Distribution of Metallogenic Provinces in Relation to Major Earth Features*

Philip W. *Guild***

Zusammenfassung

„Die Verteilung metallogenetischer Provinzen in Bezug auf Großeinheiten der Erde"

Aus der Theorie und den Beobachtungen in Zusammenhang mit der globalen Tektonik ergeben sich neue Wege 1) für die Abgrenzung und Verteilung einiger metallogenetischer Provinzen bezogen auf die Platten in ihrer heutigen Position; 2) bei der Aufstellung von möglichen, unterschiedlichen genetischen Modellen; und 3) bei der Analyse der Verteilung älterer Lagerstätten in Bezug auf a) ihre ursprüngliche Zusammengehörigkeit oder b) die Lage und Beschaffenheit früherer Plattenränder.

Es gibt im wesentlichen zwei Möglichkeiten: 1) Lagerstätten wurden an einem Plattenrand oder in der Nähe desselben oder 2) innerhalb von Platten gebildet. Jede der beiden Möglichkeiten läßt sich weiter unterteilen: 1 a) an konstruktiven (wachsenden), 1 b) konservativen (transformativen) oder 1 c) destruktiven (verschluckenden) Rändern; 2 a) innerhalb ozeanischer Plattenteile, 2 b) an wandernden Kontinentalrändern oder 2 c) innerhalb kontinentaler Plattenteile. Ziemlich klare Beispiele für 1 c sind die Andine (Kontinent/Ozean) und die Westpazifische (Ozean/Ozean oder Inselbogen) Provinz. Zweifelsfreie Beispiele für 1 a sind relativ selten, für 1 b völlig unsicher. Bekannte endogene Lagerstätten der Kategorie 2 sind naturgemäß auf Kontinentalgebiete beschränkt (2 c); es ist hingegen unwahrscheinlich, daß es überhaupt welche für 2 a oder 2 b gibt.

Diese Einteilung ist zu sehr vereinfacht, um allen Möglichkeiten Rechnung tragen zu können. So findet man z. B. in einem großen Gebiet der Cordillieren in den westlichen Vereinigten Staaten Merkmale von 1 c und 2 c vereint; die Unter-

---

[*] Publication authorized by the Director, U.S. Geological Survey.

[**] Prof. Dr. Ph. W. *Guild*, U.S. Geological Survey, Washington, D.C. 20244, USA.

strömung hörte ohne Zweifel zu dem Zeitpunkt auf, sobald der Mittelpazifische Rücken überfahren war, doch wurden die Verteilung und der Charakter älterer Lagerstätten ebenso von Strukturen der reaktivierten Plattform beeinflußt. Daraus läßt sich zwingend schließen, daß die mafitischen und alkalisch-mafitischen Lagerstätten von 2 c tatsächlich verhinderten wachsenden Plattenrändern (1 a) in kontinentaler Umgebung zugehören. Es ergeben sich ohne Zweifel noch weitere Komplikationen.

Die hier wiedergegebene Einteilung legt nur noch einmal in neuen Worten lange bekannte Begriffe dar, ohne ein geeignetes Mittel darzustellen, um die Ergebnisse aus der metallogenetischen Forschung mit neuen Informationen und Theorien aus anderen Gebieten der Erdwissenschaften zu korrelieren.

Abstract

Global tectonic fact and theory provide new ways of 1) categorizing the known distribution of some metallogenetic provinces with respect to the present lithospheric plates; 2) restricting possible alternative genetic models; and 3) analyzing distributional patterns of older deposits with respect to a) original contiguity, or b) the positions and nature of former plate boundaries.

In the simplest terms, deposits may form at or near 1a) accreting, 1b) transform, or 1c) consuming margins of plates; or 2a) within oceanic parts, 2b) at trailing continental margins, or 2c) within continental parts of plates. Some deposit types have clearly definable positions; others combine feature of two positions, either sequentially or simultaneously.

Analysis of mineral-deposit data in plate-tectonic terms may give new insight into such problems as mantle vs crustal provenance of ore elements and the energy to concentrate them.

Introduction

Global tectonic fact and theory are stimulating revisions in „traditional“ ways of looking at geology. Metallogeny, „the study of the genesis of mineral deposits, with emphasis on their relationship in space and time to regional petrographic and tectonic features“, (AGI, 1972, p. 445) is no exception (*Guild*, 1971, 1972a, 1972b, 1973; *Mitchell* & *Garson*, 1972; *Sawkins*, 1972; *Sillitoe*, 1972a, 1972b, 1972c). The restriction of many types of geologically young deposits to regions of subduction *(Guild*, 1972a) has led various workers to construct models for the genesis of porphyry copper *(Mitchell* & *Garson*, 1972; *Sawkins*, 1972; *Sillitoe*, 1972b) and other sulfide deposits. If the global tectonics is in fact a valid concept as the mass of rapidly accumulating evidence seems to suggest, most if not all ore deposits will have characteristic relationships to the lithospheric plates that can be useful: (1) to categorize them; (2) perhaps to restrict alternative genetic models; and (3) to analyze the distributional patterns of older deposits with respect to (a) original contiguity (*Petrascheck*, 1968; *Schuiling*, 1967), or (b) the positions and nature of former plate boundaries (*Guild*, 1973). The emphasis here will be on the first of these; I will attempt to develop systematically the characteristic settings of a number of deposit types in terms of their positions at or near the margins of, or within, the lithospheric plates and secondarily to discuss how these may bear on some genetic problems.

The major features of the theory are reviewed briefly to set the scene (figures 1 and 2). At present, the surface of the globe consists largely of about eight major plates which are growing (accreting) along rises, for the most part near the midlines of the oceans, and moving symmetrically away. The plates are up to 150 kilometers thick; most have areas of both continental crust and much thinner oceanic crust overlying upper-mantle material. The plates rest on and move over the asthenosphere, a zone of little or no strength revealed by seismic data. Because the area of the earth remains essentially constant, additions to the plates at accreting margins must be balanced at the converging (consuming) margins; this is accomplished by descent of one plate beneath the other along a subduction zone marked by pronounced seismic activity (the Benioff zone). Two situations are illustrated in figure 2, collision of oceanic crust with a continent to produce a Cordilleran margin (the Andes) and with a small ocean basin to produce an island arc (Japan). Recent work (*Karig*, 1971) suggests that some arcs are moving away from the neighboring continents; thus a better example of an ocean/ocean confrontation would be the Mariana Arc, at present largely submerged.

The descending lithosphere partially fuses to form magmas whose composition varies with depth; at about 100 to 200 km these may have the calc-alkaline character (*Dewey* & *Bird*, 1970) with which many of the common hypogene ore deposits are associated (*Fonteilles*, 1967). These magmas rise to form extrusive and intrusive masses. Where two continental plates collide, as in the Himalayas, neither plate can descend, the force is dissipated in severe crushing with little or no magma generation, and endogenic ore deposits do not form.

Transform movement occurs where plates slide past each other without addition or subtraction as is taking place along most of the margin between North America and the Pacific Ocean today.

The present plates are considered to have developed by splitting of a single landmass (Pangaea) or of two landmasses (Laurasia and Gondwana) in post-Paleozoic time. Only a few „modern“ splits of continental masses are shown on figure 1. — the Red Sea-Gulf of Aden and the Gulf of California — but many more, both active and inactive, are known or suspected (see, e. g. *Burke* & *Whiteman*, 1972; *Grant*, 1971, with respect to Africa).

In the simplest global tectonic terms, ore deposits can be thought as formed:

1. At or near plate margins
   a) Accreting (diverging)
   b) Transform
   c) Consuming (converging)

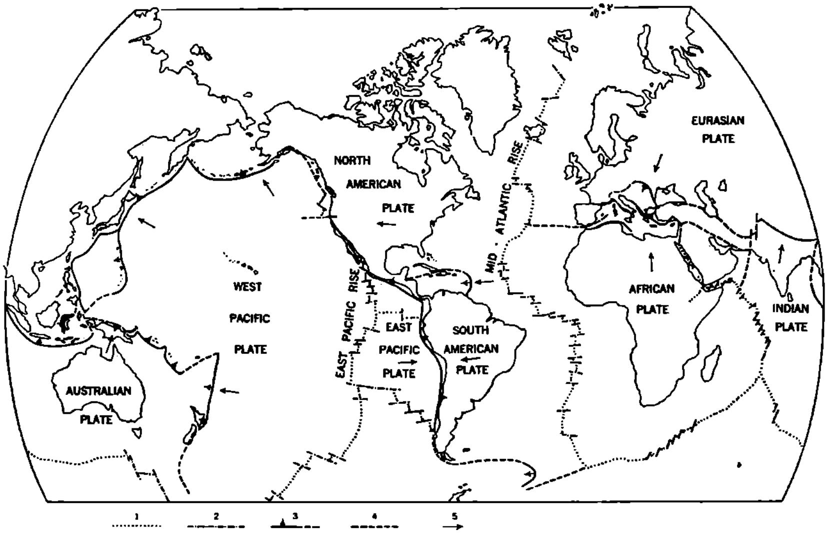

Fig. 1. Major lithospheric plates. 1) Accreting plate margin; 2) transform plate margin; 3) consuming plate margin with dip direction of downgoing plate; 4) margin of uncertain nature and (or) location; 5) relative plate motion.

2. Within plates
   a) In oceanic parts
   b) At trailing continental margins
   c) In continental parts

This oversimplification can serve as a starting point from which to evaluate the principal facts of the distribution of many types of ore deposits. The plate tectonic positions of some are clear, of others doubtful or nonspecific (two or more positions are possible), and of still others the conjunction of two factors seems to be required.

Table 1 (modified from *Guild,* 1971) expands the brief classification above with examples and draws attention to significant difference in the shapes and orientation of deposits, districts, and provinces. Those associated with plate margins tend to be elongated and to parallel the margins; furthermore, mineralization is roughly of the same age as the host rocks, ranging from syngenetic(?) to perhaps the close of a succeeding orogeny. By contrast, many deposits and districts formed within plates tend to be equidimensional; epigenetic mineralization may occur in far older host rocks; and provinces can cross the depositional-structural grain of a region at any angle. The remainder of this paper will be essentially an annotation of the table and discussion of some of its implications.

Table 1

Proposed relationship of some ore-deposit types to lithospheric plates

Deposits formed	Types, possible examples
1. *At or near plate margins*	Orientation of deposits, districts, and provinces tends to parallel margin
a) Accreting (diverging)	Red Sea muds. Ancient analogs? Certain cupriferous-pyrite (massive sulfide) ores, Cyprus? Newfoundland? Podiform Cr (may be carried across ocean and incorporated in island arc or continental margin)
b) Transform	Podiform Cr, Guatemala? Cu and Mn, Boleo, Baja California
c) Consuming (converging)	Chiefly of continent/ocean or island arc/ocean type; deposits formed at varying distances on side opposite oceanic, descending plate Podiform Cr, Alaska FeS_2-Cu-Zn-Pb stratabound massive sulfide, New Brunswick, Japan (Kuroko ores), California, British Columbia Mn of volcanogen type associated with marine sediments, Cuba, California, Japan Magnetite-chalcopyrite skarn ores, Puerto Rico, Hispaniola, Cuba, Mexico, California, British Columbia, Alaska Cu (Mo) porphyries, Puerto Rico, Panama, SW United States, British Columbia, Philippine Is., Bougainville Ag-Pb-Zn, Mexico, western United States, Canada Au, Mother Lode, California; Juneau Belt, Alaska Bonanza Au-Ag, western United States W, Sn, Hg, Sb, western North and South America
2. *Within plates*	Deposits tend to be equidimensional, distribution of districts and provinces less oriented (may be along transverse lineaments)
a) In oceanic parts	Mn-Fe (Cu, Ni, Co) nodules Mn-Fe sediments in small ocean basins with abundant volcanic contributions? Evaporites in newly opened or small ocean basins
b) At continental margins of Atlantic (trailing) type	Black sands, Ti, Zr, magnetite, etc. Phosphorite on shelf
c) In continental parts	Au (U) conglomerates, Witwatersrand Mesabi and Clinton types of iron formation Evaporites, Michigan Basin, Permian Basin; salt, potash, gypsum, sulfur Red-bed Cu; Kupferschiefer and Katangan Cu-Co U, U-V deposits, Colorado Plateau Fe-Ti-(V) in massif anorthosite, Canada, U.S. Stratiform Cr, Fe-Ti-V, Cu-Ni-Pt, Bushveld Complex Carbonatite-associated deposits of Nb, V, P, RE, Cu, F Kimberlite, diamonds Kiruna-type Fe-(P), SE Missouri Mississippi Valley type deposits, Pb-Zn-Ba-F-(Cu, Ni, Co)

Although the Red Sea metalliferous sediments *(Degens & Ross,* 1969) are the best known, least equivocal example of deposits formed at position 1a, accreting plate margins, certain of the stratabound massive sulfides, categorized in 1c (consuming margins) in table 1, are similar to them in both composition and form. Those pyrite and cupriferous pyrite deposits which occur in ophiolite sequences, generally believed to be generated at rises during ocean-floor spreading *(Bird & Dewey,* 1970), are also pleaced in 1a by a number of workers *(Hutchinson,* 1971; *Sillitoe,* 1972c; *Updahyay* & *Strong,* 1973). As the evidence for an island arc (1c) environment for many deposits such as Kuroko ores *(Tatsumi* & *Watanabe,* 1971) is incontrovertible, two plate positions are apparently possible for genesis of these stratabound massive sulfides. Gross distribution of these deposits (fig. 3) will not distinguish between those formed in 1a or 1c, except for the youngest, because the „conveyor belt" movement of the ocean floors toward subduction zones will cause deposits formed on accreting margins to end up near consuming margins eventually. The Paleozoic belts of the Urals (Variscan or Hercynian) and Scandinavia-Appalachia (Caledonian) probably mark former plate margins *(Guild,* 1973), but their nature at the time of ore deposition can only be determined from the sedimentary and petrologic features of the associated rocks.

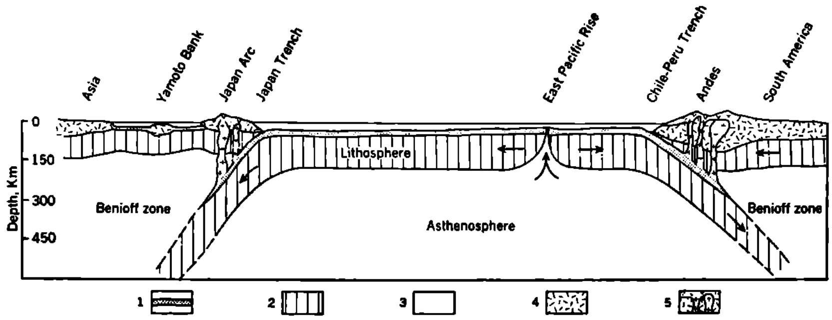

Fig. 2. Schematic section from South America to Asia illustrating major features of the plate tectonic theory. Not to scale. Based on *Dewey* & *Bird* (1970) 1) Oceanic crust; 2) upper mantle; 3) lower mantle; 4) continental crust; 5) calc-alkaline magmas, intrusive (+) and extrusive (v) products.

Chromite ores have several possible plate positions. Podiform masses in alpine peridotite are believed to have segregated in the mantle before introduction into the crust as already solidified masses carried up in crystal mushes *(Thayer,* 1942; *Guild,* 1947; Flint et al., 1948). Upwelling of the mantle peridotite, the depleted pyrolite of *Green* & *Ringwood* (1969) from which tholeiitic basalt magma has been abstracted, can introduce chromite at accreting margins. Obduction of

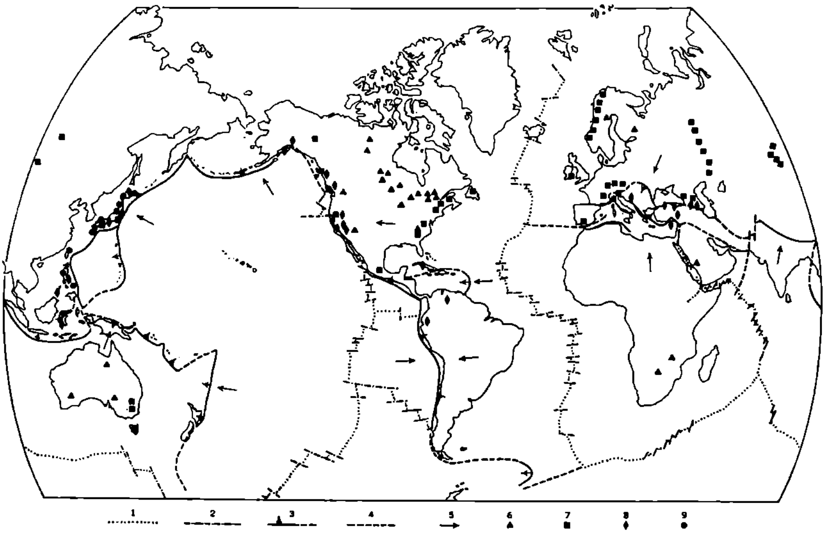

Fig. 3. Distribution of stratabound massive sulfide deposits. 1) Accreting plate margin; 2) transform plate margin; 3) consuming plate margin with dip direction of downgoing plate; 4) margin of uncertain nature and (or) location; 5) relative plate motion; 6) Precambrian deposit; 7) Paleozoic deposit; 8) Mesozoic deposit; 9) Cenozoic deposit.

ophiolite slices at consuming margins after their transport across an ocean floor by plate movement can emplace them in island arcs or continental margins. I believe that intrusion of peridotites along convergent margins by rheomorphic action can bring chromite segregations directly from the mantle as in the small oval intrusions of the Kenai Penisula *(Guild,* 1942) and Baranof Island *(Guild* & *Balsley,* 1942) of Alaska. Yet another possibility is along transform faults. *Dewey* & *Bird* (1970, p. 2630) suggest that serpentinite is injected along a zone of cataclasis on the active segment; chromite deposits could accompany this serpentinite. Chromiferous peridotite in lenses along the Motagua and Polochic fault zones in Guatemala may have had this origin. However, it has been suggested *(Newcomb,* 1973) that the Motagua fault zone is a Paleozoic suture; if so, the chromite deposits along it would have positions analagous to those in the Zagros crush zone of Iran.

Guilbert (1971) suggested that the copper and manganese deposits at Boleo on the west shore of the Gulf of California formed near or on a transform fault (position 1b). I subsequently speculated that the mineralization occurred at the intersection of the East Pacific Rise itself and an incipient transform fault *(Guild,* 1972a, p. 23), which would make the site a combination of 1a and 1b. It now seems probable to me that additional examples of such conjunctions (hybrid positions) will turn up as we learn more about the details.

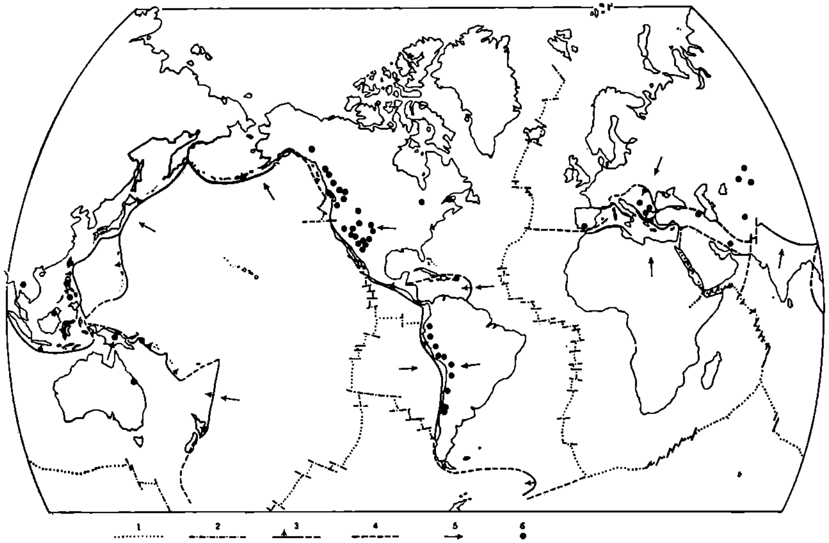

Fig. 4. Distribution of porphyry copper and molybdenum deposits. 1) Accreting plate margin; 2) transform plate margin; 3) consuming plate margin with dip direction of downgoing plate; 4) margin of uncertain nature and (or) location; 5) relative plate motion; 6) porphyry deposit.

Turning to the consuming margins, 1c, we see that many of the most common ore types have this position. In explanation, it seems evident that the energy to concentrate elements comes from forces activated by plate collision (magma generation, metamorphism, etc.). However, the elements (chiefly metals) may come from the downgoing oceanic plate, the overriding continental plate, or both. *Sillitoe* (1972b) has marshalled impressive evidence to support derivation of the porphyry copper deposits from the oceanic plate. Figure 4 shows that most porphyry deposits (both copper and molybdenum) are near the boundaries of the present plates and on the continent or island-arc side above the subduction zones. The simplest, most clearcut examples are along the Andean chain in South America and in the arcs of the Western Pacific. Elsewhere, particularly in the Southwestern Province of North America, the picture is not so clear. Instead of linear patterns paralleling closely plate margins, the deposits form a more or less equidimensional cluster 1200 by 1500 km across, in which lineaments or other intraplate structures seem to have exerted a major control on their distribution (*Tweto* & *Sims*, 1963, *Titley*, 1970; *Lowell*, 1973). The width of the zone and extended time span (Jurassic to Miocene) seem to preclude a simple relation to a Benioff zone. These deposits, and perhaps the Siberian porphyry deposits as well, may better be classed with those of „reactivated platforms“ (*Guild*, 1972b), and hence fit more closely category 2c than 1c.

A number of other deposit types shown as 1c in table 1 may also be hybrid in the sense that they display characteristics of both plate margins and continental plate interiors.

Zonation of the base metals perpendicular to continental margins is a common phenomenon. In general, copper predominates near the margins in the eugeosynclinal parts of orogens, whereas lead and zinc are localized in the miogeosynclines and on platforms. *Laznicka* & *Wilson* (1972) have quantified this relationship using data from 4500 deposits throughout the entire world; their copper-lead lines (limits between copper-rich and lead-rich provinces) of Mesozoic and Tertiary mineralization lie near the plate margins. However, they note *(Wilson & Laznicka,* 1972, p. 45) that in the western United States three isolated major deposits, Butte, Bingham, and Ely, lie within the Paleozoic and Mesozoic miogeosynclinal domain. Lead isotope studies (e. g., *Murthy* & *Patterson,* 1961; *Stacey, Zartman* & *NKoma,* 1968, and *Zartman* & *Stacey,* 1971) indicate derivation of part of the lead from crustal rocks (because of its two-stage or multistage nature). Many districts of the western United States are localized on transverse structures and especially at intersections (e. g. *Billingsley* & *Locke,* 1941; *Mayo,* 1958; *Wisser,* 1959; *Jerome* & *Cook,* 1967; *Landwehr,* 1968). The upper lithospheric plate seems to have controlled the distribution of the deposits, and probably was the source for at least part of their metals as well.

Ores of lithophile elements such as tungsten and tin may be other examples of metals with hybrid plate positions. The distribution of tungsten deposits in the western United States (see e. g., *Kerr,* 1946, fig. 1) suggests that factors other than proximity to, or distance from, a subduction zone were operative in their genesis. The western limit of the deposits coincides approximately with the quartz diorite line *(Moore,* 1959; *Moore* & al., 1963), hence they might be thought of as another example of control of chemical composition by depth of magma generation *(Kuno,* 1959; *Dickinson,* 1968). It seems more likely, however, that the tungsten was derived from crustal materials by palingenesis *(Smirnov,* 1968) than from descending oceanic floor. The long-lived tin belts *(Schuiling,* 1967; *Petrascheck,* 1968) also indicate that certain areas have remained anomalously high in this element and that rejuvenation has played an important role, as *Schneider-Scherbina* (1964) has advocated for the tin deposits of Bolivia.

Deposits within plates

Many of the deposits formed within plates are exogenic and do not require extensive comment here. The nodules of the ocean floor are well known. Iron-manganese formations such as that in Aroostook County, Maine *(Pavlides,* 1962) and western New Brunswick were deposited at a time — Late Ordovician-Early Silurian(?) — when a contracting small ocean basin may have existed between an island arc and the mainland *(Bird* & *Dewey,* 1970, p. 1049). Numerous evaporite sequences have formed in newly opening rifts (South Atlantic, Red Sea, Gulf of California) because of the restricted circulation of oceanic water. They could be considered as deposits at site 1a but because of their exogenic nature are placed here.

The products of tholeiitic magmas within the oceanic parts of plates (Hawaiian islands, etc.) are noteworthy for their lack of endogenic mineral deposits, and the likelihood that any conventional ore deposits were formed in position 2a seems remote.

The trailing continental margins (2b) are logical and obvious loci for heavy-mineral accumulations. The beach placers of rutile and (or) ilmenite, plus zircon, on the fragmented margins of Gondwana are outstanding examples. Source rocks for the titanium minerals, especially the rutile, are probably areas of granulite-facies metamorphism in the hinterland (Eric R. *Force*, U. S. Geol. Survey, oral communication, 1972). These are examples of a two- or multistage history in which ore genesis begins in one plate environment and subsequently is completed in another. Such deposits contrast with the hybrid type that combines features of two plate positions simultaneously. Conversion of a passive margin with heavy-mineral concentrations to an active one *(Dewey* & *Bird*, 1970, p. 2638—2640) could introduce a third stage of ore concentration through palingenesis of low-grade clastic terrigenous materials.

Very diverse types of deposits are formed in 2c, the continental parts of the lithospheric plates. Here are the major deposits of sedimentary, exogenic ores, both the Proterozoic iron formations and the Phanerozoic ironstones, and also the evaporites of the large basins. Redbed copper and the somewhat related uranium and uranium-vanadium deposits of the Colorado Plateau and elsewhere form here, as do the Kupferschiefer and Katangan copper deposits, whatever their precise genesis may be.

Endogenic deposits in continental settings form another major group that comprises both those with more or less close association with igneous rocks of widely different compositions and those with no, or at best equivocal relationship to any igneous activity. The igneous-associated deposits include the stratiform chromite deposits (Bushveld, Stillwater, et al.) and the nickel-copper-platinum and the vanadium-bearing titaniferous magnetite layers best exemplified in the Bushveld. The immense size, uniformity of composition and structure, and relationship of the Bushveld Complex to the subjacent sedimentary rocks attest to intrusion of mafic magma from a deep source (lower crust or mantle) into a stable platform.

The nonlayered iron-titanium deposits, also moderately vanadiferous, that occur in the massif-type anorthosite bodies in many parts of the world, and iron-(apatite) and iron-copper deposits in Missouri associated with alkali-rich extrusive and intrusive rocks are other example of deposits introduced into continental lithosphere from deep sources.

Deposits of 2c discussed thus far are not numerous enough to have been generally related to lineaments (although such major examples as the Great Dyke and

Muskox indicate that the magma arose along extensive fractures that must have penetrated the sialic crust), but the distribution of carbonatite-associated deposits of niobium, vanadium, phosphate, and rare earths shows definite linear patterns that are not related to orogenic belts. This is also true for the kimberlites. Certain magnetite, titanium, and barite deposits are among the less common but in places very large deposits that also have this general lithospheric plate setting. Examples are known on all the continents, and they span much of the geologic record since early Precambrian time. In the southern hemishere many may be related to the Mesozoic breakup of Gondwana, but others are probably associated with abortive fracturing that did not lead to actual rifting *(Burke & Whiteman,* 1972).

Prime examples of deposits with little or no apparent relationship to magmatic rocks are the so-called Mississippi Valley type of lead-zinc-(copper)-barite-fluorite ores, which are, in North America at least, obviously in 2c. Without going into the details, which have been thoroughly documented in a symposium organized by Charles Behre *(Brown,* 1967), many are located in carbonate platform rocks overlying old shield areas. The deposits in any one district have a pronounced tendency to be restricted to one or a few favorable stratigraphic units; various local features (reefs, pinchouts, solution breccias, etc.) determine the precise depositional environment. However, on a continental scale the North American districts occur along lineaments which are also the loci of alkaline intrusive rocks, including kimberlites, and of cryptoexplosion structures. The best documented of these, the 38th parallel lineament, has been traced some 1300 km in a westerly direction from the Appalachians to the mid-continent and may extend at least another 900 km to the Rocky Mountains *(Heyl,* 1972). *Snyder* (1970) lists 8 mineral districts, 10 igneous features, and 8 explosion events along or near it and draws attention to similar features, the Tennessee lineament near the 36th parallel and the Galena lineament near the 42nd, that are also loci of major districts together with igneous and explosion phenomena. In Canada, the Pine Point district directly overlies the McDonald fault that divides the Slave and Churchill Provinces of the Shield and has been traced in the subsurface many hundreds of kilometers to the southwest across the Phanerozoic Interior Lowlands. All these structures must have been long-lived; intermittent activity along the 38th parallel lineament extended from at least Cambrian to Tertiary time, and seismic events are continuing at present. It seems evident, and the inclusions in the kimberlites prove *(Brookins,* 1969), that the fracture zone penetrated the sial at times, but the source of the metals in the ore deposits was not necessarily in the mantle. Lead isotope data indicate that at least some of the lead was derived from crustal rocks and it may well be, as *Snyder* (1970, p. 91) and others have suggested, that heat rising along lineament zones has increased the geothermal gradient and provided the energy to concentrate metals from the connate brines in deep basins. We probably have another example of multistage ore concentration. Whether the North American pattern is applicable to that in the Eastern, Hemisphere is a question I am prepared to answer, but the similarities of the deposits described by numerous European colleagues *(Brown,* 1967) to those of the Mississippi Valley districts are so close in many respects that some common mode of origin seems inevitable.

A relatively unimportant district may provide a clue to the relationship between platforms, cover, and deep fractures in metallogenesis. Lead-zinc-(copper-fluorite) deposits in the Benue trough of Nigeria *(Farrington,* 1952) occur in Cretaceous sedimentary and volcanic rocks that filled a rift (aulacogen) that is believed to have opened at the triple junction formed as South America and Africa began to separate *(Grant,* 1971). Though most are veins in clastic or volcanic rocks, some apparently are stratiform in limestone; the mineralogy is, in any case, reminiscent of the Mississippi Valley type under discussion. *Dewey & Burke* (1973) have recently suggested that such structures (including this one) form in response to uplift of crustal lithosphere over mantle plumes. Such plumes would provide the relatively low but persistent heat indicated by fluid-inclusion studies *(Roedder,* 1971) to have been present during a prolonged period in districts in the eastern United States. *Macintyre* (1973) has suggested that plumes in continental settings are responsible for emplacement of nephelinitic, carbonatitic, and kimberlitic rocks, and that periodic pluming may have reactivated major lineaments and rifts. This new concept of deep vertical movement and consequent upward propagation of energy from subcrustal sources, with or without magma transfer, may provide the mechanism called for years ago by *Billingsley & Locke* (1941, p. 59) to account for many of the ore districts of the United States. It also can explain the relationship between doming and ore districts documented by *Wisser* (1960).

Conclusion

If the Benue trough and, by extrapolation, the Mississippi Valley deposits are in any way rift associated, we seem to have come nearly full circle, except that the deposits in 2c are in a continental setting whereas those in 1a have an oceanic one. Both seem to derive their primary energy from vertical, deep-seated sources, but the ore-forming elements of the former may have been concentrated from disperse crustal reservoirs in contrast to a supposed mantle source for those in 1a. Similarly, the deposits tentatively assigned to 1c but noted as transitional to those of platforms have many similarities to deposits discussed under 2c. From the plate-tectonic viewpoint I suggest that the critical distinction here is whether subduction and regeneration of elements present in the downgoing slab played a dominant role in ore formation or whether energy (heat) was the principal or only factor directly related to plate convergence.

The tentative classification of table 1 is far from definitive; for example, many types of deposits are not mentioned. Obviously more facts are needed concerning the environments of deposits and the relationship between various categories, and, of course, both the validity of the plate tectonic concept and its details require confirmation through additional research. However, I believe that we are in a position to define some fundamental problems of ore genesis and hence to design studies directed toward their solution. We should also be able before too much longer to explain the distribution of the so-called metallogenic provinces in rational terms that are consonant with the major aspects of earth science that seem to be evolving so rapidly.

References

American Geol. Inst. (1972): Glossary of Geology, Washington, D. C. 805+52 p.

Billingsley, P. & *Locke*, A. (1941): Structure of ore districts in the continental framework. — Am. Inst. Min. and Met. Engrs. Trans., *144*, p. 9—64.

Bird, J. M. & *Dewey*, J. F. (1970): Lithosphere plate-continental margin tectonics and the evolution of the Appalachian orogen. — Geol. Soc. America Bull., *81*, p. 1031—1060.

Brookins, D. G. (1969): Riley County, Kansas kimberlites and their inclusions (abs.). — Geol. Soc. America Abs. with Programs for 1969, pt. 2, p. 4.

Brown, J. S. ed. (1967): Genesis of stratiform lead-zinc-barite-fluorite deposits (Mississippi Valley type deposits). — A symposium, New York, 1966: Econ. Geology Mon. *3*, 443 p.

Burke, K. & *Whiteman*, A. J., 1972, Uplift, rifting, and the breakup of Africa (abs.). — Am. Geophys. Union Trans., *53*, p. 517.

Degens, E. T. & *Ross*, D. A., eds. (1969): Hot brines and Recent heavy metal deposits in the Red Sea. — Springer-Verlag, Inc., New York, 600 p.

Dewey, J. F. & *Bird*, J. M. (1970): Mountain belts and the new global tectonics. — Jour. Geophys. Research, *75*, p. 2625—2647.

Dewey, J. F. & *Burke*, K. (1973): Plume generated triple junctions (abs.). — Am. Geophys. Union Trans., *54*, p. 239.

Dickinson, W. R. (1968): Circum-Pacific andesite types. — Jour. Geophys. Research, *73*, p. 2261—2269.

Farrington, J. L. (1952): A preliminary description of the Nigerian lead-zinc field. — Econ. Geology. *47*, p. 583—608.

Flint, D. E., de *Albear*, J. F. & *Guild*, P. W. (1948): Geology and chromite deposits of the Camagüey district, Camagüey Province, Cuba. — U.S. Geol. Survey Bull. *954-B*, p. 39—63.

Fonteilles, M. (1967): Appréciation de l'intérêt metallogénique du volcanisme de Madagascar à partir de ses caractères pétrologiques. — France, Bur. Recherches Géol. et Minères Bull. No. *1*, p. 121—154.

Grant, N. K. (1971): South Atlantic, Benue trough, and Gulf of Guinea Cretaceous triple junction. — Geol. Soc. America Bull., *82*, p. 2295—2298.

Green, D. H. & *Ringwood*, A. E. (1969): The origin of basaltic magmas. — In: P. J. *Hart*, ed., The Earth's crust and upper mantle, Am. Geophys. Union Geophys. Mon. *13*, p. 489—495.

Guilbert, J. M. (1971): Known interactions of tectonics and ore deposits in the context of new global tectonics. — Am. Inst. Min. Metall. Petrol. Engrs., Soc. Mining Engrs. Preprint *71-S-91*, 19 p.

Guild, P. W. (1942): Chromite deposits of Kenai Peninsula, Alaska. — U.S. Geol. Survey Bull. *931-G*, p. 139—175.

— (1947): Petrology and structure of the Moa chromite district, Oriente Province, Cuba. — Am. Geophys. Union Trans., *28*, p. 218—246.

Guild, P. W. (1971): Metallogeny: a key to exploration. — Mining Eng., *23*, no. 1, p. 69—72.

— (1972a): Metallogeny and the new global tectonics. — Internat. Geol. Cong., 24th, Montreal, Repts., sec. *4*, p. 17—24.

— (1972b): Massive sulfides vs. porphyry deposits in their global tectonic settings (abs.). — Jour. Mining Met. Inst. Japan, *88*, p. 725.

— (1973): Massive sulfide deposits as indicators of former plate boundaries (abs.). — Econ. Geology, *68*, p. 137—138; U.S. Geol. Survey Open-file report, 11 p.

Guild, P. W. & *Balsley,* J. R., *Jr.* (1942): Chromite deposits of Red Bluff Bay and vicinity, Baranof Island, Alaska. — U.S. Geol. Survey Bull. *936-G,* p. 171—187.

Heyl, A. V. (1972): The 38th parallel lineament and its relationship to ore deposits. — Econ. Geology *67,* p. 879—894.

Hutchinson, R. W. (1971): Volcanogen sulfide deposits and their metallogenic significance (abs.). — Mining Eng., *23,* no. 12, p. 71.

Jerome, S. E. & *Cook,* D. R. (1967): Relation of some metal mining districts in the western United States to regional tectonic environments and igneous activity. — Nevada Bur. Mines Bull. *69,* 35 p.

Karig, D. E. (1971): Origin and development of marginal basins in the western Pacific. — Jour. Geophys. Research, *76,* p. 2542—2561.

Kerr, P. F. (1946): Tungsten mineralization in the United States. — Geol. Soc. America Mem. *15,* 241 p.

Kuno, H. (1959): Origin of Cenozoic petrographic provinces of Japan and surrounding areas. — Bull. Volcanol., ser. 2, *20,* p. 37—76.

Landwehr, W. R. (1968): The genesis and distribution of major mineralization in western United States. — Econ. Geology, *63,* p. 967—970.

Laznicka, P. & *Wilson,* H. D. B. (1972): The significance of a copper-lead line in metallogeny. — Internat. Geol. Cong., 24th, Montreal, Repts., sec. *4,* p. 25—36.

Lowell, J. D. (1973): Regional characteristics of southwestern North America porphyry copper deposits. — Am. Inst. Min. Metall. Petrol. Engrs., Soc. Mining Engrs., Preprint *73-S-12,* 37 p.

Macintyre, R. R. (1973): Possible periodic pluming (abs.). — Am. Geophys. Union Trans., *54,* p. 239.

Mayo, E. B. (1958): Lineament tectonics and some ore districts of the southwest. — Mining Eng., *10,* p. 1169—1175.

Mitchell, A. H. & *Garson,* M. S. (1972): Relationship of porphyry copper and circum-Pacific tin deposits to paleo-Benioff zones. — Inst. Mining and Metallurgy Trans. B., *81,* no. 783, p. B10—B25.

Moore, J. G. (1959): The quartz diorite boundary line in the western United States. — Jour. Geology, *67,* p. 198—210.

Moore, J. G., *Grantz,* A. & *Blake,* M. C., *Jr.* (1963): The quartz diorite line in northwestern North America. — U.S. Geol. Survey Prof. Paper *450-E,* p. E89—E93.

Murthy, V. R. & *Patterson,* C. (1961): Lead isotopes in ores and rocks of Butte, Montana. — Econ. Geology, *56,* p. 59—67.

Newcomb, W. E. (1973): Late Paleozoic tectonics of the Motagua fault: a subduction-collision scar? (abs.). — Am. Geophys. Union Trans., *54,* p. 471—472.

Pavlides, L. (1962): Geology and manganese deposits of the Maple and Hovey Mountains area, Aroostook County, Mainer. — U.S. Geol. Survey Prof. Paper *362,* 116 p.

Petrascheck, W. E. (1968): Kontinentalverschiebung und Erzprovinzen. — Mineralium Deposita, *3,* p. 56—65.

Roedder, E. (1971): Fluid-inclusion evidence on the environment of formation of mineral deposits of the Southern Appalachian Valley. — Econ. Geology, *66,* p. 777—791.

Sawkins, F. J. (192): Sulfide ore deposits in relation to plate tectonics. — Jour. Geology, *80,* p. 377—397.

Schneider-Scherbina, A. (1964): Epocas y zonas metalogenéticas. — In *Ahlfeld* Federico, and *Schneider-Scherbina,* A., Los yacimientos minerales y de hidrocarburos de Bolivia: Bolivia Min. de Minas y Petroleo, Bol. 5, 188 p., p. 31—39.

Schuiling, R. D. (1967): Tin belts on the continents around the Atlantic Ocean. — Econ. Geology, *62,* p. 540—550.

Sillitoe, R. H. (1972a): Relations of metal provinces in Western America to subduction of oceanic lithosphere. — Geol. Soc. America Bull., *83,* p. 313—318.

— (1972b): A plate tectonic model for the origin of porphyry copper deposits. — Econ. Geology, *67*, p. 184—197.

Sillitoe, R. H. (1972c): Formation of certain massive sulphide deposits at sites of sea floor spreading. — Inst. Mining and Metallurgy Trans. B., *81*, no. 789, p. B141—B148.

Smirnov, V. I. (1958): The sources of ore-forming material. — Econ. Geology, *63*, p. 380—389.

Snyder, F. G. (1970): Structural lineaments and mineral deposits, eastern United States. — In AIME World Symposium on Mining and Metallurgy of Lead and Zinc, v. 1, Mining and concentrating of lead and zinc. — Am. Inst. Min. Met. and Petrol. Engrs., New York, p. 76—94.

Stacey, J. S., *Zartman*, R. E. & *NKomo*, I. T. (1968): A lead isotope study of galenas and selected feldspars from mining districts in Utah. — Econ. Geology, *63*, p. 796—814.

Tatsumi, T. & *Watanabe*, T. (1971): Geological environment of formation of the Kuroko-type deposits. — Soc. Mining Geol. Japan, Spec. Issue *3*, p. 216—220. (Proc. IMA-IAGOD Meetings '70, IAGOD Vol.).

Thayer, T. P. (1942): Chrome resources of Cuba. — U.S. Geol. Survey Bull. *935-A*, p. 1—74.

Titley, S. R. (1970): Paleotectonic environment of Arizona porphyry copper deposits (abs.). — Geol. Soc. America Abs. with Programs, 2, no. 7, p. 707—708.

Tweto, O. & *Sims*, P. K. (1963): Precambrian ancestry of the Colorado mineral belt. — Geol. Soc. America Bull. *74*, p. 991—1014.

Updahyay, H. D. & *Strong*, D. F. (1973): Geological setting of the Betts Cove copper deposits, Newfoundland: an example of ophiolite sulfide mineralization. — Econ. Geology, *68*, p. 161—167.

Wilson, H. D. B. & *Laznicka*, P. (1972): Copper belts, lead belts, and copper-lead lines of the world. — Internat. Geol. Congress., 24th, Montreal, Repts., sec. *4*, p. 37—51.

Wisser, E. H. (1959): Cordilleran ore districts in relation to regional structure. — Canadian Inst. Mining Metall., Bull. *561*, p. 34—42.

— (1960): Relation of ore deposition to doming in the North American Cordillera. — Geol. Soc. America Mem. *77*, 117 p.

Zartman, R. E. & *Stacey*, J. S. (1971): Lead isotopes and mineralization ages in Belt Supergroup rocks, northwestern Montana and northern Idaho. — Econ. Geology, *66*, p. 849—860.