CORRELATIONS BETWEEN MANGANESE AND COPPER ORE DEPOSITS AND THEIR RELATIONSHIP TO PLATE TECTONICS

by

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ABSTRACT

Correlations between manganese and copper ore deposits and their relationship to plate tectonics

by Michael Thonis

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Review of the distribution and mode of origin of copper and manganese ores has disclosed three principal loci of mineralization in the orogenic environment. They are (1) calc-alkaline magmatism; (2) ophiolite emplacement; and (3) marginal basin development.

Calc-alkaline magmatism, initiated on subduction zones by the partial melting of metal-rich oceanic crust, supplies both copper and manganese to the porphyry copper systems within an island arc or cordilleran environment. Ophiolite emplacement bodily encorporates the copper- and manganese-rich oceanic crust into an orogenic system, by either accretion or obduction. The high heat flow and magmatism, which produce marginal basins, cause copper and manganese to be transferred from the upper mantle to the basin crust.

Each mode of origin involves a sequential process beginning with uptake of the two metals into partial melts, followed by entrance of the metals into the hydrothermal environment. Here, the copper-, manganese-, and sulphide-rich solutions interact with meteoric waters to precipitate copper sulphides and leave manganese (II) complex ions in solution. The manganese (II) complexes are transported to the sedimentary surroundings where they are oxidized to form stratabound deposits of manganese (IV) oxides. In the case of calc-alkaline magmatism, the sedimentary manganese is deposited at a lower level than the porphyry copper, while the opposite occurs for marginal basin development. Ophiolite emplacement involves juxtaposition of the ore deposits within a deformed oceanic crust.

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Title: Professor of Mineralogy & Geochemistry
INTRODUCTION

Within the last few years, geologists have gathered a considerable store of knowledge concerning the oceanic lithosphere. It has become increasingly clear that the oceanic crust is remarkably enriched in many valuable metals, including manganese and copper. Concurrent with this advancement has been the concept of plate tectonics which has demonstrated that the oceanic crust is susceptible, if not destined, to re-emplacement along continental margins, either through magmatic or tectonic processes. It is not surprising, therefore, that continental margins (modern and ancient) are particularly fruitful areas of mineral exploration. What is surprising, however, is that so little has been done to elucidate the genetic connections between plate consumption and terrestrial ore deposition. The result is that exploration models have succeeded on a global scale, but have largely failed on a regional basis.

Plate consumption is principally accomplished via the subduction mechanism. There are three important ramifications of subduction: calc-alkaline magmatism, ophiolite emplacement, and marginal basin development. Considerable success has been met in relating porphyry copper deposits to calc-alkaline magmatism (Guild, 1972;
Mitchell and Garson, 1972; Sawkins, 1972; Sillitoe, 1972a), and massive copper sulphide deposits to ophiolite emplacement (Guild, 1972; Sawkins, 1972; Sillitoe, 1972b). Virtually nothing has been done, however, to relate manganese deposition to any of the three possible loci, basically because there is so much debate over the source of manganese in manganese deposits. This thesis aims to compare the behaviors of copper and manganese, and to show that manganese enters the terrestrial environment through routes similar to those of copper.

I wish to express my indebtedness for the many helpful suggestions and untiring guidance provided by Professor Roger G. Burns, my thesis advisor.
II  THE OCEANIC CRUST

II.1  The configuration of the oceanic crust

As the thesis develops, repeated reference will be made to the oceanic crust and its tectonic emplacement at convergent plate margins. Furthermore, the physical and chemical configurations of the oceanic crust will be an important premise to many of the conclusions drawn in the ensuing discussion. It is worthwhile, therefore, to review here current knowledge on oceanic crust, and to place a particular emphasis on its chemistry.

In a broad classification, typical oceanic crust is divided into three layers, labeled 1, 2, and 3, which directly overlie the upper mantle. Layer 1 consists of variably consolidated sequences of terrigenous and pelagic sediments having a total thickness averaging 0.3 km (Coleman, 1971; Dewey and Bird, 1971). This layer is wedge-shaped, thickening away from the oceanic rises and toward the continental margins. The terrigenous sediments include normal land-derived silts, muds, and clays of the continental margin, as well as graded sands and silts laid down by turbidity currents. The extensive pelagic sediments, on the other hand, include biogenic siliceous oozes (radiolarian and diatomaceous), biogenic calcareous oozes (foraminiferal), and red clays.
Half of the North Pacific sea floor is now capped by red clay, while biogenic pelagic sediments make up another quarter (Horn, Horn, and Delach, 1970).

Layer 2 underlies layer 1, and mainly consists of extrusive tholeiitic basalt with some hyaloclastite and alkali basalt. These extrusives are usually in the form of pillow flows which often show conversion to spilite. Layer 2 has an average thickness of 1.4 km, and commonly shows low grade metamorphism to zeolitized basalt, greenschist-facies metabasalt, and amphibolite, the higher metamorphic grades being at the bottom of the layer (Cann, 1968; Christensen, 1970; Coleman, 1971; Dewey and Bird, 1971).

Beneath layer 2 lies layer 3, a uniform 4.7 km thick and consisting predominantly of gabbro with minor diorite and trondhjemite. Cumulate textures are typical of these rocks. The effects of metamorphism are considerable in layer 3, and yield amphibolite, metabasalt, granulite, and probably pyroxene-hornblende-plagioclase gneiss associated with serpentinite. Strong mylonite fabrics and considerable serpentinization appear to be restricted to zones of transform faulting. The top of layer 3 is marked by sheeted complexes of dolerite dyke swarms which protrude into the bottom of layer 2 (Cann, 1968; Christensen, 1970; Coleman, 1971; Dewey and
Bird, 1971).

The upper mantle underlies the oceanic crust (layers 1, 2, and 3), although the transition zone (Mohorovicic discontinuity) is very complex. Just below the crust, the mantle consists of an ultramafic suite of harzburgite, dunite, lherzolite, and garnet peridotite, with a minor amount of serpentinization. The dunite and harzburgite appear to be basalt-depleted versions of primitive lherzolite and/or garnet peridotite (Coleman, 1971; Dewey and Bird, 1971).

II.2 The generation of the oceanic crust

The most likely sites for the generation of layers 2 and 3 of the oceanic crust are at the oceanic rises along divergent plate margins. Kay, Hubbard, and Gast (1970) describe the production of new oceanic crust as occurring by the successive emplacement of intrusive gabbro prisms into tensional sites located along oceanic rises. As diapirs of primitive upper mantle (lherzolite and/or garnet peridotite) rise beneath axial valleys, approximately 30% partial melting (through adiabatic decompression) yields a liquid of tholeiite, leaving a residual solid of dunite and harzburgite. The resultant magma chambers, located 25 to 30 km below the rise crests, supply intrusive gabbro (layer 3) and extrusive tholeiitic
Fig. 1  A schematic representation of an oceanic rise.

Layer 1 sediments
Layer 2 pillow basalts (copper-bearing)
Layer 3 gabbros
Upper mantle
Alkali basalt component
Tholeiitic magma
Basalt-filled rift with dolerite dykes
Manganese-rich basal sediment layer
Manganese nodules
basalt (layer 2), as well as some basic tuff, to the separating plate margins. The dolerite dike swarms are the conduits which link the extrusive basalt with the intrusive gabbro (Dewey and Bird, 1970). Away from the axial valleys and on the flanks of the oceanic rises, only magmas of relatively little partial melting are tapped. These magmas supply minor amounts of alkali basalt to layer 2.

Dewey and Bird (1971) further point out that differentiation may also account for the more silicic rock types, such as diorite and trondjemite, found among layer 3 gabbros. On a larger scale, the 30% partial melting of the upper mantle yields a depleted cap of dunite and harzburgite extending 16 km below the base of layer 3. This depleted mantle probably flows away from the ridge axis, the viscosity increasing as the area of high heat flow is abandoned and as the alkali basalt fraction is withdrawn.

II.3. The distribution of copper and manganese in the oceanic crust

The distribution of copper and manganese in the oceanic crust is not very well known, although the few data available suggest that the metals have their principal origin at the oceanic rises. Engel, Engel, and Havens (1965) report that oceanic tholeiites,
sampled near Atlantic and Pacific rises, contain 77 ppm copper and 0.17 wt% manganese oxide. Moore and Calk (1971) indicate that virtually all their samples of pillow basalts from various oceanic rises contained abundant spherules and globules having 4.0 to 10.83 wt% copper in the form of copper sulphide. These features apparently developed by diffusion of the copper from the basalt melt to nearby immiscible sulphide melts, followed by reaction between the copper and sulphur to form copper sulphide. It has been estimated that layer 2 basalts contain approximately 800 ppm sulphur (Moore and Fabbi, 1971). Manganese sulphides, whether as spherules, globules, or extrapillow minerals, have not been found in layers 2 and 3.

Bostrom and Peterson (1966, 1969) and Bostrom, Joensuu, and Fisher (1969) have demonstrated that active oceanic rises with corresponding high heat flow are the principal loci for volcanic emanations rich in manganese and, to a considerably lesser extent, copper. They suggest that the metal-rich sediments which form upon the rises spread with their underlying pillow basalts away from the rises, to become progressively buried by oceanic sediments (layer 1). Support for the hypothesis of a manganese-rich horizon at the base of layer 1 has come from Cook (1971) and Cronan et al. (1972) who report a basal sediment unit containing
laminated metallic oxides and trace metals syngenetic with biogenic pelagic sediments. The unit, which is approximately 10 to 25 m thick, is found throughout extensive areas of the eastern equatorial Pacific. Cronan et al. (1972) report an average manganese content of 4.52 wt % and an average copper content of 917 ppm. Normal pelagic sediments from the Pacific Ocean average 0.4784 wt % manganese and 0.0323 wt % copper (Cronan, 1969).

Another prime site for manganese and copper accumulation is the very top of the oceanic crust, where ferromanganese nodules and encrustations develop at the water-sediment or water-basalt interface (Mero, 1965; Horn, Horn, and Delach, 1973b). The manganese content of these nodules ranges between 10 to 30 wt %, and the copper content ranges between 0 to 2 wt %. Many other elements exist in minor and trace amounts (Horn, Horn, and Delach, 1973a). The formation of ferromanganese nodules and the factors affecting their formation are highly debated issues (see, for instance, Horn, 1972). Bonatti, Kraemer, and Rydell (1972) summarize the geochemistry as follows:

"Marine iron-manganese deposits display a great variability in their physical and chemical properties and are formed by a number of different processes. A simple genetic classification
of these deposits has been attempted, where the main criterion for the classification is the source of Fe and Mn. Hydrogenous deposits are those formed by slow precipitation of Fe and Mn from "normal" sea water. They are characterized by Mn/Fe ratios between 0.5 and 5 and a relatively high content of trace metals. They are widespread in abyssal plains with low sedimentation rates and also on topographic highs. Hydrothermal deposits are formed by precipitation from submarine thermal solutions produced in areas of high heat flow often associated with volcanism, such as along active oceanic ridges and rifts. They are characterized by variable Mn/Fe ratios, with very high Fe contents near the source, and low trace metal content except in areas where sulfides form due to local conditions. In halmyrolytic deposits Mn is partly supplied by submarine weathering of basaltic debris, as in some areas of the southeast Pacific. Diagenetic deposits are formed under reducing conditions in sediments rich in organic matter where manganese is mobilized during diagenesis and reprecipitated near the sediment-water interface. These deposits are characterized by high Mn/Fe ratios and low trace metal content. They are found in hemipelagic
regions of the oceans and in enclosed seas. Deposits formed by a combination of processes are common."

A great deal of evidence suggests that the diagenetic source of manganese is dominant (Hammond, 1974). The distinct possibility exists, then, that much of the metal content in nodules is derived from the manganese- and copper-rich basal sediment layer, which originally gained its metal content via hydrothermal processes. However, it would be unreasonable to suppose that nodule chemistry might indicate the metal history of a given oceanic rise system, for other factors certainly exist. For instance, Arrhenius (in Hammond, 1974) indicates that the high metal content of nodules found between the Clarion and Clipperton Fracture Zones in the east Pacific is due to the area being below the carbonate precipitation level, and therefore free of carbonate dilution.
III  CALC-ALKALINE MAGMATISM

III.1  The correlation between porphyry copper deposits and subduction zones

The concept of lithospheric plate subduction has recently been invoked to explain the inescapable observation that metallogenic provinces have a spatial and temporal relationship to eugeosynclinal development. Particularly outstanding are the works of Guild (1972), Mitchell and Garson (1972), Sawkins (1972), and Sillitoe (1972a), who demonstrate the perfect correlation between porphyry copper deposits and subduction zones. Weaker, but nevertheless justifiable, correlations have been made between many massive sulphide and base metal deposits and subduction zones (Guild, 1972; Mitchell and Garson, 1972; Sawkins, 1972). Dorr, Crittenden, and Worl (1973) suggest that the circum-Pacific distribution of manganese is related to the subduction of oceanic lithosphere at convergent plate margins.

The correlation between porphyry copper deposits and Mesozoic-Cenozoic orogenic belts is well established. Along the entire length of the western Americas, deposits occur consistently over active and fossil subduction zones, with marked deposition in British Columbia and the Arizona-New Mexico area. Particularly outstanding is the narrow band of deposits in the Andes, extending 4000 km from Ecuador through Peru and Chile to Argentina.
Fig. 2 The distribution of porphyry copper deposits (information from Sillitoe, 1972a).
In the western circum-Pacific, porphyry copper deposits are found in Quadacanal, Bouganville, New Guinea, Borneo, the Philippines, Taiwan, and Okinawa (Sillitoe, 1972a). The OK Tedi porphyry copper deposit in New Guinea may be as young as 5 million years (Guild, 1972). Japan, however, seems to lack porphyry copper deposits, although there is a significant number of stratabound copper sulphide deposits along its entire length (Tatsumi, Sekine, Kanehira, 1970; Guild, 1972). All the deposits in the western circum-Pacific lie over active or recently active subduction zones.

Elsewhere, porphyry copper deposits likewise occur over Cenozoic-Mesozoic subduction zones, such as in the Dominican Republic and Puerto Rico, as well as in the Alpine belt in Romania, Yugoslavia, central Bulgaria, Turkey, Armenia, Iran, and West Pakistan (Sillitoe, 1972a). The deposits of Uzbekistan and Kazakhstan, USSR are the only known Paleozoic deposits (Sillitoe, 1972a), although Hollister, Potter, and Barker (1973) have reported the possibility of Paleozoic deposits in the North American Appalachians.

Inevitably, porphyry copper deposits are found in calc-alkaline igneous rocks, particularly calc-alkaline stocks and cupolas (Guild, 1972; Mitchell and Garson, 1972; Sawkins, 1972; Sillitoe, 1972a, 1973). Furthermore, porphyry copper deposition is seen as being contempo-
aneous with the emplacement of associated intrusive rocks, although deposition is a rather late event in the emplacement of the entire calc-alkaline suite of intrusive and extrusive rocks surrounding the deposit (Sillitoe, 1973). It appears that porphyry copper deposition is a regular feature of calc-alkaline magmatism. However, erosion quickly removes most deposits, since porphyry coppers are usually emplaced near the surface (Mitchell and Garson, 1972; Sawkins, 1972; Sillitoe, 1973). This latter observation would explain why most deposits, with the exception of those in Uzbekstan and Kazakhstan, are restricted to the Mesozoic and Cenozoic.

Less readily explained by erosion, however, is the observation that deposits in island arcs are all Cenozoic in age, while those found upon continents (cordillera-type) are either Mesozoic or early Cenozoic (Mitchell and Garson, 1972). Also interesting is the seemingly pulse-like nature of porphyry copper deposition in the Andes (Sillitoe, 1972a). The Chilean deposits, specifically, were emplaced during discrete episodes, now manifested by north-south trending intrusive belts which get progressively younger away from the coast. Each pulse was separated by a quiescent period of 15 to 25 million years (Farrar et al., 1970).
The generation of calc-alkaline magmas

The principal concept employed to explain the correlations between porphyry copper deposits, calc-alkaline magmatism, and subduction zones is Ringwood's (1969) view that subducted oceanic lithosphere undergoes frictional heating along a Benioff zone, leading to the partial fusion of oceanic crust and consequent rise of andesitic magmas. Toksoz, Minear, and Julian (1971) indicate that the rate of subduction prevents the downgoing slab from warming to the temperature of the surrounding mantle. According to their models, melting should not occur until considerable depth, deeper than that expected by frictional heating alone. Typical depths for the generation of calc-alkaline magmas along Benioff zones are reported as 150 to 250 km (Mitchell and Garson, 1972) or 120 to 200 km (Dewey and Bird, 1970), as computed by noting the position of volcanic centers relative to Benioff seismic planes. These depths correspond to temperatures of 1000 to 1600 °C (Toksoz, Minear, and Julian, 1971), which necessitate the presence of volatiles if melting is to occur. Wyllie (1971) emphasizes the role of water, probably included in the oceanic crust as chloride-rich pore water and hydroxyl-bearing minerals (e.g. clays, amphiboles, micas), to lower melting temperatures. The partial melting of layers 1, 2, and 3 is the most
likely source of calc-alkaline magmas (Oxburgh and Turcotte, 1970) and their related copper metal contents (Mitchell and Garson, 1972; Sawkins, 1972; Sillitoe, 1972a).

The resulting melts rise to form either island arcs just beyond continental margins or cordillera-type volcanic belts upon continents, as typified by Japan and the Andes, respectively (Dewey and Bird, 1970). Dewey and Bird (1971) suggest that the oblique convergence of an oceanic plate with a continental margin may be an important factor in determining whether an island arc or a cordillera will develop along a given continental margin. Another factor may be the dip of the subduction zone, for if melting is assumed to occur at a constant depth, then a steeply dipping slab will display volcanism very near the trench while a gently dipping slab will display volcanism far from the trench and possibly inland of the continental margin. Also, if melting can occur within a depth interval of 150 to 250 km, then a gently dipping subduction zone will display a broader belt of volcanism than a steeply dipping zone. This might partly explain the large width of the North American Cordillera. Another possible explanation for cordillera-type volcanic belts is the collision of several island arcs with a continental margin due to multiple subductions occurring behind the arcs (Dewey
Fig. 3 The development of an island arc and its associated porphyry copper deposits.
PORPHYRY COPPER DEPOSITS

OCEANIC CRUST

LITHOSPHERE

ASTHENOSPHERE

ISLAND ARC

PARTIAL MELTING
and Bird, 1970) and consequent transformation of the accreted arcs into continental crust. This might explain why porphyry copper deposits in cordillera-type volcanic belts are Cenozoic and Mesozoic in age, while deposits in island arcs are only Cenozoic. The Mesozoic deposits may have been emplaced in island arcs which have since been incorporated into cordilleras.

In the case of cordillera-type volcanism, crustal contamination of the ascending magma appears to be essentially absent, as indicated by geochemical data (summarized by Sillitoe, 1972a) and by the fact that cordillera-type magmas and island arc magmas have the same bulk chemistries (andesitic). However, both cordilleras and island arcs commonly contain rock types other than calc-alkaline. Green and Ringwood (1968) point out that the rise of calc-alkaline magmas should generate partial melting of the mantle wedge above the subduction zone, yielding tholeiitic and alkalic basalts. Thus, the eruptive chains are marked by a volcanic suite consisting principally of basalts, dacites, rhyolites, and especially andesites. Underlying these eruptive chains are plutonic or batholithic root zones of calc-alkaline composition, which have been shown to be comagmatic with the overlying volcanics (Hamilton and Myers, 1967; Hamilton, 1969). As this entire complex becomes exposed by erosion, the resulting clastics are
deposited on the flanks of the eruptive chains, to await deformation and metamorphism. It is this environment, equated with the classical eugeosyncline (Coney, 1970; Dewey and Bird, 1970), which plays host to porphyry copper deposition.

III.3 The porphyry copper system

Sillitoe (1973) convincingly depicts the development and configuration of a typical porphyry copper system by piecing together various examples which expose different levels of such systems. Most interesting is the recognition that porphyry copper deposits span the boundary between the plutonic and volcanic environments by being situated in and about the cupolas and stocks of calc-alkaline plutons underlying stratovolcanoes. Furthermore, the entire porphyry copper system, including characteristic brecciation, alteration, and mineralization, is roughly ellipsoidal in shape with a vertical extent of 8 km and a diameter of 4 km. The top of the system is essentially the top of the stratovolcano, and the top of the copper deposit is typically 1.5 to 3 km beneath the summit.

Porphyry copper deposits are usually of huge tonnage, commonly in excess of 500 million tons (Sillitoe, 1972a), and are therefore of great importance both economically and geologically. The deposits character-
Fig. 4 The porphyry copper system (adapted from Sillitoe, 1973). The outer dashed line represents the extent of alteration. The inner dashed line represents the extent of the porphyry copper deposit.

Subaerial portion of volcano (strato-volcano)
Submarine portion of volcano ("basement")
Calc-alkaline cupola
Breccia zones
Cu, Fe, S, and Gypsum from fumaroles
Cu-Pb-Zn-precious metal veins
istically occur as upright cylinders or inverted cups of low grade (less than 1.0 % copper), disseminated and stockwork, pyrite-chalcopyrite mineralization, accompanied by hydrothermal alteration and brecciation. The alteration consists of potassium silicate type within the intrusive cupola or stock, sericitic in the pre-volcano basement immediately surrounding the intrusive, and propylitic in a wide zone from the sericite zone to the outside of the porphyry copper system. Between the top of the intrusive and the top of the stratovolcano (wherein lies the porphyry copper deposit), there exist patches of silicification and advanced argillic alteration. Brecciation begins at the top of the intrusive and may extend upward to the top of the volcano (Sillitoe, 1972a, 1973).

It appears, then, that during the final stages of the development of a calc-alkaline stratovolcano, crystallization of the comagmatic pluton releases metal-bearing, chloride-rich fluids under high pressure. These fluids alter, brecciate, and mineralize the crystallized parts of the pluton, as well as the surrounding basement and overlying stratovolcano, and then find their way upward to become fumaroles and hot springs (Mitchell and Garson, 1972; Sillitoe, 1972a; 1973).
III.4 Other mineralization

A very important observation is that copper is not the only mineralization common to a porphyry copper system. Sillitoe (1973) clearly demonstrates that the porphyry copper system is typically marked by copper, lead, zinc, and precious metal veins in the basement and stratovolcano, and by copper, iron, gypsum, and native sulphur in the sublimates at high-temperature fumaroles. Williams (1967), although not specifically mentioning porphyry copper, reports that deposits of native sulphur and pyrite are common features of submarine and subaerial volcanic craters, and that these deposits emanate from high level magma chambers beneath stratovolcanoes. Likewise, Sawkins (1972) demonstrates that most sulphide ore deposits, whether of lead, zinc, copper, etc., are directly related to calc-alkaline volcanics overlying plutonic roots. He cites examples from all around the circum-Pacific, and ascertains a genetic relationship between the hydrothermal sulphide deposits situated below volcanic summits and the stratabound sulphide deposits found on the flanks of volcanic centers.

Mitchell and Garson (1972) draw attention to the origin of stratabound sulphide deposits in eugeosynclinal belts. They note that such deposits consistently occur in modern island arcs, or in older terrains resembling
modern island arcs, and that these sites consist of thick stratigraphic successions of pillow lavas, volcanic breccias and tuffs, and fine-grained sediments. These successions closely resemble the host rocks of island arc porphyry copper deposits. It is their contention, therefore, that porphyry coppers and stratabound sulphides are formed in the same volcanic centers and from the same intrusive magmas. However, this association has never been recognized in the field, probably because erosion removes the high level porphyry copper deposits before the low level stratabound deposits are exposed. The stratabound deposits are at lower levels because they form in the deep basins flanking the stratovolcanoes.

Perhaps the best example of stratabound sulphide mineralization related to porphyry copper development is the region of Kuroko ore deposition in the western half of Northeast Japan. This region is the so-called "Green Tuff" zone of Miocene age, characterized by a eugeosynclinal sedimentary pile up to 3000 m thick. The stratigraphic succession surrounding the volcanic centers includes submarine flows, tuffs, breccias, and pyroclastics of andesitic, dacitic, rhyolitic, and basaltic composition, as well as their first-order derivatives of turbidites, shales, mudstones, and sandstones (Matsukuma and Horikoshi, 1970).
Fig. 5  The distribution of the Kuroko deposits in Japan (information from Tatsumi, Sekine, and Kanehira, 1970). Region A is northeast Japan; B is the inner zone of southwest Japan; and C is the outer zone of southwest Japan.
The Kuroko ores themselves are conformable to semi-conformable stratabound deposits of fine-grained barite-Zn-Pb-Cu-Ag-bearing sulphide ore. They are commonly found associated with stratabound chalcopyrite ores, gypsum deposits, and copper-bearing siliceous stockworks and disseminations (Matsukuma and Horikoshi, 1970). It should be recalled that Sillitoe (1973) regarded copper, iron, gypsum, and native sulphur as integral parts of porphyry copper systems. It should further be noted that the Kuroko deposits display alteration zones of argillization, silicification, and sericitization (Matsukuma and Horikoshi, 1970), suggesting a similarity between Kuroko ore fluids and those of porphyry coppers.

Most importantly, however, the Kuroko deposits have a remarkable spatial relationship to rhyolitic and dacitic intrusives, domes, and breccia zones, and with volcanic centers in general (Jenks, 1966). The massive chalcopyrite ore ("Oko") is often seen to be mineralogically and spatially transitional between the Kuroko and the "Keiko" ores. The Keiko ores are "highly-silicified rocks composed mostly of quartz replacing underlying intrusive rocks and pyroclastics, with some sulphide minerals, and common breccia structures" (Matsukuma and Horikoshi, 1970). The very strong suggestion is that erosion has eliminated the high
level porphyry copper deposits, having cut down to the bottoms of the porphyry copper systems (where lie the Keiko ores) and only a small way down through the low-lying marine and lacustrine successions (where lie the Kuroko ores).

This brief description of the Kuroko deposits has served to demonstrate that the mineralization inherent in a porphyry copper system may escape or "bleed" from the system, to become incorporated into the sedimentary environment. This rather expanded view of a porphyry copper system suggests that much of the eugeosynclinal ore deposition has the same origin as porphyry copper deposition, namely the subduction of oceanic crust. The porphyry copper system itself, however, is essentially the hypothermal and mesothermal part of an extremely abbreviated hydrothermal system, starting with retrograde boiling in calc-alkaline magma chamber and ending with the very beginnings of epithermal mineralization only 1.5 to 3.0 km further up.

III.5 Manganese mineralization

The above arguments suggest that eugeosynclinal sedimentary manganese is also derived from the porphyry copper system. Williams (1967), while reviewing the role of submarine volcanism in producing ore deposits, states:
"Fumarolic activity within an environment of island arc volcanoes appears to be especially conducive to the formation of iron, manganese and base-metal deposits, as testified on a small scale by their recent development in the West and East Indies and along the shores of the Solomon Islands in the Pacific Ocean."

Park (1956) indicates that eugeosynclinal sedimentary manganese is chiefly found among calc-alkaline tuffs and clastics, usually in the vicinity of volcanic centers. Very often, such deposits of sedimentary manganese are seen to grade into hydrothermal systems of manganese oxides (Park, 1956; Suslov, 1970; Dorr, Crittenden, and Worl, 1973). Many of these veins exist in volcanic breccia zones (Dorr, Crittenden, and Worl, 1973), and are associated with copper, lead, zinc, and silver (Roy, 1968).

Although eugeosynclinal sedimentary manganese deposits inevitably lie among calc-alkaline host rocks, dilution by terrigenous and carbonate sedimentation is common (Varentsov, 1964). The deposits are therefore formations of interbedded manganese oxides or carbonates, calc-alkaline tuffs and flows, and sedimentary limestones, shales, etc. Horizons of jasper are very common, almost to the point of being characteristic. No matter what the degree of sediment dilution, however, a volcanogenic
source of manganese is always required (Shatskiy, 1964; Sokolova, 1970; Varentsov, 1964).

In discussing the geologic conditions of manganese formation, Sapozhnikov (1970) states:

"Ore accumulations may occur among lavas and tuffs and sometimes among their associated jaspers. In these cases ore material was deposited in the immediate vicinity of the center of eruption.... Moreover, the ore is interlayered with jasper and with bodies of volcanic rocks. Manganese compounds were probably derived from such sources as submarine and terrestrial fumaroles close to volcanic systems, possibly on the slopes of the volcanoes.... During a well defined volcanogenic-sedimentary process there is an association of ores of manganese with those of iron as well as with jaspers and other siliceous rocks. Ore accumulations are often associated with Pb-Zn-mineralization."

He goes on to say:

"Economic volcanogenic-sedimentary manganese-bearing deposits...were formed after the main phase of volcanic activity, when the intensity of volcanic activity decreased and lava extrusion and tuff accumulation decreased considerably. These deposits are remote from the volcanically
active areas. The above-mentioned favorable conditions only exist in geosynclinal regions and prevail during the final stage of their development."

The above descriptions make it clear that manganese deposition accompanies the development of calc-alkaline metal-rich stratovolcanoes. Like porphyry copper deposits which develop beneath stratovolcanoes, these sedimentary manganese deposits form during the later stages of magmatic activity. By studying pertinent geochemical data and field relationships, Borchert (1970) concluded that manganese becomes enriched in residual melts which rise to become calc-alkaline plutons beneath comagmatic stratovolcanoes, and then crystallize to release manganese-rich magmatic solutions. As these solutions pass through the stratovolcano, most of the manganese remains in solution to eventually deposit in the sedimentary environment. Although Borchert (1970) does not address porphyry copper deposits, his conclusions concerning manganese deposits clearly indicate that eugeosynclinal manganese enters the sedimentary environment via the porphyry copper system. It must be emphasized, however, that copper itself need not be present in order for the porphyry copper system to exist and bear manganese. The important observation
is that both metals are related to the crystallization of calc-alkaline magma chambers beneath comagmatic stratovolcanoes.

III.6 The porphyry copper-manganese system

The arguments presented in the previous section suggest that both the copper and the manganese contained within subducted oceanic crust are incorporated into partial melts which rise to form calc-alkaline volcanic chains and comagmatic roots. Expulsion of the ore-bearing solutions from the cupolas of these roots leads to brecciation and intense hydrothermal activity marked by hypothermal and mesothermal conditions. The typical porphyry copper system is emplaced so close to the surface that the environment surrounding the stratovolcano essentially replaces the epithermal zone. Therefore, the very soluble manganese oxides and carbonates, which would normally precipitate in the epithermal part of a hydrothermal system, are instead deposited in the sedimentary environment. Since both copper and manganese are common metals in the oceanic crust, it is most probable that both metals simultaneously enter the porphyry copper system.

Since the epithermal zone is preempted by the sedimentary conditions surrounding the volcanic vents, this hydrothermal zone yields its typical mineral
assemblages to the sedimentary environment. Thus, disseminated and stockwork copper sulphides (porphyry coppers) precipitate in the hypothermal and mesothermal zones, with some copper entering the sedimentary environment to form stratabound copper sulphide deposits. Presumably, native copper deposits will develop if there is a shortage of sulphur. Meanwhile, manganese oxides move entirely through the hypothermal and mesothermal zones, to precipitate in the sedimentary environment, and to form ore accumulations even at considerable distance from the volcanic centers. The more distant deposits will be marked by a higher percentage of terrigenous and carbonate materials and by a smaller percentage of volcanogenic materials than those deposits formed very near their parent stratovolcanoes.

An important question to be answered is why there are no significant manganese deposits adjacent to porphyry copper deposits. Certainly, much of the answer lies in the erosion factor, which eliminates the high level porphyry copper while exposing the low level sedimentary deposits. Another factor, emphasized by Sapozhnikov (1970), is the dilution of manganese by pyroclastic material in the vicinity of volcanic centers. Manganese, unlike the metals of typical massive sulphide deposits, distributes itself over wide areas, apparently as far as nonvolcanogenic-
Fig. 6  The distribution of copper and manganese deposits around calc-alkaline volcanic centers.

Subaerial portion of volcano (strato-volcano)
Submarine portion of volcano ("basement")
Basin sediments
True basement beneath volcano
Calc-alkaline pluton
Porphyry copper deposit
Eugeosynclinal sedimentary manganese deposits
sedimentary environments. Thus, ore accumulations can only occur at the sites of anomalous metal concentration or where dilution by pyroclastics is minimal. The result is that massive sulphide deposits lie relatively close to volcanic centers, while sedimentary manganese ores will appear to lie further out.

III. 7 The distribution of manganese ores relative to porphyry copper deposits

Although porphyry copper deposits and eugeosynclinal sedimentary manganese deposits are cogenetic, the difference between their respective levels of emplacement generally precludes simultaneous exposure. It is therefore futile to compare the distribution of the two ores with the hope of finding them juxtaposed within the same mining district. It is worthwhile, however, to see whether significant manganese deposits can be found along strike of porphyry copper deposits. Variations in erosion from one area of a volcanic chain to another might expose different levels, thereby revealing manganese ores in the more heavily eroded sections while preserving porphyry copper ores in the least eroded. The degree of erosion, though, may be related to the amount of uplift, thereby exposing manganese at the same elevation as porphyry copper.
The actual relative distributions of manganese and copper ores bear out the prediction that significant manganese deposits are not found in the vicinity of porphyry coppers but are found in the same terrains. In Japan, for instance, sedimentary manganese ores are found in the central and northern parts of the eugeosynclinal Green Tuff region, spatially removed from the Kuroko deposits (Tatsumi, Sekine, Kanehira, 1970). Despite the apparent lack of porphyry copper deposits, it is predicted that significant manganese deposits occur at the flanks of the Kuroko deposits, but somewhat below the level of erosion. The common occurrence of hydrothermal manganese veins throughout the Green Tuff region (Nakamura and Hunahashi, 1970) may result from the remobilization of buried sedimentary ores due to solution activity.

The sedimentary manganese ores of Chile are a good example of the correlation between manganese and porphyry copper mineralizations. Manganese oxides are found in the Plateau area of northern Chile (Ossa, 1970) and in the Central Valley of central Chile (Aguirre and Mehech, 1964). Although the Andean porphyry copper deposits are principally in the Plateau area, they avoid the manganese districts of northern Chile, where the erosion level is considerably deeper than elsewhere in the Plateau (Sillitoe, 1972a). The
Fig. 7 The distribution of significant eugeosynclinal sedimentary manganese deposits.
manganese ores of the Central Valley in central Chile lie just to the west of the porphyry copper deposits, and are most likely derived from the porphyry copper systems. Erosion in the valley has exposed the low level manganese ores, while the high level porphyry copper deposits have been spared. It is not surprising that the Central Valley ores consistently contain 1 to 3% copper (Hewett, 1966).

Such correlations exist elsewhere throughout the world. In Cuba, sedimentary manganese ores associated with calc-alkaline igneous rocks form a central band extending the entire length of the island (Park, 1942; Simons and Straczek, 1958). Along strike, in the Dominican Republic and Puerto Rico, these ores give way to porphyry copper deposition. Likewise, in the Yugoslavia-Rumania-Bulgaria area (Hewett, 1966), manganese oxides and carbonates lie within the same calc-alkaline terrains as do significant porphyry copper deposits. And in the well-eroded area of central Morocco, the Alpine eugeosyncline contains an amazing number of sedimentary manganese deposits (Hewett, 1966), but no porphyry copper ores.

The extensive area of porphyry copper deposition in the North American Cordillera reveals very little economic manganese mineralization. This paucity is so acute, in fact, that the United States depends entirely
on foreign sources for its manganese (Dorr, Crittenden, and Worl, 1973). However, the presence of porphyry copper deposits may very well indicate the existence of manganese deposits at depth. In the southwestern United States, the numerous porphyry copper deposits are surrounded by thick sequences of clastics which may very well hold immense accumulations of manganese ore. The common hydrothermal veins of manganese in the area (Hewett, 1965) are probably a result of remobilization of the buried sedimentary ores, due to high heat flow. Although the depths of these sedimentary accumulations may be prohibitive to mine economically, this region should be regarded as a high-potential area for exploration.

Also, the area between Arizona and British Columbia should be explored intensively for both copper and manganese. The porphyry copper ores in Arizona and British Columbia all lie within a single subduction-generated batholithic/eugeosynclinal belt which trends through Nevada and Idaho (Hamilton, 1969). Although some porphyry copper deposits have been found in both states, the frequency of such deposits is considerably less than elsewhere along the belt. The possibility exists that the subducted oceanic crust contained an inhomogeneous distribution of metals, but there is yet no direct evidence to believe this true.
IV OPHIOLITE EMPLACEMENT

IV.1 The equivalence of ophiolites and oceanic crust

The term "ophiolite," in its classical sense, does not imply any particular mode of origin, but rather denotes a conspicuous sequence of rocks consisting of ultramafic bodies at the stratigraphic bottom, complex gabbro intrusives higher up, basalt pillow flows next, and sediments on top. Ophiolites *per se* have been recognized in suture zones, sutured melange terranes, olistostrome gliding melanges, thrust wedges, terranes overlain by melanges, and giant nappes overlying melanges (Dewey and Bird, 1971). Inevitably, ophiolites are associated with overlying or underlying blueschist metamorphism (Coleman, 1971).

The remarkable resemblance of ophiolites with oceanic floor, both in terms of chemistry and geometry, has prompted the widespread belief that ophiolites are indeed oceanic floor, emplaced tectonically into orogenic belts (Dietz, 1963; Coleman, 1971; Dewey and Bird, 1971). This then explains the apparent paradox of a high-temperature origin coupled with a low-temperature emplacement. The ophiolite suite is generated by intrusive, extrusive, and sedimentary behavior at a divergent plate margin, and is then transported by sea-floor spreading to a convergent
plate margin where it is tectonically emplaced into an orogenic belt.

With regard to the configuration of oceanic crust, Dewey and Bird (1971) state:

"There is a remarkable degree of correlation between these present models for the oceanic crust and mantle and the internal sequence, structure, and composition of ophiolite complexes. In well-developed ophiolite suites, harzburgite and dunite, often strongly banded, foliated and tightly folded, with podiform chromitites (upper mantle), pass upwards through a complex transition zone (Mohorovicic discontinuity), involving a large clinopyroxene component, cumulate textures, and layered/intrusive relationships between basic and ultrabasic rocks, into cumulate and sometimes foliated gabbros (layer 3). Diorites and trondjemites commonly occur as discrete intrusive bodies in, and as diffuse facies of, the gabbro. The gabbros pass up into diabase and basaltic pillow lavas, often through a transitional sheeted complex consisting, in its central parts, of 100% basic dikes. Sheeted complexes are difficult to account for over wide areas, except by a plate accretion (sea-floor spreading) mechanism."
Note that the sediments associated with ophiolite suites are essentially the consolidated equivalents of layer 1. Thus, radiolarian and diatomaceous cherts, massive limestones, and organic-rich shales, as well as occasional sandstones and siltstones, are the typical sediments overlying ophiolite pillow basalts. Also note that the ultramafic, gabbroic, basaltic, and sedimentary components of the ophiolite suite are each independently very conspicuous features, and may alone be indicators of ophiolite emplacement. However, caution should be employed while distinguishing ophiolite pillow basalts from the basaltic component of volcanic chains generated by instabilities in the mantle wedges overlying subduction zones.

IV.2 The mechanism of ophiolite emplacement

Despite the general agreement that ophiolites are essentially oceanic floor segments found in mountain belts, the mechanism of emplacement of these bodies is not completely understood. It is known, however, that ophiolite emplacement is integrally associated with plate subduction, either by the accretion of oceanic crust onto the wall of the upper plate (in oceanic trenches) or by the bodily thrusting of the oceanic crust onto a continental margin (Dewey and Bird, 1971; Oxburgh and Turcotte, 1971). The
Fig. 8  The development of an ophiolite through accretion (A) and obduction (B).
latter case, often called "obduction" (Coleman, 1971), differs from the former by the direction of subduction relative to the continental margin. During subduction, accretion occurs as the oceanic lithosphere underthrusts a continental margin and leaves slices of the oceanic crust "plastered" to the continent or island arc. Obduction occurs as the continent attempts to underthrust the oceanic lithosphere and then rebounds isostatically with the ophiolite on top. Both cases are associated with blueschist metamorphism and melange terranes because both cases involve subduction.

IV.3 The copper- and manganese-rich ophiolites of Japan

As was discussed earlier (section II.3), the oceanic crust contains significant amounts of copper and manganese, both of which appear to be related to volcanism under oceanic rises. Dredged samples of basalts from oceanic rises have yielded abundant spherules and globules containing copper sulphides, suggesting that massive sulphide deposits might occur under favorable circumstances, perhaps after moderate metamorphism. Geochemical studies across oceanic rises and deep-sea drilling projects have revealed a manganese oxide-rich sediment layer at the base of layer 1. Furthermore, ocean expeditions have outlined extensive areas of ferromanganese nodule deposition on the sea.
floor, particularly in the Pacific Ocean.

Japan offers one of the best examples of copper and manganese mineralization related to ophiolite emplacement. Although the country has apparently experienced a very complex tectonic history, Japan can be grossly divided into three regions: northeast Japan, the inner zone of southwest Japan, and the outer zone of southwest Japan. As described earlier, northeast Japan contains a typical eugeosynclinal terrane of calc-alkaline volcanism and associated copper and manganese mineralization. Southwest Japan, however, differs considerably in that it represents the collision of two island arcs driven together by the consumption of oceanic lithosphere between them (Uwey and Bird, 1970). The inner zone of southwest Japan roughly represents one of the two island arcs, and is Late Paleozoic to Triassic in age. The outer zone represents the second island arc, and is Jurassic to Cretaceous in age. Blueschist metamorphism is pronounced at the eastern sides of both zones.

Both zones are seemingly dominated by ophiolite terranes, and these terranes are marked by abundant copper and manganese mineralization (Kanehira and Tatsumi, 1970; Tatsumi, Sekine, and Kanehira, 1970; Watanabe, Yui, and Kato, 1970). The outer zone, especially, is entirely occupied by two parallel
Fig. 9  The distribution of ophiolitic copper and manganese deposits in Japan (information from Tatsumi, Sekine, and Kanehira, 1970). Region A is northeast Japan; B is the inner zone of southwest Japan; and C is the outer zone of southwest Japan.
and adjacent mineral belts, extending along the entire length of southwest Japan, which together outline layers 1, 2, and 3. The western belt (Sanbagawa terrane) consists of conformable copper sulphide deposits associated with pyrrhotite and sphalerite in the metamorphosed equivalents of basalts and gabbros (layers 2 and 3). Ultramafic rocks are commonly exposed in the Sanbagawa terrane and probably represent the upper mantle component of the ophiolite suite. All the deposits are generally bed-like or lenticular in form, and lie conformably in crystalline schists.

The eastern belt (Chichibu and Shimanto terranes) consists of sedimentary manganese oxides found stratigraphically above or directly upon layer 2 basalts. These deposits are intimately associated with chert beds, up to 100 m thick, which undoubtedly were originally siliceous oozes (basal unit, layer 1). Units of sandstone, shale, limestone, and minor pyroclastics overlie and are within the manganese-bearing chert beds. They substantiate the conclusion that the ores are genetically related to ophiolite development and not to calc-alkaline volcanism in the eugeosynclinal environment.

The inner zone, unlike the outer zone described above, does not feature regular belts of copper and manganese mineralization, nor is the zone dominated by
ophiolite occurrences. However, the numerous deposits that do exist are inevitably associated with ophiolitic rocks, and once again the copper is contained in layers 2 and 3 while the manganese is restricted to layer 1. It is likely that the inner zone ophiolites are part of a melange terrane, as attested to by the extremely varied lithologies surrounding each ophiolite occurrence, and by the complex juxtaposition of different ores and their host rocks (layers 1, 2, and 3). On the other hand, the outer zone ophiolites appear to have been emplaced as a uniform whole, suggesting the possibility of obduction.

IV.4 Other copper- and manganese-rich ophiolites

Ophiolites so consistently contain deposits of copper and manganese that such mineralization must be considered typical of ophiolite terranes. Significant ophiolite-type deposits of copper and manganese occur in the Franciscan formation of California (Park, 1956; Hewett, 1966), the Klamath Mountains (Irwin, 1972), the Olympic Peninsula (Park, 1956), Newfoundland (Sillitoe, 1972b), Cuba (Park, 1942, 1956; Simons and Straczek, 1958; Hewett, 1966), Morocco (Hewett, 1966), southern Spain and Portugal (Williams, 1967), the Italian Alps (Sillitoe, 1972b), Cyprus (Johnson, 1972; Sillitoe, 1972b), the northern Caucasus (Bogdanov and Kutyrev,
Fig. 10  The distribution of ophiolites containing significant copper and manganese deposits.
Magakian, 1972), Turkey (Sillitoe, 1972b), the southern Urals (Bogdanov and Kutyrev, 1972; Magakian, 1972), the Philippines (Bryner, 1969), eastern Australia (Solomon, Groves, and Klominsky, 1972), Timor in Indonesia (Audley-Charles, 1972), and certainly elsewhere. In every case, the copper sulphides are found in layer 2 basalts, and the manganese is found in layer 1 sediments. The ages range from the Precambrian to the Cenozoic.
V MARGINAL BASIN DEVELOPMENT

V.1 The formation and configuration of marginal basins

Along with calc-alkaline volcanism and ophiolite emplacement, there is one other principal by-product of subduction at convergent plate margins. This is the formation of marginal basins. Karig (1971) has demonstrated that the small marginal basins located behind island arcs, such as the Philippine Sea and the Sea of Japan, are produced by thermal diapirs rising off subduction zones at depths of 200 to 400 km. These thermal diapirs are essentially rising zones of high heat flow generated at the surfaces of subducted lithospheric slabs, probably by shear strain. As a diapir rises upward, it produces a relatively low density mantle (as indicated by geophysical data) which upwells and spreads outward so as to force the basin floor apart. The high heat flow near the surface of the basin (also indicated by geophysical data) triggers volcanism which fills the widening rift with basaltic magmas, thereby producing new oceanic crust. The principal difference between this mechanism and oceanic crust accretion is that marginal basins will only develop where upwelling mantle forces the basin floor apart, whereas crust accretion occurs as a result of plate divergence and consequent adiabatic decompression.
Fig. 11  The development of a marginal basin.
Marginal basins are therefore bounded by steep scarps marking the original walls of the initial rift valley. As spreading commences and sediments rapidly fill the developing trough, continued normal faulting pervades both the new basaltic crust and the overlying sediments. At the beginning, the basin (excluding sediments) is shallower than normal oceanic areas by 2 km or more, but this discrepancy diminishes in approximately 20 to 40 million years (Karig, 1971; Menard, 1967). Active extension apparently occurs only directly behind the island arc and is symmetrical about the median rift, so that particularly wide basins must be generated by periodic relocation of the spreading center over time. Furthermore, the sea-floor spreading which occurs about a median rift will force the island arc oceanward, thereby flattening the subduction zone. This may have important implications to the longevity of subduction. Also, the existence of large rising diapirs with circular plan sections may explain the arcuate nature of island arcs (Karig, 1971).

Dewey and Bird (1971) indicate that the crust of marginal basins will have a gross similarity to typical oceanic crust insofar as there will exist extrusive and intrusive products of magmatism (layers 2 and 3). However, they point out that marginal basins may be expected to show the following distinctive features:
"1. Thick sedimentary sequences above the pillow basalts (e.g. Sea of Okhotsk...). These may consist of volcanogenic andesitic flysch aprons... building from the inner margins of adjacent arcs and/or salt deposits such as those suspected to constitute a large part of layers in the western Mediterranean basins...and/or continental rise sediments on the continental edges of marginal basins.

2. Complex and repeated intrusive and extrusive relations in layers 2 and 3 as a result of the patchy rise of diapirs below existing oceanic crust.

3. Irregular block faulting above rising diapirs, with the development of patchy unconformities and an irregular thickness distribution of layers 2 and 3.

4. A large amount of andesite mixed with the tholeiites and alkali basalts.

5. Repetitions of basalt and andesite in the thick flysch apron.

6. General pervasive metamorphism of layers 2 and 3 and the lower parts of the sedimentary sequence due to the persistent high heatflow."

Except for the volcanogenic andesitic flysch apron at the arc side, the marginal basin represents the
typical miogeosynclinal environment. In the case of a cordillera-type orogeny, the development of a marginal basin may be substituted by upward doming, block faulting, and associated thrusting in the miogeosynclinal zone. In British Columbia, for instance, ophiolites are found near the coast, a calc-alkaline volcanic chain occurs further inland, followed by a broad upwarp of diapiric gneiss doming with flanking imbricate thrust sheets (Coleman, 1971; Price and Mountjoy, 1970). Dewey and Bird (1971) indicate that in the case of marginal basins, the basin crust (layers 2 and 3) and upper mantle may be tectonically uplifted to become exposed as a sort of ophiolite. It is unlikely that the upper mantle is likewise emplaced into cordillera-type miogeosynclines, although ultramafic intrusives found in such environments may have an upper mantle magmatic source due to the high heat flow.

Although there is a basic difference between the mechanisms leading to plate divergence in ocean basins and in marginal basins, the gabbroic and basaltic magmas (layers 3 and 2) which fill the resulting rifts are in both cases partial melt derivatives of upper mantle material. Accordingly, the compositions of the volcanic rocks are virtually identical, at least with respect to their major and minor element chemistries (Dewey and Bird, 1971), which suggests that such factors
as depth of origin and degree of partial melting are the same.

V.2 Copper and manganese in marginal basins: the deposits of central Kazakhstan

By analogy with the processes occurring at oceanic rises, the median rifts of marginal basins should be the sites of copper deposition and manganese emanation. At oceanic rises, crystallizing basalt magmas concentrate copper into sulphide spherules and globules while manganese is concentrated into residual solutions. Likewise, at median rifts, copper should be concentrated into the layer 2 basalts, while manganese should pass upward into the submarine and sedimentary environments. However, the median rifts may be overlain by a thick and highly faulted sequence of sedimentary materials. It should therefore be expected that the manganese-rich solutions reach the surface via the fault conduits, and precipitate their metal contents in the miogeosynclinal environment.

The only known occurrence of manganese in an existing marginal basin has been reported by Hanor and Drever (1971) while dredging in the Mariana Trough near Guam in the western Pacific. They recovered a 6 cm wide vein of manganese oxide containing 48.0 wt % Mn, 0.8 wt % Fe, 0.05 wt % Cu, 0.17 wt % Ni, and 0.02 wt % Co.
The Mariana Trough is an actively developing marginal basin (Karig, 1971) which lies just west of the Mariana Arc and represents the most recent widening of the Philippine Sea to force the Mariana Arc even further eastward from its original location in the Philippines. The Mariana Trough is marked by particularly high heat flow and is clearly related to westward subduction of the Pacific Plate into the Mariana Trench.

The Atasu deposits in central Kazakhstan, USSR are a remarkable example of manganese mineralization in a now uplifted Paleozoic marginal basin. The arcuate northwest-southeast trending basin, which is approximately 1600 km long and 400 km wide, is structurally complex, consisting of a thick sedimentary sequence overlying basaltic, gabbroic, and ultramafic rocks (Maksimov, 1960; Rozhnov, 1970). The sediments immediately overlying the igneous rocks are Lower Paleozoic in age, and consist mainly of quartzites, jasper quartzites, quartz-sericite schists, siltstones, sandstones, argillaceous shales, conglomerates, and tuffs, the grade of metamorphism decreasing upward. In many places, these sediments are intruded and occasionally overlain by basaltic rocks. Overlying these Lower Paleozoic formations are the ore-bearing sediments of Middle Paleozoic age, consisting of thick sequences of limestones, silts, argillites, and sandstones.
Actually, these Middle Paleozoic sediments overlie the Lower Paleozoic sediments only at the flanks of the basin, for the Lower Paleozoic rocks are confined to the north and south edges and thin toward the median. Likewise, the Middle Paleozoic sediments are thinnest at the middle of the basin, commonly pinching out along the median to expose the underlying basalt basement (Kavun, 1970; Kalinin, 1970).

The manganese ore deposits are typically sheetlike elongated bodies ranging up to 20 m in thickness and covering several square km. They have oolitic textures and finely bedded structures, with manganese contents averaging 23 to 25%. The ores are principally oxides in the forms of hausmannite, braunite, and jacobsite, although carbonates are somewhat common. Iron oxide is everywhere associated with the manganese ores, as are lead, zinc, and barite, along with trace amounts of copper, nickel, and cobalt. Throughout the Atasu area, and often superimposed upon the sedimentary manganese deposits, there is a distinct phase of hydrothermal lead, zinc, and barite mineralization (Kavun, 1970; Kayupova, 1970).

In terms of marginal basin development, it would appear that continuous sedimentation accompanied the spreading of the central Kazakhstan troughs that the oldest sediments are now found buried at the flanks of
the Paleozoic basin. As sea-floor spreading continued, sedimentation progressively buried newly formed crust and became the host of manganese mineralization. The complicated ultramafic, gabbroic, and basaltic basement, as well as the igneous products found throughout the sediment profile, were the result of a complex axial accretion process accompanying high heat flow and mantle upwelling and hindered by an extremely rapid sedimentation rate.

Although the manganese mineralization is clearly related to sedimentation in the central Kazakhstan basin, the source of the manganese is not readily clear. Rozhnov (1970), however, synthesized the structural nature of the basin with the spatial distribution of the manganese and noted a relationship between ore formation and deep faulting. He pointed out that the central Kazakhstan basin is actually a large Paleozoic graben consisting of smaller grabens, horsts, and flexures, the formation of which were synchronous with sedimentation. This is quite in accordance with Dewey and Bird's (1971) characterization of marginal basin development, where complicated block faulting and rapid sedimentation accompany the sea-floor spreading.

Rozhnov demonstrated that the manganese mineralization was most significant over deep faults which
acted as volcanic foci supplying ore-bearing solutions and some volcanic ash to the sedimentary environment. He also noted that the most significant faulting, with respect to mineralization, occurred at the deepest parts of the sea bottom and probably in the vicinity of large magma chambers. These sites were also the localities of intense rifting and downwarping. It is clear that the source of the manganese was the median rift volcanism associated with the opening of the central Kazakhstan marginal basin in Paleozoic times.

Recognition that the central Kazakhstan basin is a Lower to Middle Paleozoic marginal basin allows an interpretation of the surrounding area. Popov (1962) indicated that two Paleozoic island arcs lie on either side of the central Kazakhstan basin. The arc to the southwest is the same age as the basin, Lower to Middle Paleozoic, and contains numerous deposits of stratabound copper sulphide. The arc to the northeast is Upper Paleozoic in age, and has a miogeosyncline to its immediate northeast. The miogeosyncline is also Upper Paleozoic in age.

It is apparent that the area consists of two island arc/marginal basin couples, one Lower to Middle Paleozoic in age and the other Upper Paleozoic. Both systems are strongly arcuate with the concave sides toward the northeast. Thus, it is unlikely that the
Fig. 12 The Paleozoic island arcs and marginal basins of Kazakhstan. Region a is the Lower to Middle Paleozoic island arc; b is the Lower to Middle Paleozoic central Kazakhstan marginal basin; c is the Upper Paleozoic island arc; and d is the Upper Paleozoic marginal basin. The extensive manganese deposits of central Kazakhstan are located throughout region b. The open circles are Paleoozoic porphyry copper deposits.
younger arc represents the oceanward side of the older arc, as one would normally expect. Instead, the younger arc must have developed within the central Kazakhstan marginal basin. The general history of the area would then involve a Lower to Middle Paleozoic subduction zone, dipping northeastward beneath the Siberian craton, which formed the older island arc and its associated marginal basin (central Kazakhstan). Continued expansion of the basin must have given way in the Upper Paleozoic to subduction of the basin floor beneath the Siberian craton, so as to form the younger island arc and its associated marginal basin. It is significant that the Almalyk, Uzbekistan porphyry copper deposit lies in the older island arc, and the Kounrad, Kazakhstan porphyry copper deposit lies in the younger.
VI DISCUSSION

VI.1 The cogenetic behavior of copper and manganese

It was assumed in the discussion of calc-alkaline magmatism that manganese and copper are cogenetic with respect to a parent porphyry copper system. Questions may arise, however, as to whether manganese and copper really do enter the stratovolcanic environment through the same conduits. Although it is certain that the two metals pass through calc-alkaline volcanic systems, it may not be clear that the two metals share the same system. Certainly, it is doubtful that every porphyry copper system must yield both manganese and copper simultaneously, but it can be shown that the likelihood of a given system having both metals is great.

It is significant that porphyry copper deposits and eugeosynclinal sedimentary manganese deposits roughly occupy the same zones so as to form fairly narrow metallogenic provinces parallel to the continental margins. Since copper and manganese are both related to stratovolcanic systems within a given province, it is probable that the two metals are incorporated into melts at the same depth along the Benioff zone. At present, there is no reason to believe that two separate melts, one copper-rich and the other manganese-rich, should develop at a given depth.
A second line of evidence for the cogenetic behavior of manganese and copper comes from geochemical studies of the Skaergaard intrusion. Williams (1959) indicates that nickel and cobalt are uptaken by the solid phases during crystallization, while copper, manganese, and iron remain in the liquid phases. During a melting process such as occurs on a Benioff zone, nickel and cobalt are expected to remain in the residual solid, while copper, manganese and iron should enter the melt. This is an interesting result, for it predicts that a ferromanganese nodule, with a typical enrichment of copper, nickel, and cobalt, will melt such that the manganese, copper, and iron will enter the calc-alkaline liquid, leaving the nickel and cobalt behind. The calc-alkaline volcanoism which yields deposits of copper and manganese also yields iron, but never cobalt and nickel. Most importantly, the Skaergaard data indicates that copper and manganese will both be uptaken, simultaneously, by the partial melt. In detail, however, copper enters the melt faster than manganese, particularly at small degrees of partial melting. Thus, the enrichment of copper will be greater than manganese, although the difference will become less acute as melting proceeds. The manganese and copper metallogenic province, then, may show a decrease of copper-to-manganese ratio landward,
The uptake of Mn, Cu, Fe, Co, and Ni into a silicate melt. \( R \) is the concentration of the metal in the partial melt to the concentration of the metal in the initial solid. (Information from Skaergaard data, Williams, 1959)
away from the oceanic trench.

The uptake of copper and manganese into partial melts is also pertinent to the production of new crust at oceanic rises and within marginal basins. In these sites, the production of crust is accomplished by the emplacement of basaltic magmas into the rift valleys which develop over rising diapirs of partially melt upper mantle. The 3kaergaard data indicate that copper and manganese will be uptaken by the partial melts, relative to normal upper mantle material. Therefore, the basaltic magmas which intrude median rifts and oceanic rises will contain enrichments of manganese and copper.

VI.2 The hydrothermal behavior of copper and manganese

At an oceanic rise, a marginal basin rift, or a porphyry copper system, manganese and copper behave as a cogenetic pair, entering the hydrothermal environment simultaneously. This, then, suggests that the presence of one metal may indicate the nearby occurrence of the other. In fact, the abundance of one metal may be a rough indicator of the ore potential of the other metal. These correlations are not readily observed, perhaps due to the different levels of final emplacement. These different levels come about through the relative mobilities of copper and manganese in the hydrothermal
environment.

While copper has its most significant ore deposits in the hydrothermal class, manganese is very much a sedimentary ore. This can be well understood in terms of the relative geochemical behaviors of copper and manganese in the presence of sulphur and oxygen. Goldschmidt (1958) writes:

"The formation of sulphides dominates the geochemistry of copper, and it may even be doubted whether any appreciable amount of copper in a truly ionic state enters the usual silicates of magmatic rocks.... The only natural sulphide mineral into which manganese enters freely is zinc sulphide, of which it is a common constituent. Near the surface of the earth, with access of oxygenated waters, oxide and hydroxide minerals of trivalent or quadrivalent manganese may in some cases enter into low-temperature hydrothermal mineral associations."

The hydrothermal behavior of copper and manganese is best represented by a vastly simplified system in which fluid phase complexes of manganese, copper, and sulphur migrate upward until the temperature and pressure fall below the critical point. From this level on up to the surface, hydrolysis of the complexes will
yield various insoluble compounds, depending on the availability of sulphur and oxygen. It would be expected that, at the bottom of the precipitating system, copper and manganese would first compete for sulphur, since the oxygen-rich meteoric waters would not reach this depth. The competing reactions might be:

\[
\begin{align*}
\text{CuS} + \text{Mn} & \rightarrow \text{MnS} + \text{Cu} & \Delta G_\circ &= -38.2 \text{ kcal} \\
\text{Cu}_2\text{S} + \text{Mn} & \rightarrow \text{MnS} + 2\text{Cu} & \Delta G_\circ &= -29.3 \text{ kcal}
\end{align*}
\]

This is an interesting result, for the manganese will be chalcophile, while the copper will appear in the metal phase. Since MnS is rather uncommon, it might be supposed that the system is much more complex than depicted here, or else meteoric waters do indeed reach this depth.

The competing reactions for sulphur and oxygen together are the following:

\[
\begin{align*}
4\text{CuS} + 3\text{Mn}_2\text{O}_3 & \rightarrow 3\text{MnS} + 4\text{CuO} + \text{S} & \Delta G_\circ &= +81.5 \text{ kcal} \\
3\text{CuS} + \text{Mn}_2\text{O}_3 & \rightarrow 2\text{MnS} + 3\text{CuO} + \text{S} & \Delta G_\circ &= +56.4 \text{ kcal} \\
2\text{CuS} + \text{MnO}_2 & \rightarrow \text{MnS} + 2\text{CuO} + \text{S} & \Delta G_\circ &= +23.8 \text{ kcal} \\
\text{CuS} + \text{MnO} & \rightarrow \text{MnS} + \text{CuO} & \Delta G_\circ &= +18.2 \text{ kcal} \\
4\text{Cu}_2\text{S} + 3\text{Mn}_3\text{O}_4 & \rightarrow 3\text{MnS} + 4\text{Cu}_2\text{O} + \text{S} & \Delta G_\circ &= +99.7 \text{ kcal} \\
3\text{Cu}_2\text{S} + \text{Mn}_2\text{O}_3 & \rightarrow 2\text{MnS} + 3\text{Cu}_2\text{O} + \text{S} & \Delta G_\circ &= +69.4 \text{ kcal} \\
2\text{Cu}_2\text{S} + \text{MnO}_2 & \rightarrow \text{MnS} + 2\text{Cu}_2\text{O} + \text{S} & \Delta G_\circ &= +32.4 \text{ kcal} \\
\text{Cu}_2\text{S} + \text{MnO} & \rightarrow \text{MnS} + \text{Cu}_2\text{O} & \Delta G_\circ &= +22.5 \text{ kcal}
\end{align*}
\]

(Thermochemical data from Latimer, 1952)
These results are very much in accordance with the observed behavior of manganese and copper in hydrothermal veins; copper is chalcophile and manganese is oxyphile. Since this behavior is somewhat universal, it might be supposed that most vein solutions containing both copper and manganese fall below the critical point upon contact with cool meteoric waters.

If the supply of sulphur is exhausted by the time the solutions have reached the earth's surface, then copper and manganese may compete for oxygen only. The reactions would typically be:

\[
\begin{align*}
4\text{CuO} + 3\text{Mn} & \rightarrow \text{Mn}_3\text{O}_4 + 4\text{Cu} & \Delta G_\circ = -184.4 \text{ kcal} \\
3\text{CuO} + 2\text{Mn} & \rightarrow \text{Mn}_2\text{O}_3 + 3\text{Cu} & \Delta G_\circ = -121.1 \text{ kcal} \\
2\text{CuO} + \text{Mn} & \rightarrow \text{MnO}_2 + 2\text{Cu} & \Delta G_\circ = -50.3 \text{ kcal} \\
\text{CuO} + \text{Mn} & \rightarrow \text{MnO} + \text{Cu} & \Delta G_\circ = -56.4 \text{ kcal} \\
4\text{Cu}_2\text{O} + 3\text{Mn} & \rightarrow \text{Mn}_3\text{O}_4 + 8\text{Cu} & \Delta G_\circ = -166.1 \text{ kcal} \\
3\text{Cu}_2\text{O} + 2\text{Mn} & \rightarrow \text{Mn}_2\text{O}_3 + 6\text{Cu} & \Delta G_\circ = -107.4 \text{ kcal} \\
2\text{Cu}_2\text{O} + \text{Mn} & \rightarrow \text{MnO}_2 + 4\text{Cu} & \Delta G_\circ = -41.1 \text{ kcal} \\
\text{Cu}_2\text{O} + \text{Mn} & \rightarrow \text{MnO} + 2\text{Cu} & \Delta G_\circ = -51.8 \text{ kcal}
\end{align*}
\]

Here too the results agree with the observations of near-surface deposits, where manganese is oxyphile and copper appears in the metal phase.

These reactions might also pertain to the sedimentary environment, if the copper and manganese solutions debouch onto a submarine floor. Where sulphur is a significant
part of the exhalative solutions, or where abundant sulphur is supplied by organic processes, copper and manganese will compete simultaneously for oxygen and sulphur, making copper chalcophile and manganese oxyophile. If there is insufficient sulphur, then copper and manganese will compete for oxygen only, making manganese oxyophile and copper elemental. It is not uncommon to find sedimentary manganese oxides in the vicinity of either stratabound copper sulphides or native copper.

Solubility is another important factor in understanding the relative depositional behaviors of copper and manganese. Manganese (II) compounds are generally quite soluble, especially in acidic solutions. When the $E_h$ and $pH$ conditions are such that copper sulphides have precipitated, $Mn^{2+}$ ions may still remain in solution, moving upward to enter the sedimentary environment, where they are oxidized to insoluble manganese (IV) compounds. Thus, it is a common observation that the largest deposits of copper occur as sulphides in hydrothermal systems while the largest deposits of manganese are found as oxides (and carbonates to some extent) in sedimentary beds.

Once manganese enters the sedimentary environment, $E_h$ and $pH$ conditions become very important in determining the locality and mineralogy of deposition. Bricker (1965) indicates that moderately high $pH$ will encourage the
precipitation of MnCO₃ if ionic carbonate is available. If it is not, then the manganese will remain in aqueous solution. At very high values of pH, Mn₃O₄ may develop, or manganese hydroxides, depending on the Eh. At very high Eh and pH, MnO₂ will precipitate. Many sedimentary basins display a zonal distribution of manganese minerals, with the manganese carbonate forming at a greater depth than the manganese oxides.

VI.3 The distributional behavior of copper and manganese

It is very likely that island arcs and cordilleratype mountain belts are largely built beneath water and then uplifted to their present positions (Gough, 1973). Certainly, the common occurrence of marine lithologies in both island arcs and cordilleras is clear evidence that much of the development occurs in the submarine environment. The consistent association of eugeosynclinal sedimentary manganese with marine lithologies, such as limestones and jaspers, is evidence that deposits of manganese develop during the submerged stages of mountain growth. Apparently, the manganese is deposited in the deep basins surrounding the porphyry copper-bearing stratovolcanoes. After uplift, erosion will first remove the porphyry copper deposits and then the deeper manganese deposits. In the case of ophiolites, however, manganese is deposited stratigraphically.
higher than copper. Deformation accompanying emplacement of the ophiolite may juxtapose ore bodies of the two metals, such as in southwestern Japan. In the case of marginal basins, manganese is again deposited stratigraphically higher than copper, but simple uplift may still preserve the original distribution of the two metals. The manganese deposits of central Kazakhstan, for instance, probably overlie yet unfound copper deposits.

The fact that there are three loci of mineralization which, under different degrees of erosion, will expose different metals, complicates the apparent distribution of metals in an orogenic belt. If an orogenic belt consists rather simply of an ophiolite, a eugeosyncline, and a marginal basin, in that order, then moderate erosion will yield a metallogenic zoning of Mn-Cu, Cu, and Mn, respectively. Extensive erosion will yield Mn-Cu, Mn, and Cu, in that order. Of course, cordillera-type systems will lack the marginal basin zone, and complicated orogenic and erosional histories will destroy the overall zoned pattern.

Sillitoe (1972c) outlines a consistent trend in western North and South America of four metal provinces elongated parallel to the continental margin. From west to east, these provinces are: Fe, Cu, Pb-Zn-Ag, and Sn-Mo. In general, the Fe province borders the coast, while the Sn-Mo province occurs more than 600 km
Fig. 14  Manganese and copper zoning as a function of the degree of erosion. A is after minor erosion; B is after significant erosion.
inland. Detailed metallogenic maps of Europe (Gabelman and Krusiewski, 1972), the circum-Pacific (Radkevich, 1972), and the world (Wilson and Laznicka, 1972) indicate a crude zoning similar to Sillitoe's. Sillitoe proposes that these provinces result from increased partial melting of oceanic lithosphere with increased depth of subduction. Different degrees of partial melting supposedly release different metals from the oceanic crust. The first melts would be enriched in iron, while the last melts would be enriched in tin and molybdenum. The trend supposedly follows the systematic increase of potash-to-silica ratios landward, as seen throughout the circum-Pacific (Dickinson, 1968) and in the Sierra Nevada Batholith (Bateman and Dodge, 1970).

There is little doubt that metal partitioning between melt and solid does play an important role in the formation of ore deposits. However, it is not clear that this mechanism alone explains metallogenic zoning. First of all, molybdenum not only occurs in the Sn-Mo province, but it also occurs in the Cu province as well. Molybdenum occurs as a common constituent of porphyry copper deposits, sometimes to the point of being the major metal. Foremost, however, is the added influence of ophiolite emplacement, marginal basin development, and erosion in determining the
metallogenic configuration of an orogenic belt. In all probability, the Fe province is related to the coastal occurrence of ophiolites (e.g. the Franciscan formation of California), while the Pb-Zn-Ag province is related to a combination of calc-alkaline magmatism and marginal basin development. The Sn-Mo province is probably related to the remobilization of metals contained in the continental crust, due to high heat flow over deeper portions of the Benioff zone.
VII CONCLUSIONS

Significant work by other authors (Guild, 1972; Mitchell and Garson, 1972; Sawkins, 1972; Sillitoe, 1972a, 1972b) has revealed that there are two principal loci of copper mineralization in developing orogenic belts: calc-alkaline magmatism and ophiolite emplacement, both of which are related to subduction. By carefully comparing the depositional behavior of copper and manganese, evidence has been presented to demonstrate that there are, in fact, at least three principal loci of copper and manganese deposition: calc-alkaline magmatism, ophiolite emplacement, and marginal basement development, all of which are related to subduction.

Although copper and manganese differ widely in their hydrothermal behavior, they enter cogenetically into the hydrothermal environment of all three loci. Once in the hydrothermal environment, copper forms sulphides while manganese forms oxides. Some of the copper sulphide (and native copper) may spill from the hydrothermal environment into the sedimentary environment. All of the soluble manganese (II) compounds will reach the sedimentary surrounding and be oxidized to insoluble manganese (IV) compounds.

In the case of calc-alkaline magmatism, copper and manganese enter the volcanic environment via the
same conduits. From this point of view, porphyry copper systems are seen as the volcanogenic parent of both copper and manganese, although manganese continues through and out of the system to form eugeosynclinal sedimentary deposits. Furthermore, it is apparent that ideal hydrothermal systems of copper and manganese, demonstrating hypothermal through epithermal conditions, are of secondary importance in comparison to porphyry copper systems emplaced at such high levels that the epithermal zone is replaced by the sedimentary environment. These latter systems are most important to economic geology insofar as they yield the greatest copper and manganese mineralization in the eugeosynclinal environment.

In the case of ophiolite emplacement, the copper and manganese mineralization serves as one line of evidence that ophiolites are indeed generated at oceanic rises. The abundance of mineralization in ophiolite terranes demonstrates the importance of this mechanism in supplying ores to the orogenic system, and further demonstrates the ability of oceanic crust to supply sufficient amounts of metal to magmas generated at subduction zones. The discrepancy between the common occurrence of copper sulphide ores in ophiolites and the apparent lack of such ores in dredged pillow basalts may be explained through remobilization of the
copper sulphide globules in the pillow basalts. This remobilization may occur upon metamorphism during tectonic emplacement of the ophiolites.

In the case of marginal basin development, the occurrence of significant mineralization in central Kazakhstan demonstrates the importance of this mechanism in producing economic manganese deposits. By analogy with the processes occurring at oceanic rises, copper deposits should form in the basalts underlying the manganese-rich sediments. Marginal basin mineralization can be regarded as miogeosynclinal in nature. Some terranes which appear to be ophiolitic may actually be uplifted marginal basins.

All three of the mechanisms discussed above de-emphasize the leaching of igneous rocks as a principal source of sedimentary copper and manganese, and strongly support the volcanogenic concept. The three mechanisms, however, are by no means the only possibilities, although they are certainly the most typical. Blissenbach (1972) and Blissenbach and Fellerer (1973) indicate that Atlantic-type continental margins may contain ores originally deposited as metalliferous muds during initial opening of mid-oceanic rift systems. The metalliferous muds in the Red Sea (Degens and Ross, 1969), for instance, may someday be part of a continental margin sediment profile. These
Sediments may be incorporated into a mountain belt upon island arc/continent or continent/continent collision (Bird and Dewey, 1970). Another possibility is the incorporation of a continental shallow sea deposit into an orogenic belt. The extensive Oligocene manganese ores of Chiatura and Nikopol (southern USSR) are examples of such epicontinental deposits (Strakhov et al., 1970; Varentsov, 1964) which may someday undergo cordillera-type orogenesis. Similar collisions and remobilizations may engulf deposits formed through such unusual processes as continental over-riding of an oceanic rise. The copper sulphides of the Salton Sea (Skinner et al., 1967) and the manganese and copper deposits of Baja California (Wilson and Locha, 1955; Wilson and Veytia, 1949) may be examples. Mantle hot spots are a more interesting possibility which may be responsible for Hawaiian mineralization (Desborough, Anderson, and Wright, 1969; Skinner and Peck, 1969). In view of the consistent correlation between porphyry copper deposits and subduction zones, however, it is unlikely that hot spots are the cause of porphyry coppers, as suggested by Livingston (1973).

The most important observation to the economic geologist is that copper and manganese enter the orogenic environment through three principal loci:
calc-alkaline magmatism, ophiolite emplacement, and marginal basin development, all of which are related to subduction. Considerable detailed work must yet be done, however, before the economic geologist has the capability of earmarking specific districts as high-potential areas for copper and manganese. The fruition of this thesis, then, depends on the ability of researchers to reconcile the classical studies of orogenesis with the modern concepts of plate tectonics.
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