. Similar bleached sandstone may overlie other ore bodies and might be an aid in prospecting.

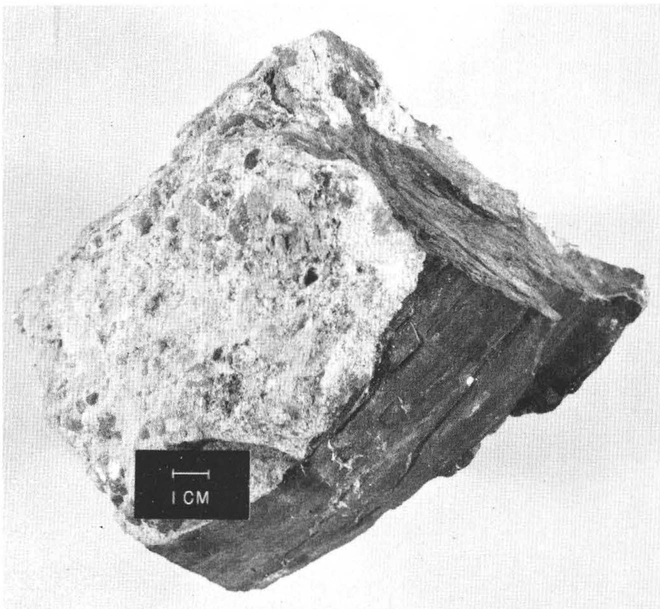


FIGURE 9.—Fossil wood replaced by massive chalcocite at the Nacimiento mine, Sandoval County, N. Mex. Massive replacement may be evidence of supergene enrichment near the water table. Sample provided through the courtesy of Lyle Talbott, Geologist, Earth Resources Co.

GUADALUPE COUNTY, NEW MEXICO

Near the town of Santa Rosa, Guadalupe County, N. Mex., a tributary of the Pecos River cuts through the copper-bearing Santa Rosa Sandstone of Late Triassic age and exposes a section of rocks of the Artesia Group of Guadalupian Permian age that includes a basal gypsum bed overlain by a fine-grained marine sandstone that has been mined for copper at the Pintada mine (fig. 6), as will be described later (p. C18). On the south side of the canyon, copper has been mined from fluvial deltaic sandstones of Late Triassic age at the Stauber mine (Harley, 1940; Holmquist, 1947; Soulé, 1956, p. 24–28). The Triasic deposit forms a tabular ore body about 1,500 by 320 ft (520 by 110 m) that C. B. Read, R. D. Sample, and J. S. Sheldon (written commun., 1943) described as a fossil sinkhole in the Triassic rocks, once the site of a bog containing abundant organic matter. They further suggested that the copper sulfides were precipitated from epigenetic copper-bearing solutions that flowed through the surrounding permeable sandstones. The Triassic deposit may also represent a syngenetic deposit formed in a manner similar to the formation of the copper-rich forest peat bog in New Brunswick, mentioned before (p. C4) and described by Fraser (1961a, b); this peat bog formed by ground water rising from the underlying copper-rich Permian rocks. The Permian marine rocks across the canyon contain irregular patches or streaks of chalcocite disseminated through the matrix of fine-grained sandstone or siltstone that contains very little organic matter and is cemented chiefly by gypsum and dolomite. Possibly the same solutions flowed through both deposits, but because the chemical environment of precipitation in each was different, the resulting deposits differ in general form and appearance.

PALEOZOIC DISSEMINATED COPPER DEPOSITS

Small (containing less than 10,000 tons) stratabound deposits of copper occur in sandstone and shale in nonmarine strata containing red beds in the Appalachian Plateau, the Appalachian fold belt, and the basins formed by Triassic block-faulting in the eastern United States (Kinkel and Peterson, 1962). Many old prospects in the Catskill Formation of Devonian age were examined during the search for uranium (McCauley, 1957; Klemic, 1962; Klemic and others, 1963), along with similar prospects in the Mauch Chunk Formation of Mississippian and Pennsylvanian age and the Pottsville Formation of Pennsylvanian age. None of the prospects were found to contain economically valuable amounts of either copper or uranium, but they do demonstrate the mobility of copper in the red-bed environment. In eastern Canada, copper deposits in rocks of Carboniferous age were mined locally in the late 19th century (Papenfus, 1931). Mineralization in the Pictou Formation of Late Pennsylvanian age occurs over an area of 500 mi^2 (1,300 km^2) in northern Nova Scotia. Although individual samples may contain as much as 67.7 percent copper (as logs replaced by chalcocite), not enough copper occurs in any one locality to make mining economical (Brummer, 1958). Figure 10 shows the general location of Paleozoic and Precambrian disseminated stratabound copper deposits.

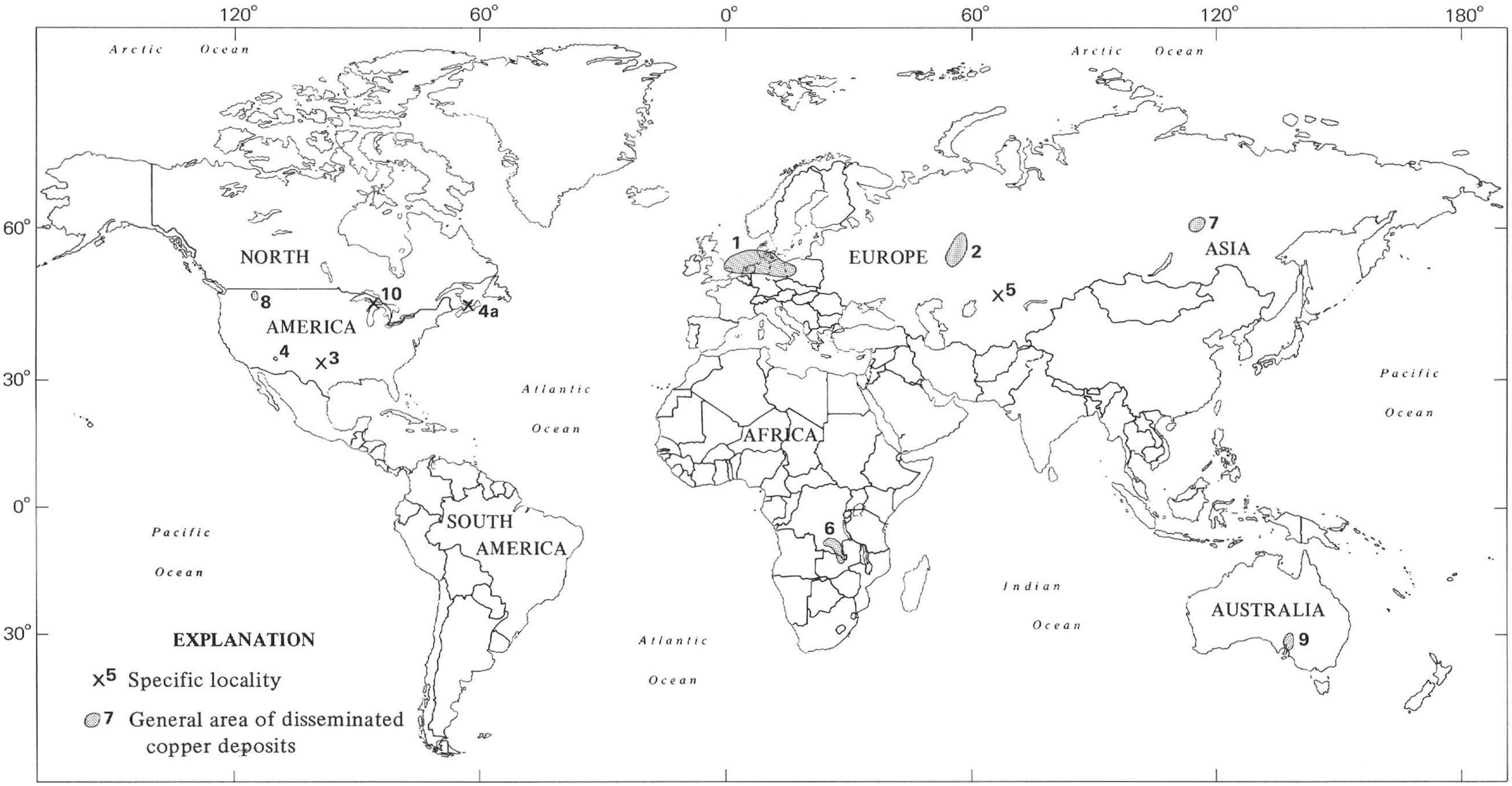


FIGURE 10.—Areas of disseminated copper deposits in rocks of Paleozoic and Precambrian ages. 1, Kupferschiefer, England through Poland. 2, West Ural foreland, U.S.S.R. 3, Creta, Okla. 4, Colorado Plateau. 4a, Northern Nova Scotia. 5, Dzhezkazgan, Kazakh S.S.R. 6, African Copperbelt, Zambia and Zaire. 7, Udokan, Siberia. 8, Belt deposits, Montana. 9, Adelaidean deposits, South Australia. 10, White Pine, Mich.

PERMIAN

KUPFERSCHIEFER, ENGLAND THROUGH POLAND

Probably the world's best known copper-rich shale is the Kupferschiefer of Late Permian age, which has been mined at Mansfeld, German Democratic Republic, for almost 1,000 years. The Kupferschiefer underlies an estimated area of 231,000 mi^2 (600,000 km^2) in Germany, Poland, Holland, and England (fig. 10). Copper concentrations greater than 0.3 percent occur in about 1 percent, and zinc concentrations greater than 0.3 percent in about 5 percent of this area. The productive mining areas account for 0.2 percent of the area and the mass of metals in areas of economic value is in the range of 30–300 million tons of copper and greater amounts of lead and zinc (data from Wedepohl, 1971). It also carries anomalously high amounts of many other metals (Harańczyk, 1964). In spite of the long-time knowledge of the Kupferschiefer, it was only during and after World War II that exploration in the Fore-Sudetian monocline of Lower Silesia (southwestern Poland) outlined copper deposits extensive enough to place Poland first in copper reserves in Europe (Krason, 1967; Harańczyk, 1970).

Many geologists regard the Kupferschiefer as the classic example of a syngenetic ore deposit. The most impressive argument for a syngenetic hypothesis is the persistence of this thin (1.6–3.3 ft (0.5–1 m), distinctive bed. Also, sulfur-, carbon-, and oxygen-isotope work (Marowsky, 1969) support a syngenetic hypothesis. The rock contains abundant organic matter, including fish remains, which gives it a characteristic dark-gray to black color. The copper and other metals are disseminated throughout the matrix of the rock as fine-grained sulfides (fig. 11). Some of the sulfides show a colloform morphology that has been compared to the framboidal texture of iron sulfides formed by bacterial action in modern anaerobic environments (Love, 1962; Temple, 1964). The Kupferschiefer is the first marine transgressive unit overlying the nonmarine Lower Permian Rotliegendes, a red sandstone sequence. The Kupferschiefer is overlain by the rest of the Zechstein sequence of marine evaporites, which includes halite and potash minerals. Friedman (1972) compared and contrasted the general environment of deposition of the Kupferschiefer and the Zechstein to the modern environment of the Red Sea, and Glennie (1972) compared the depositional environment of the Rotliegendes to modern coastal deserts. Both authors found many similarities. In southwestern Poland, the upper Rotliegendes began with a windswept desert surface (hammada) formed on an underlying metamorphic terrane. The hammada was followed by a pebble- and sand-strewn desert plain (serir) as the topographic hollows were filled (Krason, 1967, p. 144). Possibly the Kupferschiefer and evaporites of the Zechstein represent a tidal marsh (sabkha) environment which developed as the sea began to transgress over the desert sands (Friedman, 1972; Renfro, 1974).

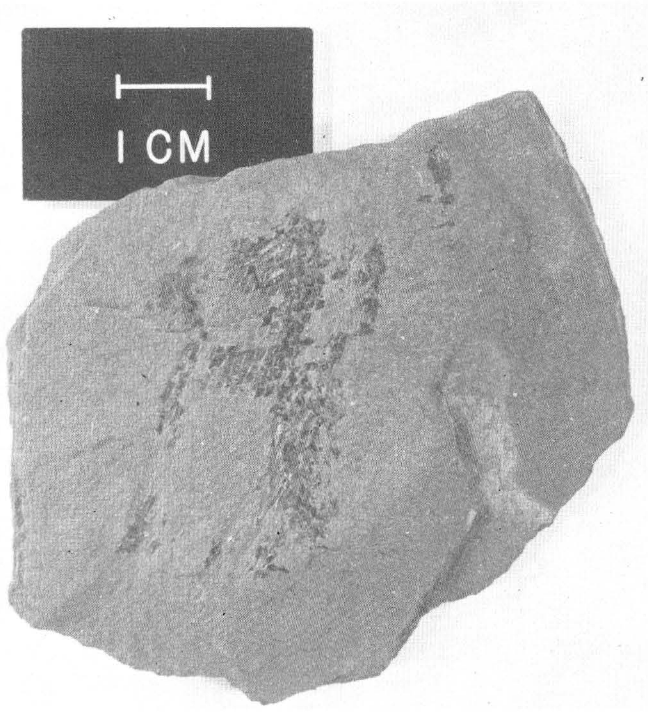


FIGURE 11.—Hand sample of the Kupferschiefer from Mansfeld, Germany, showing fossil fish remains. Ore minerals are too fine grained to be visible. Sample supplied through the courtesy of A.V. Heyl.

If the metals in the Kupferschiefer were deposited simultaneously with the enclosing sediment, several possible sources for the metals can be considered—the metals could have been derived from (1) upwelling nutrient-rich seawater (Brongersma-Sanders, 1968, 1969); (2) hydrothermal solutions that reached the surface of the Harz Mountains and drained into the sea (Ekiert, 1958); (3) erosion of older mineral deposits (Richter, 1941); (4) submarine metal-rich springs (Dunham, 1961, 1964; Hirst and Dunham, 1963); or (5) the underlying nonmarine red beds (Deans, 1950; Wedepohl, 1964, 1971; Lur'ye and Gablina, 1972; Renfro, 1974). In the Fore-Sudetian monocline of Poland, Harańczyk (1970) found copper-bearing shales separated from lead-bearing shales by a narrow zone of mineralized sandstone. He related the lead mineralization to a more restricted part of a lagoonal margin and the copper to lagoonal inflow and outflow areas. He, too, favored a syngenetic hypothesis and suggested that bacterial action was highest in the marginal parts of the lagoon. The vertical and horizontal zoning of the copper, lead, and zinc sulfides (Wedepohl, 1971) and the abnormally high contents of many other trace elements have also been used to support the syngenetic hypothesis. A group of Russian geologists who studied the Fore-Sudetian deposit (Narkelyun and others, 1970) emphasized the mineralization in sandstones underlying the copper-bearing shale and also in the overlying dolomite and anhydrite. They favored a sedimentary origin for the metals with postdepositional or diagenetic concentration. Oberc and Serkies (1968) also described the Fore-Sudetian as a diagenetically differentiated deposit. Davidson (1964, 1965) suggested that the metals were introduced into the Kupferschiefer from deep circulating brines derived from the overlying evaporite sequence (see also Ridge, 1968). Many of these hypotheses are equally attractive, and debate on the genesis of the ore deposits in the Kupferschiefer is sure to continue for many more years.

WEST URAL FORELAND, U.S.S.R.

In Late Permian time, the environment of the eastern part of the Russian platform (West Ural foreland) was very similar to that of the two Germanies and Poland where equivalent Zechstein sediments were being deposited. Three belts of copper deposits occur in the Russian Permian rocks (fig. 10). (The following description is from Lur'ye and Gablina (1972).) The trend of the copper mineralized zone is subparallel to the Ural Mountains. One belt, in the Perm region, is 280 mi (450 km) long and 75 mi (120 km) wide; the second is in the Orenburg region and is 370 by 62 mi (600 by 100 km); and the third, in the valley of the Zay River, is 250 by 50 mi (400 by 80 km). More than 7,500 mines were located on these deposits in the 18th and 19th centuries. Although the ages of the host rocks range through three stages of the Late Permian, most of the deposits are related to marine transgressions over continental sediments. Individual copper deposits are confined to a small stratigraphic range, but they are not confined to a single bed. Mineral zoning in these deposits is described as being similar to that in the Kupferschiefer and in the African Copperbelt. The major factor controlling mineralization appears to be the physiochemical conditions at the time of deposition—not lithology. The copper deposits occur at a sharp boundary between oxidizing and reducing conditions, but not where either reducing or oxidizing conditions lasted for a long time. Lur'ye and Gablina (1972) suggested that the copper was originally eroded from massive sulfide deposits in the Urals and deposited in the continental red-bed sediments. Then ground water flowing through the continental sediments concentrated the copper which was precipitated from ground-water springs as they discharged into reducing areas of the sea following marine transgression. The same explanation can account for the areal and vertical zonation of the ore minerals. Some copper deposits are found in ancient river channels, and the more porous sediments of the channels may have been ground-water channels after burial (Lur'ye and Gablina, 1972).

CRETA, OKLAHOMA

The descriptions of the copper mineralization in the Permian rocks of Europe indicate similarities between those rocks and the Permian rocks of Oklahoma, Texas, and Kansas. Both areas have red-bed sequences that include evaporites and transgressive marine shales. The paleoenvironment appears to have been similar. A thorough study of the Russian literature might provide valuable concepts for exploration and development of copper deposits in marine and deltaic rocks in the United States. Krason (1974) has also pointed out the similarities between the setting of the Kupferschiefer and that of some of the Permian of the south-central United States. While none of the deposits in the Permian of the United States, with the exception of Creta, Okla., have proven to be economic, we will describe some areas of copper deposits, as their geology may reveal some modes of origin and suggest localities where larger deposits might be looked for.

Several examples of copper deposits in marine sandstone and shale occur in Permian strata of northeastern New Mexico, northern Texas, and southwestern Oklahoma (fig. 6). Copper deposits in the Flowerpot Shale near Creta and Mangum, Okla., south and west of the Wichita Mountains granitic uplift, are currently being mined or explored. The following discussion is taken from reports by Ham and Johnson (Ham and Johnson, 1964; Johnson and Ham, 1972) and from conversations with D. C. Brockie, Chief Geologist for Eagle-Picher Industries, Inc. (oral commun., 1973). The copper mineralization has occurred in two greenish-gray silty shale beds in the upper part of the Flowerpot Shale. Individual mineralization areas in the Creta area cover several tens of square miles. The main ore bed ranges in thickness from 6 to 18 in (15–46 cm) and lies about 10 ft (3 m) below the Kiser Dolomite Bed of the Flowerpot. A similar 4-inch-thick (10 cm) bed occurs about 5 ft (1.5 m) below the Kiser but cannot be mined economically. As mined, the main bed has an average thickness of about 7 in (18 cm) and an average grade of about 2.3 percent (Johnson, 1974). No zonation of the sulfide minerals has yet been reported in detail. Chalcocite is the most important ore mineral (Gann and Hagni, 1974; Kidwell and Bower, 1974). It occurs as octahedral crystals 1–25 microns in diameter, in pellets and aggregates as much as 200 microns in diameter, and as fillings in pore spaces in sandy laminae (Kidwell and Bower, 1974). Chalcopyrite occurs in the shales overlying the richest chalcocite. Pyrite is the next most abundant sulfide after chalcocite (Gann and Hagni, 1974). Malachite occurs as a weathering product of the copper sulfides. Detailed study by Kidwell and Bower (1974, p. 110) with a scanning electron microscope indicated that "* * * most of the chalcocite is an early replacement of syngenetic pyrite." Thus, copper-bearing solutions flowed through the ore beds after the formation of pyrite, and these deposits could be termed "diplogenetic." Where exposed by mining, the ore bed is overlain by a bed of gypsum that facilitates selective removal of the overburden. The ore is underlain by barren gray clay that looks like the ore, but lacks chalcocite. The Permian rocks exposed in the area are dominated by reddish-brown siltstone having thin interbeds of light-gray to white gypsum, dolomite, and clay beds. No coarsening of the sediments or thickening of the beds is evident as they approach the overlap onto the granitic knobs of the Wichita Mountains, although the mountains must have contributed debris at least locally in Permian time. Most of the sediments appear to be tidal-flat muds or very shallow water marine deposits. Smith (1974) decided that the equivalent Flowerpot in northern Texas had been deposited in a sabkha environment.

North of the Wichita Mountains, the Flowerpot Shale is locally more than 400 ft (122 m) thick (MacLachlan, 1967, p. 88–89) and consists of red-brown mudstone with gray-green spots and interbedded gypsum, especially near the top of the formation. The Flowerpot also contains some thin bands of gray shaly mudstone and some very fine grained sandstone. It is underlain by evaporites, including anhydrite and salt in the Wellington Formation, and red mudstone, gypsum, and arkosic sandstone in the Hennessey Shale. The Flowerpot is conformably overlain by the Blaine Gypsum, which is locally more than 200 ft (60 m) thick. All these units were assigned to interval B of the Permian by MacLachlan (1967, p. 88–89).

GARVIN COUNTY, OKLAHOMA

South and east of the Wichita Mountains, the Garber Sandstone occurs between the Wellington Formation and the Hennessey Shale. The Garber Sandstone is a coarse-grained red sandstone and sandy mudstone that becomes coarser grained eastward and may be as much as 400 ft (122 m) thick. Copper deposits occur in this sandstone, especially at a locality about 6 mi (9.6 km) north of Pauls Valley (Stroud and others, 1970, p. 13). Pauls Valley is north of the Wichita-Arbuckle Mountain uplift in which a granitic core was exposed in Permian time. The granitic core contributed feldspathic debris to a delta. The high copper values, as much as several percent, are in greenish-gray beds of fine-grained quartzose sandstone that are overlain by dolomite or ankerite-cemented sandstone (fig. 12). Other beds in the sequence contain more feldspar, especially plagioclase, and more clay minerals, suggesting a possible difference in permeability and diagenetic alteration from the ore beds. Silver accompanies the copper, and reaches a maximum content of several hundredths of a percent at the base of the copper-bearing bed that overlies a red mudstone. In thin sections, quartz grains are seen to be locally corroded and partly replaced by chalcocite and authigenic carbonates. This suggests an epigenetic or diagenetic origin for the mineralization. These deposits are stratabound, and although none have proved to be economic so far, there may be possibilities for future development of deposits in this area.

GUADALUPE COUNTY, NEW MEXICO

Copper deposits similar to those in the Flowerpot Shale in Oklahoma occur in the Artesia Group of Permian age

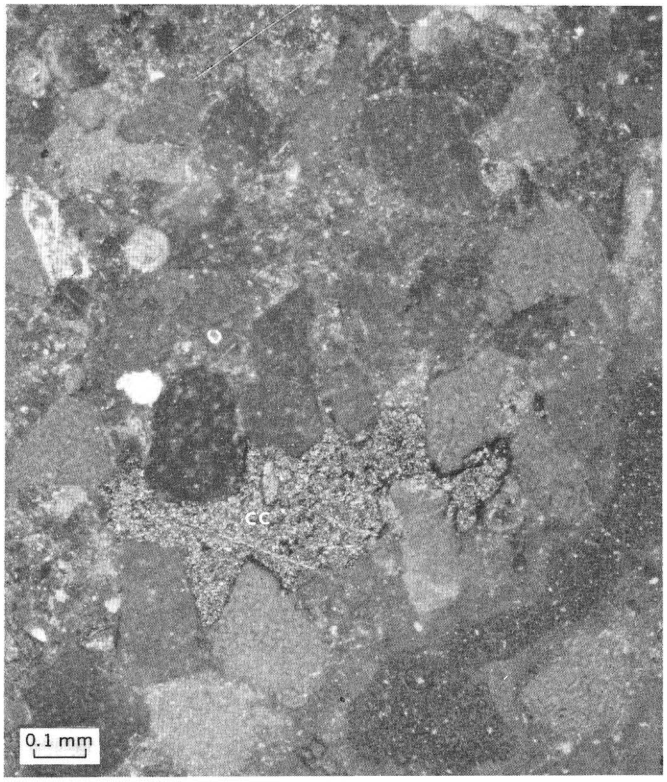


FIGURE 12.—Chalcocite bleb (CC) in carbonate-cemented Garber Sandstone of Permian age, Garvin County, Okla. Exposures by reflected light and by light transmitted through crossed polars; sample WRM-73.

in northeastern New Mexico, near the town of Santa Rosa, Guadalupe County (Kelley, 1972). The copper at the Pintada mine (Sandusky and Kaufman, 1972), across the canyon from the Stauber mine described previously (p. C14), occurs as irregular patches and streaks of chalcocite disseminated through a matrix of fine-grained greenish-gray sandstone otherwise cemented with gypsum and dolomite. Only minor amounts of carbonaceous matter and clay minerals are present. The deposit is confined to a section about 10 ft (3 m) thick, but the distribution of copper within this interval is erratic, ranging from a few parts per million to 10 percent in hand samples that look similar (fig. 13).

Copper in the Flowerpot Shale of Oklahoma and in the Artesia Group of New Mexico may have had similar origins. In both areas, the copper deposits are associated with rocks containing evaporites, including halite (see McKee and others, 1967, pl. 19). Therefore, copper could have been introduced into the rocks diagenetically by chloride brine shortly after deposition. The copper in both formations occurs in greenish-gray beds that are interbedded with barren reddish-brown mudstones, implying that copper mineralization occurred only where the rock was in a reduced state. Perhaps syngenetic pyrite was diagenetically replaced by copper sulfide.

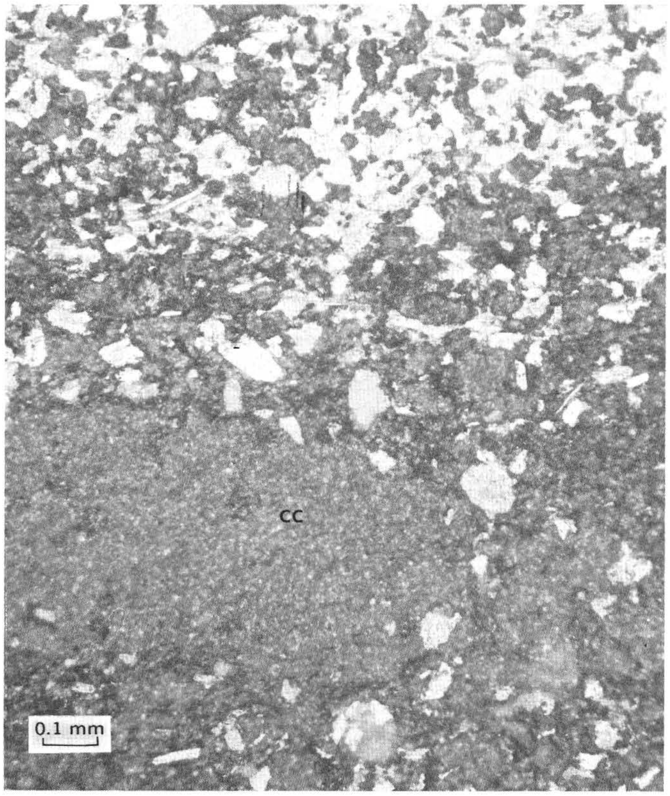


FIGURE 13.—Chalcocite disseminated in arkosic siltstone from the Artesia Group of marine Permian rocks near Santa Rosa, N. Mex. Locally the chalcocite (CC) has replaced parts of the framework grains. Exposures by reflected light and by light transmitted through crossed polars; sample CU-5D.

SOUTHERN COLORADO AND NORTHERN NEW MEXICO

Isolated lenses and nodules of copper minerals in association with uranium and other metals are characteristic of the Sangre de Cristo Formation of Pennsylvanian and Permian age in southern Colorado and northern New Mexico (Tschanz and others, 1958). Equivalent rocks in the subsurface of Texas are reported to contain nodules of metal-rich asphaltite that may be the source for helium in the Panhandle gas field of Texas (Pierce and others, 1964, p. G40–G46). These and similar small deposits may be comparable to the Colorado Plateau type of uranium deposit described by Fischer (1970).

CARBONIFEROUS

DZHEZKAZGAN, KAZAKH S.S.R.

Upper Paleozoic rocks in Kazakhstan in the southern U.S.S.R. (fig. 10) contain large stratiform copper deposits in the Dzhezkazgan area (Davidson, 1962; Druzhinin, 1973; also, written commun., 1967). The copper-bearing rocks of this area range in age from Devonian to Permian, but the most important deposits are in rocks of Carboniferous age. Popov (1959) noted that at least nine beds of commercial ore occur in the Variscan (late Paleozoic) fold belt, and possibly as many as 27 different zones of mineralized rock occur within 2,300 ft (700 m) of strata. Sutulov (1973, p. 138) estimated that Dzhezkazgan has the potential of producing 200,000–300,000 tons of copper per year. The ore beds are greenish gray, whereas the bulk of the strata is red or reddish brown. The ore occurs in elongated zones which form multistaged en echelon bodies. Although copper is the principal product, lead and zinc are produced locally as byproducts. Popov (1959) related the distribution of ore to portions of the deltaic sequence where freshwater mixed with saltwater, but also noted the association of ore with carbonaceous matter, salt, and gypsum. Druzhinin (1973), who studied the Dzhezkazgan deposits in great detail, stated that the copper was deposited in the nearshore part of an inland sea in an arid climate. The beds containing copper mineralization are generally found in sandy to conglomeratic sediments deposited in the subaqueous part of the delta of a postulated major river draining into a restricted gulf. The mineralization is further related to regressive facies in a series of oscillations of sea level in Carboniferous time. Druzhinin (1973) compared the Dzhezkazgan copper deposits to those at Roan-Antelope in the African Copperbelt and suggested that only minor diagenetic redistribution and concentration occurred after deposition and that the beds were soon "sealed" with diagenetic calcite. Acid volcanic detritus is found in the ore-bearing section, but is not regarded as a source of the ore minerals. Germanov, Panteleyev, and Golubovich (1970) suggested an association between ore and hydrocarbons or soluble organic matter, and they noted that some deposits are surrounded by a halo of ground water containing copper-bearing soluble organic matter—a point that may be useful in exploration, but that may not clearly be related to the origin of the deposits. Vol'fson and Arkhangel'skaya (1972), in a review article on copper-bearing sandstone deposits, refuted the syngenetic hypothesis for Dzhezkazgan and supported a hydrothermal-epigenetic origin, suggesting that the ore-bearing fluids came up along deep faults related to block-faulting in the area.

At the time that the ore-bearing strata were being deposited in Kazakhstan, Russia and Siberia may have been two separate continents (Hamilton, 1970). Moreover, the copper-bearing rocks are close to structures and facies classed by K. A. W. Crook (oral commun., 1973) as the "Pacific" type geosyncline, meaning that the rocks are graywackes and arkoses composed of much volcanogenic material; they contain abundant reactive minerals and not much quartz. Together, these various observations may suggest a plate-boundary type of depositional environment.

PRECAMBRIAN DISSEMINATED COPPER DEPOSITS

AFRICAN COPPERBELT, ZAMBIA AND ZAIRE

The African Copperbelt in Zambia and Zaire (fig. 10) produces nearly 20 percent of the world's copper. In 1970, Zambia produced 686,000 tons of copper; the average grade of ore mined was 3.8 percent, and the estimated commercial reserves were 27.2 million tons of copper. Zaire, in 1970, produced 386,000 tons of copper; the average grade of ore mined was 4.2 percent copper and cobalt, and estimated commercial reserves were 18.1 million tons of copper (de Vletter, 1972, p. 253). Almost all of the more than 1 million tons of copper mined in 1970 was derived from sedimentary rocks.

The host rocks for the copper deposits in the African Copperbelt are Precambrian sedimentary rocks—older than 840±40 m.y. and younger than 1,300±40 m.y. (Drysdall and others, 1972)—that have been folded and slightly to moderately metamorphosed. The primary control of mineralization appears to be stratigraphic, not structural or lithologic, although the control has been debated since modern exploration and mining began in the 1920's. The principal evidence for a syngenetic origin of the copper is given by Garlick (1961) and by Mendelsohn (1961), with more evidence and explanation presented in Garlick's later papers (Garlick, 1963, 1964, 1969; Garlick and Fleischer, 1972). A preview of Garlick's ideas was presented by Davis (1954). Malan (1964) described primary sedimentary control of the mineralization associated with algal stromatolites, and Binda (1972) applied palynological methods to identify microfossils associated with the ore minerals. Voet and Freeman (1972) attempted to relate copper mineralization in the basal arenaceous members of the ore zone to lode deposits in paleoridges of older gneiss and schist, whereas Vink (1972) explained sulfide mineral zoning in terms of changing environments of deposition in shallow-water saline basins. Local redistribution of elements caused by regional metamorphism has been described by Jolly (1972). Dechow and Jensen (1965) found that regional metamorphism had also affected sulfur isotopes and so sulfur isotope studies did not clearly confirm either a biogenetic or a magmatic source for the sulfur in the ore deposits, although they tended to suggest the biogenetic.

Many of the copper deposits of the area occur in the lowest marine (or aqueous) transgressive unit; this unit overlies nonmarine, locally eolian, detritus derived from an older crystalline terrane of considerable relief consisting of granite, gneiss, and schist. In the copper deposits, the sulfide minerals show a consistent zonal pattern with respect to the strandline but the pattern is independent of lithologic changes. Garlick and Fleischer (1972, p. 283) proposed a paleogeographic setting where barren rock was present adjacent to the strandline near a highland of older rock from which streams delivered copper, cobalt, iron, and other metals. The barren zone represents the area covered by a surface layer of oxygenated water. Seaward, copper is the first element to be precipitated in the anoxic deeper water, followed by increasing amounts of iron to produce the following sequence—chalcocite, bornite, chalcopyrite, and pyrite.

In contrast, from a detailed sedimentological study of the Lower Roan sediments at Mufulira, Zambia, van Eden (1974) proposed that the crossbedded sandstones underlying the main ore-bearing beds are not of eolian origin, but were deposited in a subaqueous environment. He suggested a combination of syngenetic and diagenetic processes as having formed the Copperbelt deposits. Much of the ore occurs in fine-grained argillaceous wackes and carbonaceous wackes that were deposited in marine nearshore basins, protected from the open sea by shoals formed by hills in the basement. Restricted circulation may have produced an euxinic environment causing syngenetic precipitation of sulfides. Ore also occurs in the clean crossbedded underlying sandstones and its deposition may be related to their permeability. Van Eden suggested that the syngenetic deposits were enriched by early diagenetic processes, and that reducing pore waters were forced into the underlying sandstones during burial. The cleaner sandstones allowed circulation of ground water, and the finer grained sediments containing organic carbon had the high reducing environment necessary for precipitation of sulfides.

At Chibuluma, Zambia, layers consisting of as much as 80 percent cobaltiferous pyrite occur in sharp contact with the underlying almost barren rock (Garlick and Fleischer, 1972, p. 289). The massive sulfide tends to fill in scours and potholes in the underlying rock. Upwards, the massive sulfide grades into quartzite arenite (or albitized arkose) cemented by a felty matrix of tiny tourmaline crystals and containing chalcopyrite. In some areas, the quartzite arenite below the massive sulfide is also cemented by a dusting of tiny tourmaline grains, and potassium feldspar grains have been albitized. Garlick and Fleischer (1972, p. 291) suggested that boron-rich saline waters flowed over the scoured surfaces and that iron, cobalt, and, later, copper were precipitated out. Sun-cracked mud layers thought to represent an extension of the scoured surfaces suggest a playa environment. Periodic flooding could have washed accumulated metal salts into the nearest standing body of water. Elsewhere, Garlick (1969, p. 121–123) described sulfide-armored argillite slabs and mudcracks which are evidence of subaerial drying. This evidence, plus the presence of anhydrite lenses in barren argillite and the identification of algal structures, prompted Renfro (1973, 1974) to propose a sabkha-environment hypothesis to explain the origin of some copper deposits.

Comparison of the sedimentary associations of the copper deposits in the African Copperbelt rocks of Precambrian Y age with those of the Kupferschiefer of Permian age reveals similarities that may pertain to the origin of many sedimentary copper deposits. Both deposits have lateral stratigraphic persistence involving copper-bearing rocks of several lithologic types, and a zonal arrangement of ore minerals that locally parallels individual lithologic facies but may crosscut on a regional scale. Both deposits occur in basal marine (or lacustrine) strata which contain evidence of fossil organisms and overlie arkosic or feldspathic sandstones deposited in a desert environment. In turn they are overlain by a carbonate or a carbonate-evaporite sequence. Both deposits are worked primarily for copper but contain anomalous to ore-grade concentrations of other metals. Sulfur-isotope studies and the framboidal forms of pyrite in these deposits suggest that the iron sulfides in these deposits are syngenetic—further, the isotope studies suggest, although they do not absolutely prove, that most of the sulfur in these deposits is of biogenetic origin. These two deposits as well as many others, such as the Flowerpot Shale of Oklahoma and Texas (Smith, 1974; Renfro, 1974), may have been deposited in what is now referred to as a sabkha-type environment.

UDOKAN, SIBERIA

One of the largest copper deposits in the world (Shank, 1972) is at Udokan, a remote area in eastern Siberia (approximately 57° N., 117° E.) (fig. 10). Although not yet fully developed due to its remoteness and rigorous climate, Udokan has a potential of 300,000–400,000 tons of copper per year (Sutulov, 1973, p. 143). The principal ore zone is in the upper part of the 33,000–39,000-ft-thick (10,000–12,000 m) Udokansk Series (Group), which is composed of slightly metamorphosed fine- to medium-grained gray to pink quartzo-feldspathic sandstone (The description of the Udokan deposit is summarized from Bakun and others (1964). Cox and others (1973, p. 175) suggested a Precambrian X age for the Udokansk Series, but they indicated that the designation is uncertain. Both the ore and adjacent barren sandstones contain 42–60 percent quartz, 20–30 percent feldspar, 5–10 percent microquartzite, and 1–10 percent hematite, magnetite, tourmaline, zircon, rutile, apatite, sillimanite, epidote, and other accessory minerals in the quartz-sericite cement. The ore-bearing zone is as much as 1,000 ft (300 m) thick and its top lies about 820 ft (250 m) below the top of the Sakukansk Suite (Formation). This zone has been mapped continuously along the Namingsk syncline, a large fold locally overturned. Data from drill holes show that the ore continues across the fold—the mineralized zone is apparently independent of structure and lithology, but is related to stratigraphy. Other mineralized zones occur in the Chitkandansk, Aleksandrovsk, Butunsk, and Namingsk Suites, all in the upper part of the Udokansk Series. The grade of ore appears to be related to several recognized facies of the deltaic sequences. Ore is in the marginal part of the subaerial delta of the principal river channel in the upper part of the deltaic succession. Diffuse copper minerals are associated with shallow-water littoral and beach sands, which are composed of well-sorted and rounded grains. One copper-bearing siltstone is associated with laminated silt and clay in which shrinkage cracks indicate a desiccating basin. The different sedimentary facies are characterized by different sulfide-mineral facies. High-energy fluvial crossbedded sandstone and conglomerate contain pyrite-chalcopyrite and bornite-chalcopyrite, whereas low-energy fluvial fine-grained sandstone and tidal lacustrine facies contain bornite-chalcocite and chalcocite. Some primary sedimentary structures are outlined, preserved, or emphasized by copper sulfides. Younger igneous rocks appear to have no relation to the ore, and most of the evidence strongly suggests a syngenetic or early diagenetic origin for the copper. Geochemical and sedimentary features suggest that the Archean rocks of the Aldan shield area to the northeast are a probable source for the sediments and minor elements, which include small amounts of lead, zinc, silver, molybdenum, and vanadium in addition to the copper.

NORTHWESTERN MONTANA

Major stratabound deposits of copper occur in rocks of the Belt Supergroup of Precambrian Y age in northwestern Montana (fig. 10). The geologic, mineralogic, and geochemical backgrounds of these rocks have been described by Harrison and Grimes (1970), Harrison and Hamilton (1971), and Harrison (1972). Although the copper deposits have only recently been explored, they are briefly described by Trammell (1970) and A. L. Clark (1971). J. D. Vine visited the area briefly in 1972 with Allan Griggs, Jack Harrison, and John Wells; each man showed the parts of the area with which he was familiar. Preliminary evidence indicates important similarities to as well as possible differences from the deposits in Udokan and the African Copperbelt just described. Because the deposits in northwestern Montana are still being explored and development is only beginning, they are not well known or understood. The copper ore appears to be unrelated to local structural features, igneous rocks, or alteration of host rocks, and the primary control may be stratigraphic. Anomalous concentrations of copper occur at many places in the Belt rocks, but concentrations of probable economic value are limited to the Revett Formation and equivalent units, and are characteristically confined to coarser grained quartzites and siltites—lithologies possibly comparable to the quartzo-feldspathic sandstones of Udokan or the quartzite arenite containing albitized feldspar in the African Copperbelt. Copper sulfides occur as disseminations, blebs, and bedding-plane concentrations, and locally as crosscutting veinlets (Allan Griggs, oral commun., 1972). The principal sulfide minerals are chalcocite, bornite, chalcopyrite, and pyrite. Whether they occur in zones related to primary sedimentary facies as in the African Copperbelt or whether they are related to some other features are questions as yet unanswered. Harrison (1972) has suggested that the principal mineralized area, centered on Spar Lake, is related to a post-Revett Precambrian structural high. Like the rocks in the Udokansk Series, rocks in the Belt

Supergroup are predominantly fine- to medium-grained clastic rocks interbedded with some argillites and carbonates. Abundant evidence such as shrinkage cracks, algal structures, and ripple marks suggest deposition in shallow-water to subaerial environments. The entire supergroup, as much as 67,000 ft (20,000 m) thick, has been slightly metamorphosed and so many of the original detrital grains are altered in shape or composition. Quartz and feldspar grains tend to be interlocked and the matrix minerals are probably mostly authigenic (fig. 14). Copper sulfides are locally associated with anomalous amounts of silver and molybdenum and possibly barium, zirconium, and boron. Concentrations of lead and zinc have also been identified locally, but generally not in association with the copper

The mineralized Belt rocks are in a mountainous terrain of 3,000- to 4,000-ft (900- to 1,200-m) relief that has commercially valuable stands of timber on the lower slopes. Good exposures of bedrock are rare and secondary copper minerals are not visible on rock surfaces. Within the zone of mineralized Belt strata, a rock may vary from a yellowish-gray weathered surface showing no copper to greenish-gray fresh rock containing several percent copper within a few inches or centimetres (fig. 15). The copper occurs in small sulfide grains that are disseminated throughout the rock and which may not be immediately recognizable as ore minerals in hand specimen. Even areas uncovered by prospecting do not show a conspicuous copper bloom. For this reason, the most successful exploration is by geochemical techniques—that is, analysis of soil samples collected along traverses perpendicular to the strike of beds likely to contain copper.

Speculation on the origin of the copper deposits in the Belt Supergroup is presently curtailed by insufficiently detailed knowledge of many aspects of the Belt. However, the small grain size and the disseminated character of the sulfide minerals suggest that they were formed before metamorphism so reduced the porosity of the rocks that fluids could not migrate freely through interstitial pores. Otherwise, the amount of ore in structures such as veins would far exceed the amount disseminated through the rocks, and the disseminated sulfides should show more relationship to structure—if they had been introduced late in the history of the rocks, the sulfides would not have had such a large areal extent. Lack of lithologic control by a chemically distinct rock type, such as a black shale, reduces the credibility of a syngenetic hypothesis, although the copper may prove to be related to facies similar to relationships suggested for the Udokansk Series. The ore in the Belt rocks is generally found in the coarser

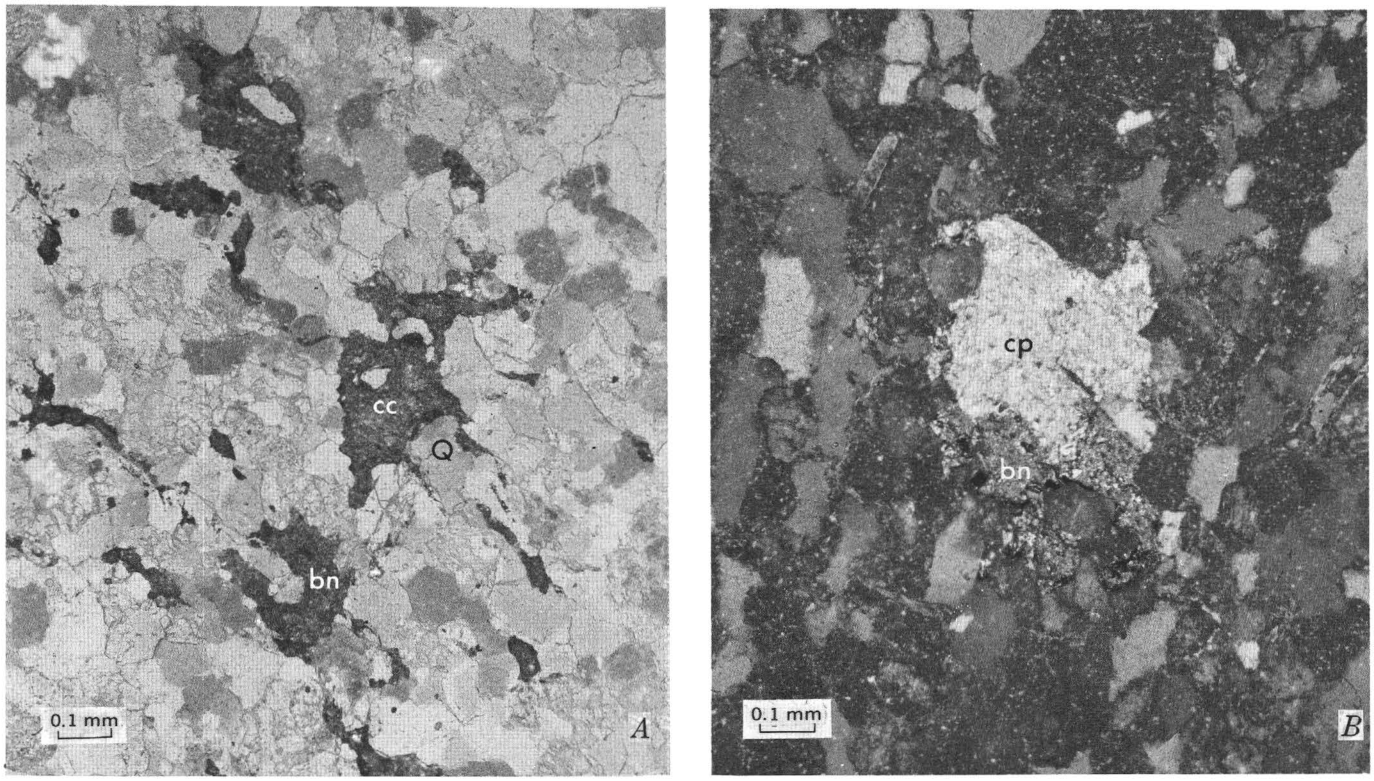


FIGURE 14.—Quartzite from the Revett Formation, Sanders County, Mont. Exposures by reflected light and by light transmitted through crossed polars. *A*, Chalcocite (cc) and bornite (bn) interlocked with quartz (Q) and feldspar grains; the relation between sulfide and framework grains probably is a result of low-grade metamorphism. Sample CU-32C; Beecher Peak area. *B*, Chalcopyrite (cp) and bornite (bn) in a feldspathic matrix; a sericite seam loops through part of the sulfide. Sample CU-31B; Sex Ridge area.

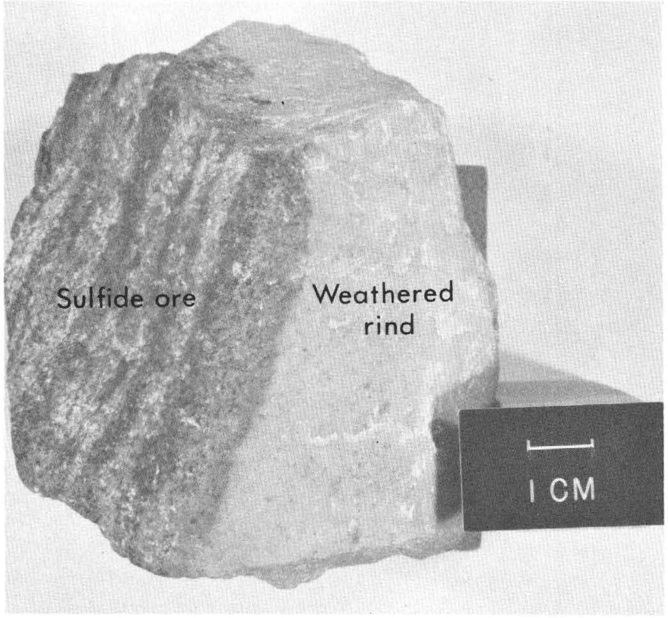


FIGURE 15.—Hand sample of quartzite from the Revett Formation showing weathered rind (without secondary copper minerals) and rich sulfide ore a few centimetres below the surface. Sample provided through the courtesy of J. E. Harrison.

grained beds, which suggests possible postdepositional redistribution of the copper. The concept of an ore fluid derived from water of compaction (Noble, 1963) may be the most tenable hypothesis for the Belt Supergroup. The Belt deposits could be diplogenetic, the copper having been brought in by circulating saline brines, but until detailed investigations of mineralogy, isotope compositions, and many other factors have been completed, we cannot dogmatically support any one theory of genesis.

SOUTH AUSTRALIA

Copper minerals occur throughout the Adelaidean System in South Australia, and Rowlands (1973) suggested that these rocks are similar in many other respects to the Belt Supergroup of Montana. The system consists of predominantly lagoonal and marginal-marine to marine sediments deposited in a shallow intracratonic epeiric basin between 1,400 and 600 m.y. ago (Rowlands, 1973). The rocks are relatively unmetamorphosed, but in places they have been weathered to depths of 660 ft (200 m) during the period of peneplanation in the late Tertiary-Quaternary. Much of the information about the rocks and mineralization has been obtained from drill cores. The rocks are varicolored but copper occurs only in green, gray, or black rocks. The most extensive copper mineralization is in the lower Willouran Series, the lowest series of the Adelaidean System. By analogy with the African Copperbelt, exploration for mineralized rock in the Adelaidean has been guided by the concept that the ore occurs directly seaward from paleostrandlines (Nigel Rowlands, oral commun., 1974). As reported by Rowlands (1973, p. 103): "Host rocks in the mineralized Willouran sediments are dolosiltites, carbonaceous dolosiltites, carbonaceous doloarenites, volcaniclastic arenites, and carbonaceous silty dolomites (some algal) * * *. The bulk of the primary copper mineralization * * * has been in medium to fine grained doloarenites." Pyrite and chalcopyrite are the primary sulfide minerals. Most commonly the chalcopyrite occurs as fine disseminated grains that are difficult to see with the naked eye (fig. 16). Chalcopyrite also occurs as coarsely recrystallized (as much as 2 mm) grains in quartz-carbonate veins (fig. 16). Except for the veins, which are diagenetic, Rowlands (1973, p. 105) stated that: "* * * bedding exercises a striking and precise control on sulphide distribution," and "The intimate association of sulphides with sedimentation processes leads me to conclude that the copper mineralization is a syn-sedimentary phenomenon."

WHITE PINE, MICHIGAN

A different type of copper deposit in marine rocks is found in the Precambrian strata at White Pine on the Keweenaw Peninsula of northern Michigan (fig. 10). This district supplies about 5 percent of the copper mined in the United States. The ore grade is about 1.2 percent copper as

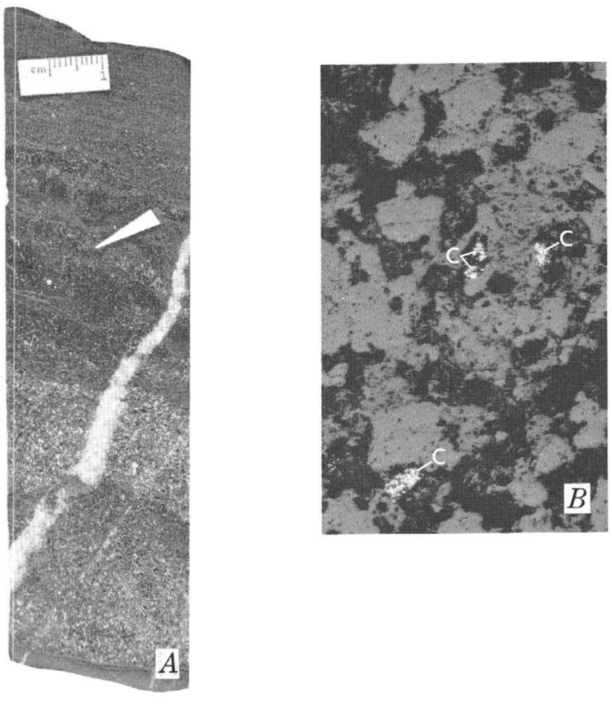


FIGURE 16.—Cupriferous drill core of Upper Callanna Beds of Precambrian age from South Flinders Range, South Australia. Specimen supplied by Nigel Rowlands of the Utah Development Company. *A*, Diagenetic calcite vein cuts the core; an arrow points to the spot where the photomicrograph was taken. *B*, Photomicrograph shows chalcopyrite (C) grains disseminated through fine-grained carbonaceous host rock.

chalcocite and native copper (Ensign and others, 1968). Both copper sulfide and native copper occur in the Nonesuch Shale, a dark-gray to black, laminated to massive shale and siltstone (fig. 17), deposited about 1 billion years ago (Barghoorn and others, 1965) in a shallow-water environment, perhaps lagoonal, and presumedly marine. Thoughts on the genesis of these copper deposits have evolved through a long series of papers (White, 1953, 1960, 1968, 1971, 1972; White and Wright, 1954, 1960, 1966; Sales, 1959; Ensign and others, 1968; S. K. Hamilton, 1969; Brown, 1970, 1971; Burnie and others, 1972; Wiese, 1973). The original White Pine mine was located along the White Pine fault and produced copper from both the Nonesuch Shale and the underlying Copper Harbor Conglomerate (fig. 18). At first, because the mine was on a structural feature, the operators assumed that the ore was epigenetic and was related to hydrothermal solutions rising along the fault. The discovery that the ore persisted along the base of the Nonesuch over many tens of square miles led to a concept of a syngenetic origin for the core and expanded known reserves immensely. Further study showed that ore locally cut across bedding and led to a more sophisticated concept of genesis—that copper-bearing solutions circulated through the shale that contained syngenetic pyrite and that the copper replaced the iron. Possibly the copper-bearing solutions arose from the Portage Lake Volcanics, which underlie the Copper Harbor Conglomerate and contain native copper deposits associated with amygdaloidal flow tops and conglomerates (White, 1968). W. T. Jolly (1974) also discussed in detail the mobility of copper, zinc, and nickel in the Portage Lake Volcanics during metamorphic dehydration.

FIGURE 18.—Native copper (Cu) associated with opaque bituminous matter (B) in the Copper Harbor Conglomerate of Precambrian age, Ontonagon County, Mich. Exposures by reflected and by plain transmitted light; sample CU-53B.

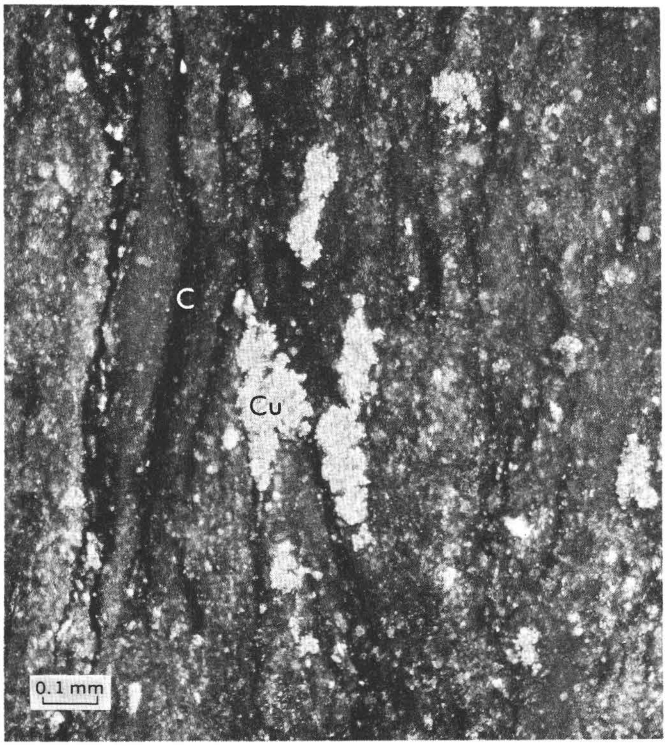


FIGURE 17.—Native copper (Cu) associated with carbonaceous films (C) in the Nonesuch Shale of Precambrian age, Ontonagon County, Mich. Exposures by reflected light and by light transmitted through crossed polars; sample CU-53I.

DIAGENESIS AND METAMORPHISM AFFECT COPPER

Although much has been written on what happens to a massive sulfide deposit during metamorphism (see Vokes, 1968, for a thorough review), data are meager on the fate of minor elements in ordinary sediments during diagenetic and metamorphic processes. Noble (1963) suggested that water of compaction may be an ore-forming fluid, and this idea has been expanded upon by Jolly (1974). Recent isotope studies suggest that meteoric and connate waters have been very important in the formation of many ore deposits (White, 1973; Addy and Ypma, 1973; Sakai and Matsubaya, 1973), even porphyry copper deposits (Taylor, 1974; Hall and others, 1973; Sheppard and Taylor, 1973).

James (1969, p. 531) speculated on what would happen after compaction and diagenesis of the modern deposits in the Red Sea; he thought that the metal-charged brines might move laterally and that the metals might be reprecipitated as sulfides in a favorable host rock such as the reef limestone of the Red Sea. Johnson (1972) discussed the relation of reefs, brine generation, and mineralization of nearby basin sediments. In a previous study of the geochemistry of lower Eocene sandstones in the Rocky Mountain region of the United States, we observed (Vine and Tourtelot, 1973, p. 25–32) that copper is one of the more mobile elements. Copper showed a significant regional variation not clearly related to any single source area, and it was among the elements enriched in a subset of green samples and depleted in a subset of red samples. Because of the mobility of copper during diagenesis, most syngenetic copper deposits will be altered through geologic time unless the host rock is impervious and chemically stable—conditions not usually found in sandstones.

The gradual alteration of sediments during lithification and burial under additional sediment is accompanied by loss of water of hydration from clay minerals, iron hydroxides, gypsum, zeolites, and other hydrous minerals. Garrels and Mackenzie (1971, p. 100) estimated that nearly one-fifth of the total mass of water on Earth is present in the pores of sedimentary rocks, thus providing ample water for diagenesis. However, by the time a rock has been altered to a low-rank metamorphic rock, such as the Revett quartzite, the hydrous clay minerals and iron oxides have been altered to mica and hematite, and the rock is nearly impervious and dry (figs. 19 and 20). Chlorite is about the only hydrous mineral that persists through the greenschist facies of metamorphism. The water lost during progressive diagenesis travels chiefly through pores in the rock, but that which is lost during metamorphism must travel through open joints and fissures in the rock. Thus, disseminated copper deposits may be formed during diagenesis, but metamorphic processes tend only to form crosscutting fissure veinlets in a preexisting orebody, such as the veinlets described for the African Copperbelt by Jolly (1972, p. 329–331). Whether concentration of copper during metamorphism would be sufficient to form a major disseminated orebody is doubtful. Such major disseminated copper deposits as those in the African Copperbelt, Udokan, and the Belt Supergroup in Montana must have been formed prior to metamorphism and only minor redistribution occurred during metamorphism.

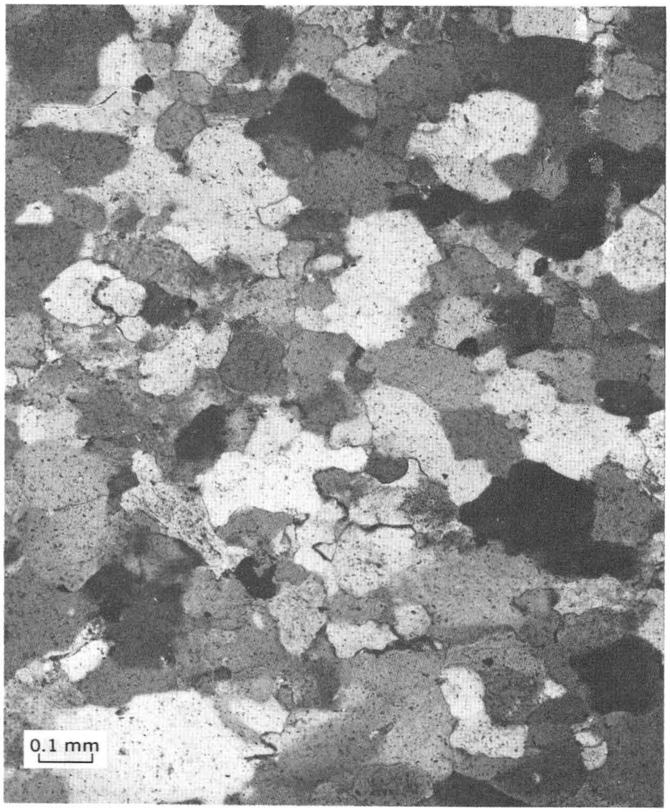


FIGURE 19.—Quartzite from the Revett Formation, Chicago Peak area, Sanders County, Mont., showing impermeable nature of feldspathic quartzite as a result of low-grade metamorphism. Crossed polars; sample CU-29A.

FIGURE 20.—Argillite from the Revett Formation, Chicago Peak area, Sanders County, Mont., showing quartz veinlet in a sericite-biotite rock. Crossed polars; sample CU-29F.

SUMMARY: METALLOGENIC PROVINCES AND THE COPPER CYCLE

A variety of copper deposits are present in many kinds of sedimentary and volcanogenic rocks. They range from syngenetic hypogene deposits precipitated on the sea floor to epigenetic supergene replacement of fossil wood by chalcocite, and they include several different types commonly grouped together under the single heading, "red-bed copper deposits." Various types of copper deposits differ in size, shape, mineral zoning, and other parameters, and understanding of these different characteristics is crucial to the search for commercial orebodies. To distinguish among the various types of deposits requires critical evaluation of all data. An overly simplified classification blurs important distinctions among deposits, including such things as origin and mode of occurrence, thus hindering both the development of known deposits and the exploration and discovery of new deposits. As pointed out by Dunham (1971), multiple working hypotheses are unavoidable when studying stratabound deposits.

The erosion of a porphyry copper deposit, or a copper-rich basalt, to produce copper deposits in a nonmarine sandstone is a fairly obvious example of the recycling of copper from an igneous terrane into a sedimentary environment. Other segments of the geochemical cycle of copper are less obvious—even speculative or unknown. If massive sulfide deposits do form part of an ophiolite sequence at a divergent plate boundary and are rafted to the margin of a continent, and if some are carried under the continent along the Benioff zone by subduction, then these deposits can be melted and incorporated into a magmatic-hydrothermal system that forms new porphyry copper deposits, as postulated by Sillitoe (1972a, b, c) and Guild (1973). Garrels and Mackenzie (1971, p. 114) have estimated that the present rate of erosion could reduce the continents to sea level in about 10 million years. Thus, a continuous recycling of copper from the continents into the sea must occur at a rate sufficient to form new deposits frequently throughout geologic time. Moreover, many marine deposits are recycled into the magmatic realm through deep burial, metamorphism and melting, or subduction. Both dispersion and concentration processes are operating continuously and ore deposits will occur when and where the processes of concentration are dominant.

COPPER DEPOSITS AND BRINES

BRINES AS DIAGENETIC AGENTS

The frequent occurrence of copper deposits in marine and deltaic sandstone and shale in basins that also contain evaporites and hydrocarbons may be no coincidence. The brines expelled from the evaporites and formed by connate and meteoric waters circulating through the evaporites, especially chloride brines, could extract and transport copper from a large volume of rock. The brines could then redistribute and locally concentrate the copper, wherever chemical, temperature, or pressure conditions were favorable for precipitation throughout the sedimentary section (Johnson, 1972). As D. E. White (1968) pointed out, at least seven different mechanisms exist for local formation of sulfide minerals from sulfide-deficient fluids. The mechanisms pertinent to the deposits discussed in this report are (1) a temperature decrease or a pH increase; (2) the action of sulfate-reducing bacteria; (3) the breakdown of sulfur-bearing hydrocarbons; and (4) sulfide in previously existing pyrite. The common heavy metals generally precipitate in the following order: copper, zinc, lead, and silver. This precipitation order may explain the zoning seen in deposits such as the Kupferschiefer. Iron sulfide is relatively insoluble (the solubility constant for ferrous sulfide is 3.7×10^{-19}) (Weast, 1972, p. B232), but copper sulfide is extremely insoluble (for cuprous sulfide the solubility constant is 2×10^{-47}) (Weast, 1972, p. B232); so it is likely that copper would readily replace iron in the formation of sulfide minerals. Shimizaki and Clark (1970) found that copper would substitute extensively for iron in pyrite at low temperature (82 percent at 100°C), but that the substitution decreases markedly with rising temperature (10 percent at 275°C).

Chloride brines are common in oil fields. A recently published analysis of an oil-field brine from the Bartlesville sand, a Pennsylvanian oil sand in eastern Kansas (McClure, 1973), showed a copper content of 0.22 mg/l in the brine. If we assume that 2 million tons of ore with an average grade of 2.5 percent (50,000 tons of metallic copper) is an economic deposit, which is particularly true if the bed can be strip mined, and if we assume that in a favorable environment an average of 50 percent of the copper in such a brine such as the Bartlesville brine would be precipitated, then it would take 2.3×10^{14} l of brine to make an ore deposit. If this hypothetical ore were in a bed 3.3 ft (1 m) thick, it would have an area of about 0.32 mi^2 (832,000 m^2). If, as D. E. White (1968) suggested for the Nonesuch Shale, the brine rose through the bed from below, we can make a rough estimate of the time needed to produce the ore deposit. We can use Darcy's law, $Q=KIA$, where Q is total flux through the bed, K is the hydraulic conductivity, I is the hydraulic gradient, and A is the area. If we assume that K is 100 gal day^{-1} ft^{-2} or 4.1 m/day (100 gal day^{-1}/ft$^{-2}\times0.041$), which is the value of K that Winter (1973, table 1) found for very fine sand, and that I is 0.001, which is small but reasonable for brines moving upward in the center of a basin, then $Q=4.1\times0.001\times832{,}000$ or $\sim3{,}410$ m^3/day. Thus it would take 183,000 years to form the ore deposit (2.3×10^{14} l$\div3.41\times10^{6}$ l$\div365$ days). (E. B. Tourtelot was aided in these calculations by Gerald Feder of the U.S. Geological Survey). A much more detailed model for ground-water flow as a mineralizing solution was constructed by W. S. White (1971) for the Nonesuch Shale of Michigan. He considered the different K's of the formations involved, both lateral and vertical movement of fluids, and many other pertinent variables; we refer the reader to this paper for a thorough discussion of the complications in hydraulic mineralization.

BRINES AS SYNGENETIC AGENTS

In the hypothetical case just posed, the mineralization would be diagenetic or diplogenetic and could occur at any time before the porosity of the sediments became so small as to restrict the movement of fluids through the rock. However, Renfro (1973, 1974) and Smith (1974) have suggested a model in which brines carrying metals could form syngenetic or very early diagenetic deposits. Renfro's hypothesis would also explain the often observed association of red or oxidized terrestrial strata overlain by an organic-rich, sulfide-bearing bed, overlain in turn by a marine evaporite sequence. He has suggested a coastal sabkha environment. A sabkha is a salt flat or marsh occasionally inundated by seawater but generally just above the high tide level; it occurs in regions of high net evaporation and so salt-encrusted flats are developed (Kinsman, 1969).Generally, whether the sabkha is coastal or continental, the water table is only 3–6 ft (1–2 m) below the surface and water from the water table rises by capillary action. According to Renfro's (1973, 1974) hypothesis, mineralized terrestrial waters must rise through a decaying algal mat to reach the surface of evaporation during a regressive cycle and they precipitate metal sulfides as they pass through the algal mat. The succeeding transgressive cycle would cover the deposit with marine dolomite and evaporites.

GROUND WATER, COPPER, AND RED BEDS

Sandstone beds of nonmarine origin are known to contain copper in many parts of the world. Whereas the copper-rich strata are generally gray or greenish gray, they commonly are part of a rock sequence that is red, reddish brown, or brown, and hence these deposits are often called red-bed deposits. This designation fails to distinguish rocks that have inherited their red color from a previous red terrane from those that have been colored red by diagenetic alteration by oxidizing solutions. Furthermore, fluvial rocks of intermontane basins are not distinguished from marginal marine and deltaic rocks which also may contain red-colored strata. This section will emphasize nonmarine rocks, especially those whose color is of secondary origin.

Syngenetic red strata—that is those strata whose color is inherited from an older, eroded red strata or from red soils developed on carbonate terrane such as was cited by Vine (1972)—are of little interest in the search for copper. Generally, a previous cycle of weathering has already removed the copper from the sediments making up such red rocks.

In certain oxidizing environments, mafic materials, such as hornblende, in first-cycle arkosic sandstone are destroyed to yield iron oxides and hydroxides that gradually alter to form a red hematite cement (Walker, 1967, p. 355–360; Walker and others, 1967). The destruction of hornblende in a desert environment, as observed by Walker and his colleagues in rocks of Pliocene and younger age in Baja California, is accompanied by the reorganization of silica and alumina to form authigenic clay minerals such as montmorillonite. The fate of the minor elements under these conditions has not been studied although previously we noted the apparent depletion of mobile minor elements from red Eocene sandstones (Vine and Tourtelot, 1973, p. 33). Chukhrov (1973) noted that the iron content of red strata is generally lower than that of sedimentary rocks of other colors. Presumably copper would be leached with the other mobile elements.

The large number of small copper deposits associated with diagenetically altered red sandstone throughout the world attests to the effectiveness of the oxidizing environment in mobilizing copper from a low-grade disseminated source. The copper is concentrated when the oxidizing solutions move into a reducing environment and become reducing themselves. Copper deposits of this type have been described by numerous people, including such eminent geologists as Emmons (1905), Lindgren (1908, 1911), Lindgren, Graton, and Gordon (1910, p. 76–79), Weed (1911), and Fischer (1937). These descriptions are readily available in the American geological literature, and as they are as timely now as when they were written, there is little point in repeating their observations.

When copper occurs in anomalous concentrations in nonmarine sandstone, it is generally accompanied by one or more other metals, including silver (Proctor, 1953), uranium and vanadium (Finnell and others, 1963, p. 49–66), or lead (Jerome and others, 1965). The common association with uranium is of particular interest because of the detailed studies of uranium deposits in recent years. Two main types of uranium deposits are now recognized (Fischer, 1970). The Wyoming roll-type uranium deposits form elongate crescent-shaped bodies scattered like widely spaced beads along a string. These bodies have been traced for miles along an interface that separates oxidized from unoxidized sandstone. The Colorado Plateau deposits form thin tabular layers nearly concordant to bedding, composed of discrete bodies enveloped in rock altered by reduction, like raisins in raisin bread. The Wyoming roll fronts are regarded as dynamic interfaces between oxidizing and reducing conditions moving downdip, like the zone of supergene enrichment in sulfide ores, whereas the Colorado Plateau deposits are seemingly formed as static bodies localized by patches of intense reduction in a generally reducing environment. Comparable types of sedimentary copper deposits may exist, but generally the distinctions have not been made.

TARGETS FOR PROSPECTING

A sequence of geologic processes, including tectonic, igneous, hydrothermal, sedimentary, diagenetic, and, possibly, metamorphic processes, may combine to produce segments of the Earth's crust that are quite different in gross chemical and mineralogic composition from adjacent segments of the crust. These differences are superimposed on whatever original inhomogeneities existed in the primitive Earth. One manifestation of this crustal differentiation is the density difference between continental and oceanic crust and the further differentiation of continental crust into stable cratons, orogenic belts, island arcs, shelf areas, and intermontane basins. Not only are these areas distinguished by different chemical and physical properties, but also by different geologic processes which dominate each realm. The economic geologist should attempt to interpret these different properties and processes to help predict suitable target areas for new mineral exploration.

Because porphyry copper deposits are generally emplaced high in the crust of mountainous areas (Sillitoe, 1972c), they erode readily. Thus, basin sediments in areas of known porphyry copper deposits may contain syngenetic and diagenetic stratabound copper deposits like those of Corocoro, Bolivia. Basins that contain evaporite deposits, petroleum, and transgressive and regressive marine sediments, like the Permian basins of the south-central United States, may have thin stratabound copper deposits analogous to the Kupferschiefer. Rift areas, such as the Gulf of Mexico-Salton Sea area, where high heat flow, abundant brines, and permeable sediments are present, are probable sites of copper deposits similar to Boleo. Fossil rift areas are also good targets. Although copper deposits in continental sandstones are generally small, remobilization of copper during weathering (supergene enrichment) can concentrate the copper to a minable deposit such as Nacimiento. Recent discoveries of major stratabound disseminated copper in Precambrian sedimentary rocks all over the world suggest that even more Precambrian deposits may exist. Areas of ancient and modern island arcs may contain both massive and disseminated sulfide deposits. Similarly, ophiolite sequences, denoting ancient spreading centers, are a good prospect for massive sulfide deposits. Thus, there are numerous prospective target areas for copper, and many of these areas remain to be tested.

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