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Good morning. My topic is, to put it mildly, a speculative one based on insufficient and frequently equivocal data. I hope, however, that it may serve to focus attention on, and perhaps contribute to, an understanding of the nature and perhaps the genesis of these ores as well as to point the way in which we economic geologists can play a role in the new cult of the plate tectonocists.

Let me first define my usage of the term. I include under massive sulfides the tabular to lenticular deposits that are essentially parallel to the stratification of the enclosing rocks and consist largely or even entirely of iron sulfide, usually pyrite. Variable, generally small amounts of chalcopyrite, sphalerite, galena, and minor gold and silver values are ordinarily present. Many of the deposits are closely associated with volcanic rocks, others are in thick sequences of graywacke or slate. A few stratabound deposits in thick carbonate sequences are also described as massive, but as they seem to be far less pyritic, I exclude them here.

The volcanic rocks range from mafic to felsic; the close correspondence between simple iron-sulfide deposits and basalts on the one hand and increasing values in base metals with the more differentiated intermediate and acid rocks on the other strongly implies a genetic relationship. Pillows and other features prove the submarine nature of the volcanism, and I believe that there is general agreement (1) that whether these deposits are syngenetic (volcanic exhalative), as some features suggest, or epigenetic, they are in fact more or less contemporaneous with the rocks in which they occur and (2) that these rocks are themselves emplaced fairly early in the geologic history of the area. In other words, most workers consider that the massive sulfide deposits are pre-orogenic and hence have undergone whatever deformation and metamorphism may have affected the region. As many deposits occur in orogenic belts, structural complexities, proximity to subsequent intrusive rocks of various kinds, partial remobilization, and metamorphism have greatly obscured their essential nature.

Now for the plate tectonics. Figure 1 shows the major lithospheric plates, which are believed to grow by addition of new crust at the mid-ocean ridges or rise and move in the directions indicated by the arrows. Note that most of them contain areas of both ocean and continent. There are only about eight major plates, but numerous fragments exist between some of them. As the earth has a constant size, crust must be consumed in some areas. This occurs where two plates with opposing motion come together: the collision may involve a continent and an ocean, as in South America; two oceanic segments, which gives rise to an island arc, as for example the Marianas; an island arc and a continent, a situation believed to have occurred repeatedly on the western coast of North America in earlier geologic time; or two continental masses, as between India and the Asian plate. A third type of plate boundary is the transform, along which two plates move past one another with neither additions nor subtractions to their areas. The eastern border of the North Pacific has this character today as the West Pacific plate slides northwestward past the North American plate along the San Andreas and Queen Charlotte faults.

Figure 2 is a schematic section from South America to Asia. Crust forms at the East Pacific Rise. To the east, it pushes under the edge of South America, descending by subduction along the seismic Benioff zone to depths of many hundreds of kilometers. On the west, the ocean crust descends under Japan. Melting of the plate produces the magmas that form the extrusive and intrusive rocks of the Andes and Japan; at depths of 100 to 200 kilometers these have the calc-alkaline character that gives rise to many of the base- and precious-metal deposits.

Table 1 summarizes the possible space relationships of ore deposits and lithospheric plates. Deposits may form either at or near plate margins, or within plates. Each major category has three subdivisions: at accreting, transform, or consuming margins; or in ocean parts, trailing continental margins; or within continental parts of plates. I believe that most types of deposits can be assigned to one or another of these positions.

I direct your attention to the upper half of the table--deposits formed at or near plate margins. The principal point I wish to make is that on this table the stratabound massive sulfide deposits, including the Kuroko ores, are placed in the category of consuming plate margins (as, indeed, are many of the other common endogenic ore types). The chief example given of deposits at an accreting margin are the Red Sea muds and possible ancient analogues. The table is, however, an old, very preliminary one that was put forth in hopes that it would stimulate critical discussion and consideration of fundamental factors of ore genesis. It is undoubtedly oversimplified, and it may in fact place deposits with completely different plate positions in the same pigeon-hole. Last year in San Francisco, Dick Hutchinson (1971) distinguished three varieties of massive sulfide deposits according to their metal contents and associated volcanic rocks. He pointed out that the pyrite-chalcopyrite type in Phanerozoic orogens are common in the ophiolites that are ordinarily considered as rift-generated. Sillitoe (1972) has recently suggested that many--even most--of the Phanerozoic deposits were originally formed at ocean rises and subsequently rafted across the oceans to be incorporated in continental margins or island arcs by obduction, or subducted and regenerated. Both use Cyprus, widely believed to represent an actual piece of mid-ocean rise comprising peridotite overlain by gabbro, sheeted dike complex, pillow basalts with numerous massive sulfide bodies, and siliceous iron-manganese-rich sediments as their type example. They may well be correct.

Also, of course, the Red Sea muds are frequently equated with the massive sulfides as modern examples. All in all, the need to up-date this table seems clear. (Parenthetically, I have myself proposed elsewhere (Guild, 1972) that the Boleo copper deposits in Baja California formed at or near an accreting margin, quite probably at its intersection with a transform fault.)

What can the distribution of deposits tell us about positions of the plates--and why choose the massive sulfides from among the numerous types? To discuss the latter question first, the massive sulfides are a distinctive class that is widely distributed throughout the geological record from the Archean to the Tertiary. Their penecontemporaneous origin has surely been the reason for their preservation through burial and downwarping during orogeny. In contrast, many deposits, notably the porphyry coppers, have been introduced late in the orogenic cycle at high levels in the crust where rapid isostatic uplift and erosion have removed most of the older ones.

This brings me to the principal theme: can the distribution of massive sulfides contribute to deciphering the pre-Mesozoic history of the Earth? Did plate tectonics antedate the breakup of Pangaea, the single continent, or the Laurasia-Gondwana pair postulate for the end of Paleozoic time? The plate tectonic theory rests largely on geophysical (seismic, magnetic, gravity, and heat flow) data and on sampling of the ocean floor. Since, according to the theory, the oceans are all young, less than about 200 million years, only the record preserved in the rocks of the land areas (chiefly the continents) can provide evidence of possible earlier plate boundaries and movement. The only surviving geophysical evidence is that provided by paleomagnetism, which may be quite equivocal, so the earlier history must, perforce, rest largely on the geologic record.

I propose now to work back in time from the relatively well known to the less known with a series of maps--a sort of time slicing. Let me say that they are far from complete--some, perhaps many, deposits are undoubtedly omitted either because they are not described in the literature or I failed to find them. Conversely, some spots may represent deposits that do not belong to this class; the descriptions, especially the older ones, are frequently inadequate and opinions as to genesis are often at variance with the genetic mode that has only recently been generally accepted.

Figure 3 shows the Tertiary deposits. The most numerous and best known, and also the least equivocal as to environment and origin, are the Kuroko ores of Japan. The Kuroko themselves are black sphalerite-galena-chalcopyrite-barite ores that commonly occur in mudstone or tuff on the flanks of rhyolite or dacite domes. They ordinarily grade down into or are underlain by yellow pyrite-chalcopyrite ores and siliceous chalcopyrite ores. Anhydrite-gypsum deposits are frequent. Ferruginous silica zones containing foraminifera are intimately associated with the ores and testify to the marine environment. Slump structures and intraformational conglomerates of ore blocks prove the syngenetic nature of the uppermost (black) ores, while alteration and stockwork veins in the lower, siliceous ores indicate they are technically epigenetic. All the Kuroko deposits are restricted to a brief episode in the middle Miocene and are attributed to volcanic emanations traversing the near-surface volcanic-sedimentary rocks and discharging onto the sea floor. Volcanism in the earlier part of the Miocene had been characterized by alkaline and tholeiitic types; it is undoubtedly significant that these high zinc-lead ores formed only after the magmatism changed to a calc-alkaline type.

As the nature of these Tertiary Japanese ores was gradually recognized, others with similar features came to be compared with them. So far as I know, only the Japanese ores are mid-Tertiary, but some early Tertiary pyrite-chalcopyrite deposits in the Philippines are thought to be of the same general type as, some believe, are deposits in the Mediterranean area.

Deposits of Mesozoic age, shown on figure 4, are widely distributed around the rim of the Northern Pacific, in the Caribbean area, and in the general area of Asia Minor. Japan, Taiwan, and the Philippines have numerous bedded cupriferous pyrite ores, with or without zinc, in volcanic, usually quite mafic sequences of flows, volcaniclastic and marine sediments, and minor intrusive sills and dikes. Deformation, metamorphism, and the intrusives have obscured the picture, but the kinship of these deposits to the Kuroko ores is now generally accepted, and their island-arc environment is clear. Numerous deposits around the northern and eastern rim of the Pacific are also in volcanic (eugeosynclinal) sequences that have been correlated with island-arc assemblages by Hamilton (1969); Souther, Monger, and Gabrielse (1971); and others without reference to the ores. These geologists believe that plate convergence caused island arcs of various ages to be driven against and welded to the continent. If so, the massive sulfides of western North America may have formed at considerable distances from their present positions.

I would like to emphasize the contrast between the Mesozoic distribution around the Pacific and that shown for the Tertiary in the previous map. With the cessation of subduction and the conversion of the boundary between North America and the Pacific to a transform margin in Tertiary time, conditions for genesis of massive sulfides, or for their incorporation into the continental margin, ceased.

Deposits of the Eastern Hemisphere occur in the general region of Tethys, where the situation between Eurasia and Africa is exceedingly complex. The Cyprus deposits have already been mentioned. Here are the Küre deposits that Dr. Suffel will talk about this afternoon. Others are known in the Transcaucasus and in Yugoslavia.

Whether associated with converging or diverging margins, the post-Paleozoic deposits are clearly localized along some, but not all, of the present-day plate margins.

Let's go back to Late Paleozoic time, shown on figure 5. Again, numerous deposits occur around the rim of the Northern Pacific, suggesting that conditions were fairly similar there to those of the Mesozoic. In the Eastern Hempshire, the Variscan deposits lie slightly to the north of the later ones but follow the general trend of the Tethys. The most noteworthy difference from the patterns we have seen so far is in the USSR, where very numerous cupriferous pyrite deposits extend along much of the eastern flank of the Urals. Warren Hamilton (1970) has interpreted the area as having had island-arc characteristics in Silurian and Devonian time, overlying a Benioff zone in an ocean that separated the Russian and Siberian platforms. Subsequent convergence welded the arc to the Russian platform. A similar situation probably existed on the southwestern flank of the Siberian platform where a belt of massive sulfides is preserved in the Altai district.

Turning now to Early Paleozoic and Late Precambrian time, we see a completely different picture in figure 6. By far the most extensive belts are those in eastern North America and northwestern Europe. If indeed there was a proto-Atlantic Ocean which opened and closed, as has been proposed by a number of persons, we may have a single Caledonian belt that extends from Alabama to northernmost Norway. The remaining deposits of which I know are widely scattered. A deposit in southern Mexico conceivably fits the eastern North America picture. A few uneconomic occurrences in Senegal might have been quite close to the Southeastern United States. There is a short belt in the Tasman geosyncline and deposits in Eastern Siberia that conceivably represent other plate boundaries in the Cambrian.

When we get back to the older Precambrian (figure 7), the situation is by no means so clear. There are several short belts in the Canadian Shield that trend northeast to east, and if they were not covered by later rocks extensions in each direction might be known. A couple of short belts seem to be present in the Baltic Shield, and isolated districts are present on the other continents with the exception (so far as I know) of South America. I must point out that even more than in the previous slides, the deposits shown are not all of the same age or necessarily related in any way. Certainly, Sullivan and Mount Isa may have nothing to do with the predominantly volcanogenic deposits shown elsewhere.

The evidence from the gross distribution of the deposits does not argue clearly for or against the existence of plates and plate motions in earlier Precambrian time. However, in contrast to most of the later deposits that are demonstrably along orogenic belts and, hence, in areas of relatively severe deformation and metamorphism, the Precambrian and, especially, the Archean deposits are in areas of only normal or perhaps subaverage tectonic and metamorphic complexity for their age. This bit of negative evidence is, at the least, not in conflict with the beliefs expressed by others that the style of Archean geology was fundamentally different from that of later geologic time, and that large-scale lateral movement did not take place until later. Dick Hutchinson may go into this much more authoritatively this afternoon.

What, if anything, can be concluded? I think the evidence is strong that lithospheric plates and plate movement extended back to some time in the mid-Precambrian. Furthermore, since sea-floor spreading will cause most deposits to end up in island arcs or on continents, their place of origin on accreting or consuming margins could be considered as of academic importance only. However, I believe there are a couple of practical aspects as well. The first relates to the possibility that there may be numerous deposits along present-day ocean rises and on the floors spreading from them. If this is the case, they constitute legitimate targets for deep-sea exploration and eventual exploitation.

The second is of considerably greater interest and significance. If these deposits have two or more fundamentally different habitats, they should have characteristics that can be identified and used as exploration guides. The ophiolites, which are thought of as rift-generated mafic rock assemblages by those who strongly "buy" them, are considered slices of ocean floor obducted (slid up on) continental margins or subducted (pushed under) and subsequently raised by faulting or cold intrusion. Massive sulfide deposits brought into their present positions in this way should have rock associations distinctive from those that formed simultaneously with volcanic magmatic extrusions in island arcs or by submarine volcano-exhalative action in eugeosynclinal sedimentary piles. Therefore, both the selection of areas for exploration and the interpretation of features revealed by detailed mapping and especially drilling should be improved by a better understanding of their nature.

From a more theoretical point of view, by no means all geologists agree on the basic features of plate tectonics, let alone their details. To the extent that these deposits constitute an aspect of the geological record which has and will continue to receive considerable attention, economic geologists are in a good position to contribute substantively to the science.

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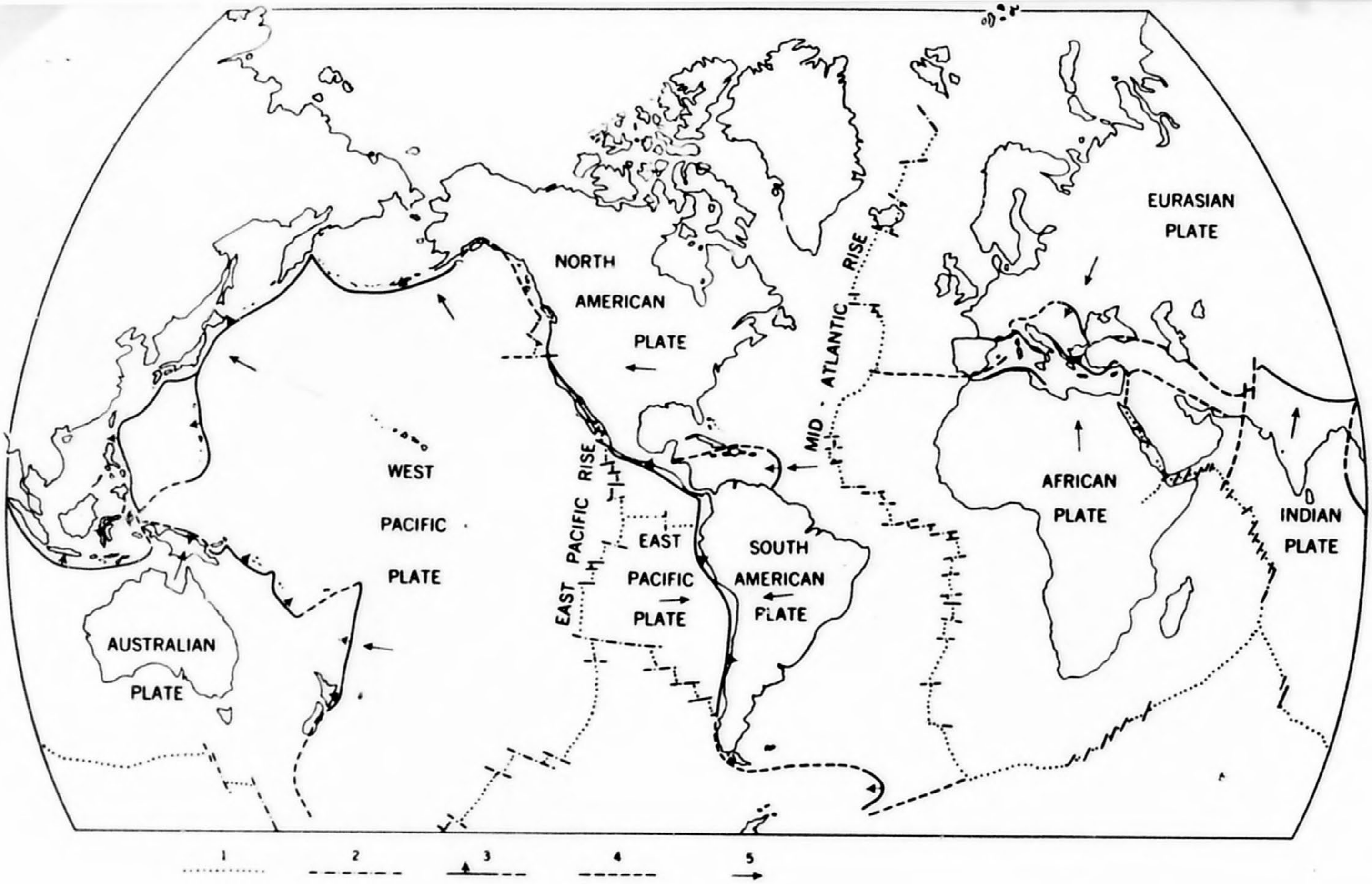

Fig. 1. Major lithospheric plates. 1) Accreting plate margin; 2) transform plate margin; 3) consuming plate margin with dip direction of downgoing plate; 4) margin of uncertain nature and (or) location; 5) relative plate motion.

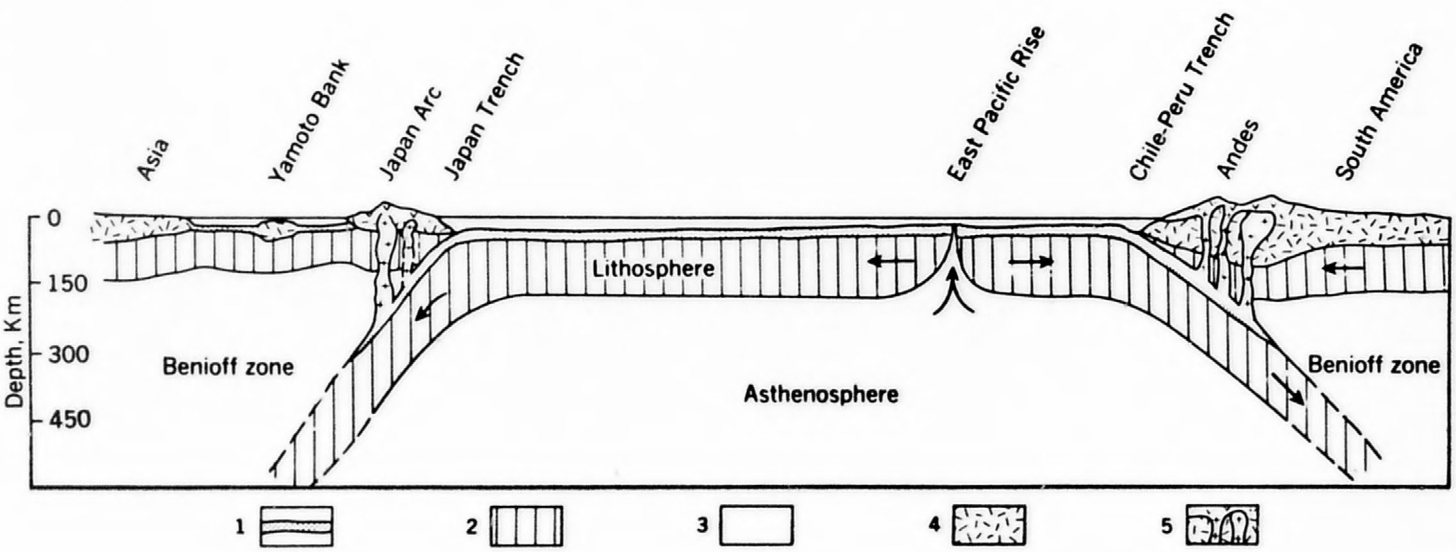

Fig. 2. Schematic section from South America to Asia illustrating major features of the plate tectonic theory. Not to scale. After Dewey and Bird (1970). 1) Oceanic crust; 2) upper mantle; 3) lower mantle; 4) continental crust; 5) calc-alkaline magmas, intrusive (+) and extrusive (v) products.

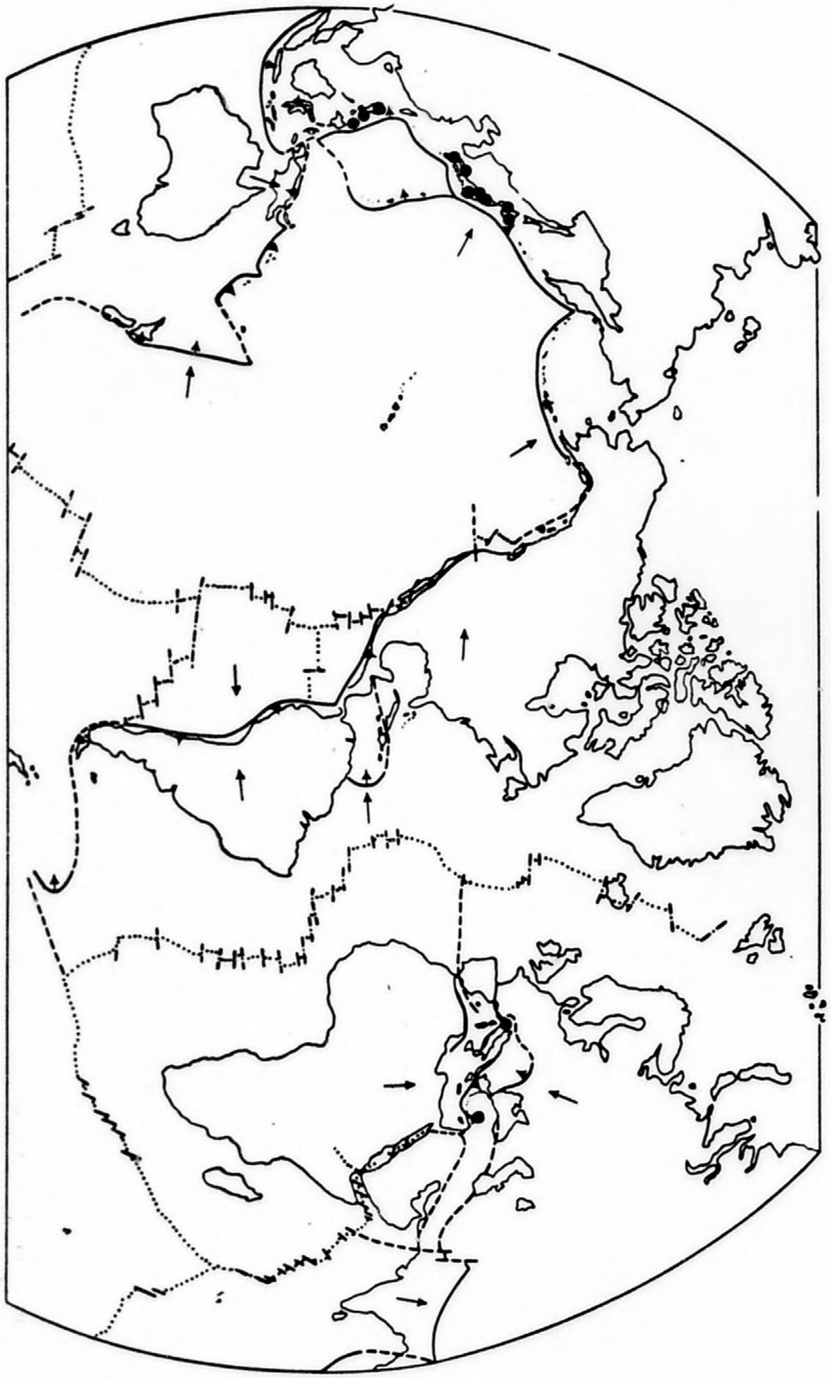

Fig. 3. Massive sulfide deposits of Tertiary age.

Table I. Proposed Relationship of Some Ore-Deposit Types to Plate Tectonics

Deposits Formed	Type, Possible Examples
At plate margins	Orientation of deposits, districts, and "provinces" tend to parallel margin
Accreting	Red Sea muds. Ancient analogs?
	Podiform Cr, (probably carried across ocean basin before incorporation in orogen)
Transform	Podiform Cr, Guatemala (?)
Consuming	Chiefly of continent/ocean, also of island arc/ocean types; deposits formed at varying distances on side opposite oceanic, descending plate
	Podiform Cr, Cuba, California, Oregon, Alaska
	FeS-Cu-Zn(Pb) stratabound massive sulfides, Cuba, California, Alaska
	Kuroko ores, Japan
	Mn of volcanogen type associated with marine sediments, Cuba. California, Olympic Peninsula
	Magnetite-chalcopyrite skarn ores, Puerto Rico, Cuba, Mexico, California, British Columbia, Alaska
	Au, Mother Lode, SE Alaska
	Bonanza Au-Ag deposits
	Cu(Mo) porphyries, Puerto Rico, Panama, Mexico, SW United States, British Columbia
	Ag-Pb-Zn, Mexico, western United States and Canada
	W, Sn, Hg, Sb
Within plates	Deposits tend to be equidimensional, distribution of districts and "provinces" less oriented
In oceanic parts	Mn(Cu, Ni, Co) nodules
	Mn-Fe sediments in small ocean basins with abundant volcanic contributions?
	Evaporites in newly opened or small ocean basins
At continental margins of Atlantic (trailing) type	Black sands, Ti, Zr, magnetite, etc.
	Phosphorite on shelf
In continental parts	Mississippi Valley-type Pb-Zn-Ba-F deposits
	Mesabi and Clinton types of iron formation
	Evaporites; Michigan Basin, Permian Basin; salt, potash, gypsum, sulfur
	Red bed Cu; Kupferschiefer and Katangan Cu
	U, U-V deposits, Colorado Plateau and elsewhere
	Ti in anorthosite
	Carbonatite-associated deposits of Nb, V, P, RE
	Diamonds in kimberlite
	Stratiform Cr, Stillwater; Cr, Fe-Ti-V, Pt, Bushveld
	Kiruna-type Fe, SE Missouri

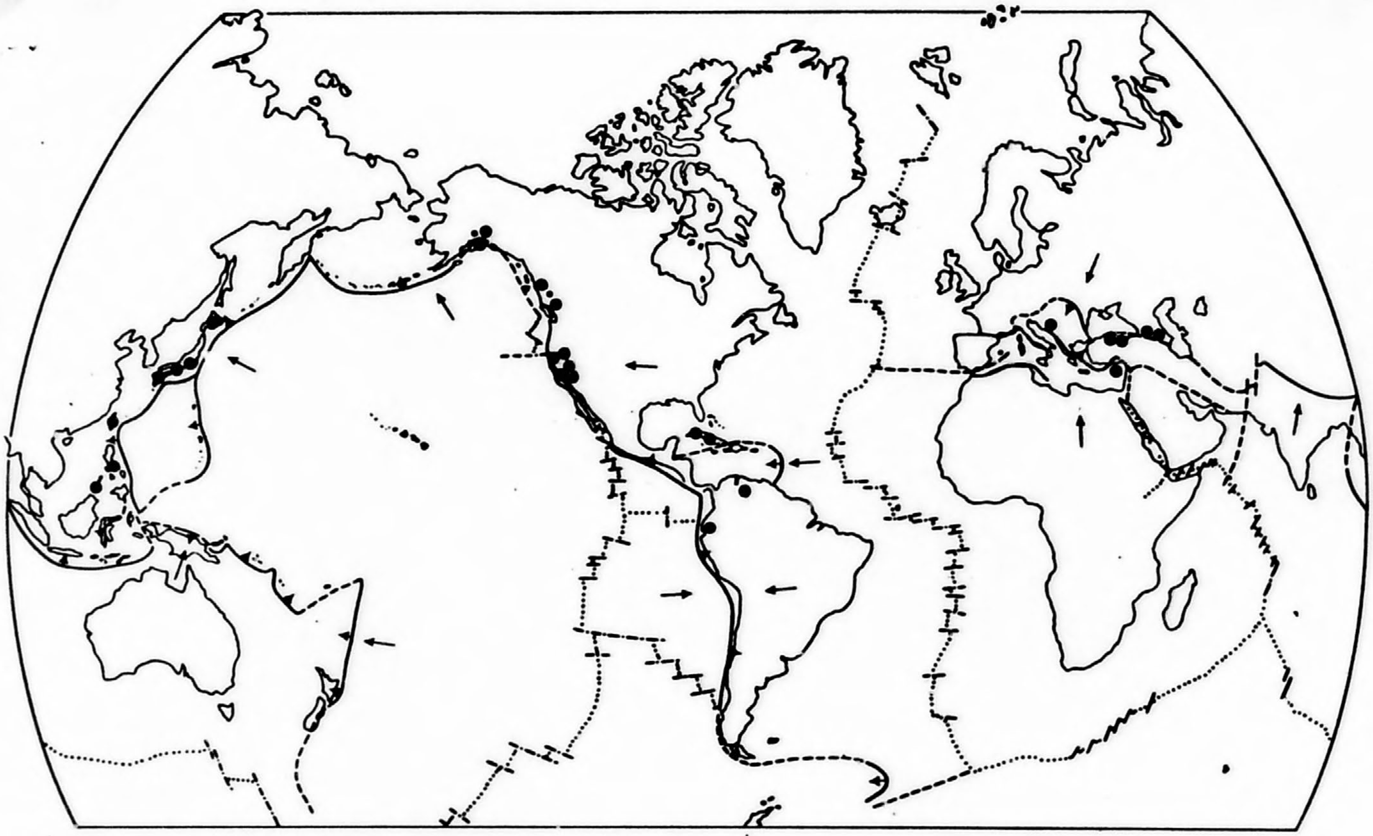

Fig. 4. Massive sulfide deposits of Mesozoic age.

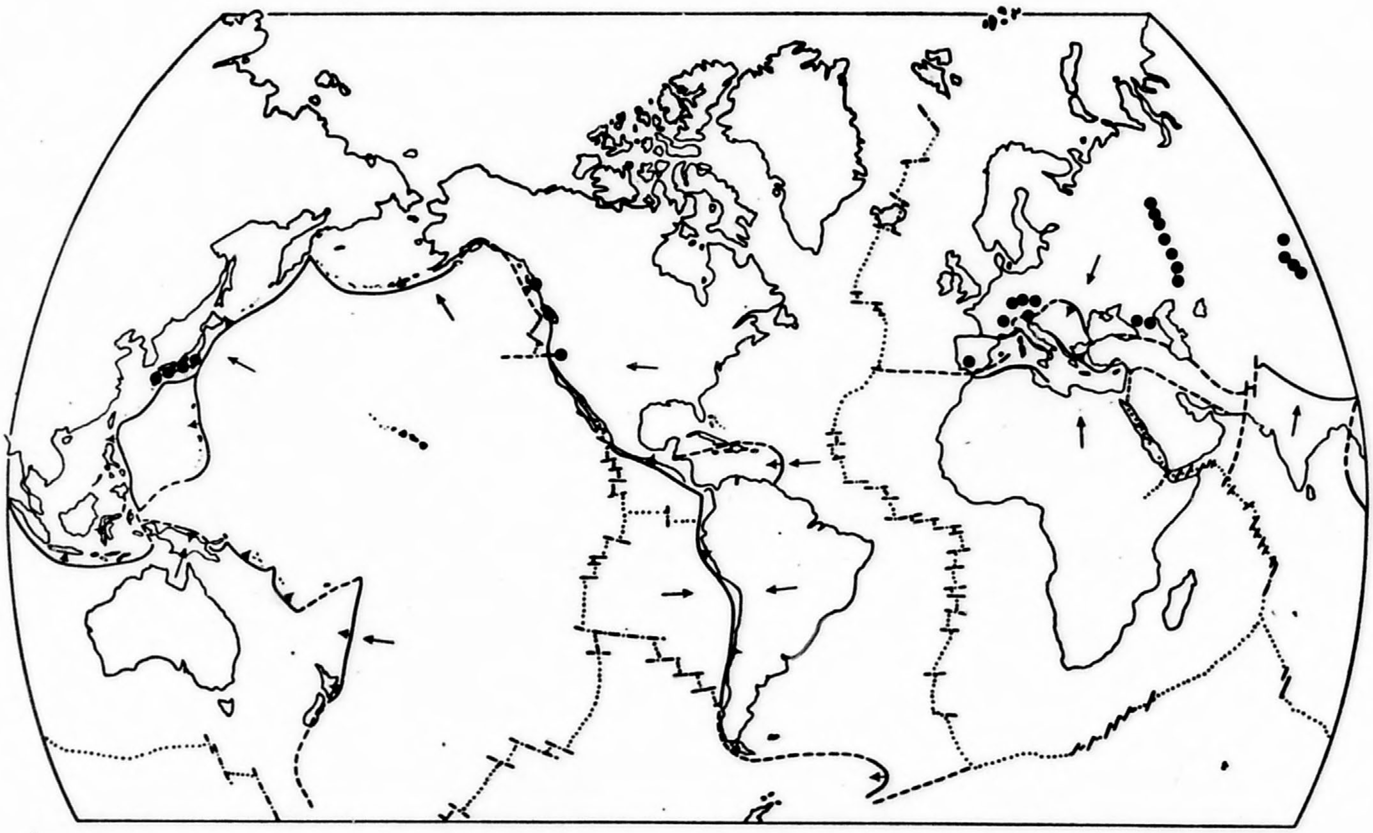

Fig. 5. Massive sulfide deposits of Late Paleozoic (Variscan or Hercynian) age.

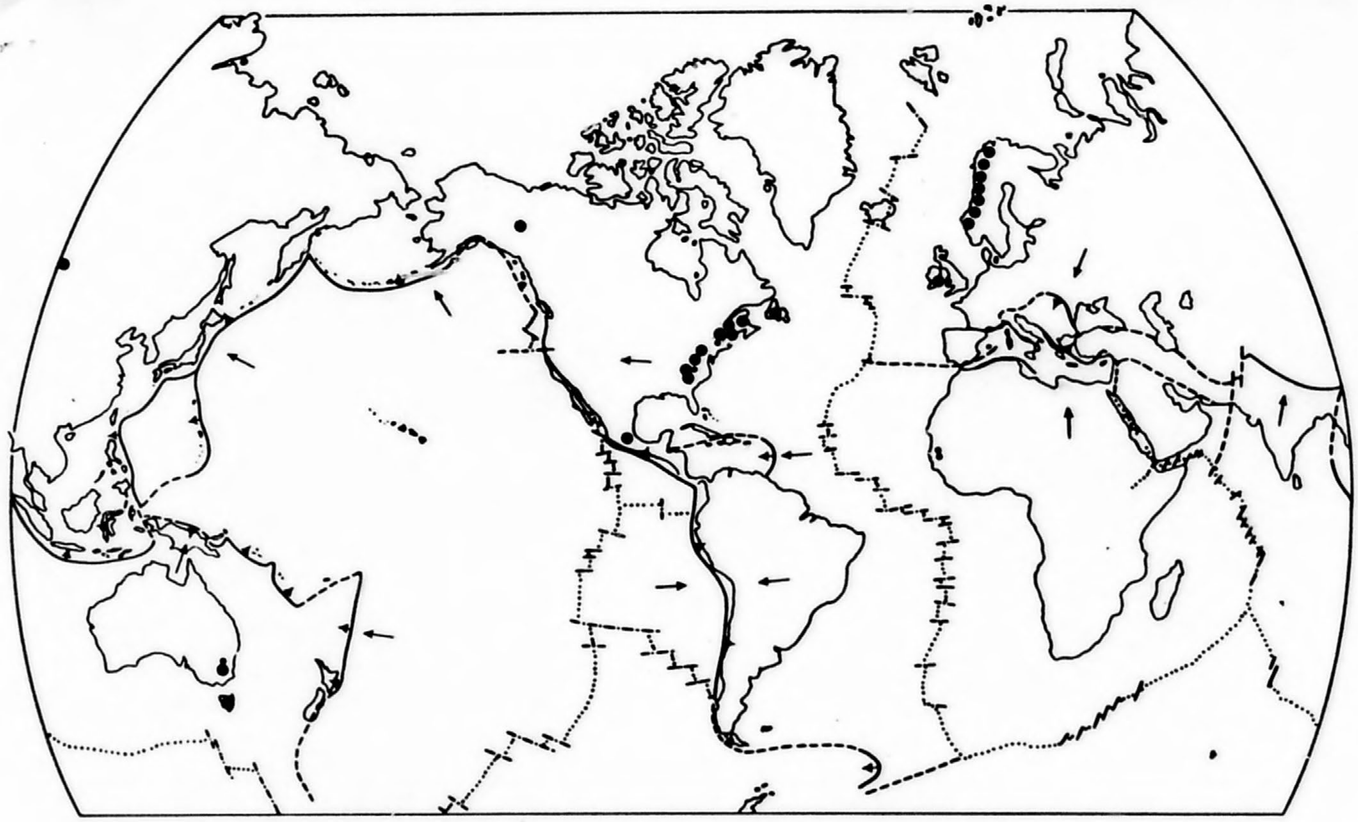

Fig. 6. Massive sulfide deposits of Late Precambrian and Early Paleozoic (Caledonian) age.

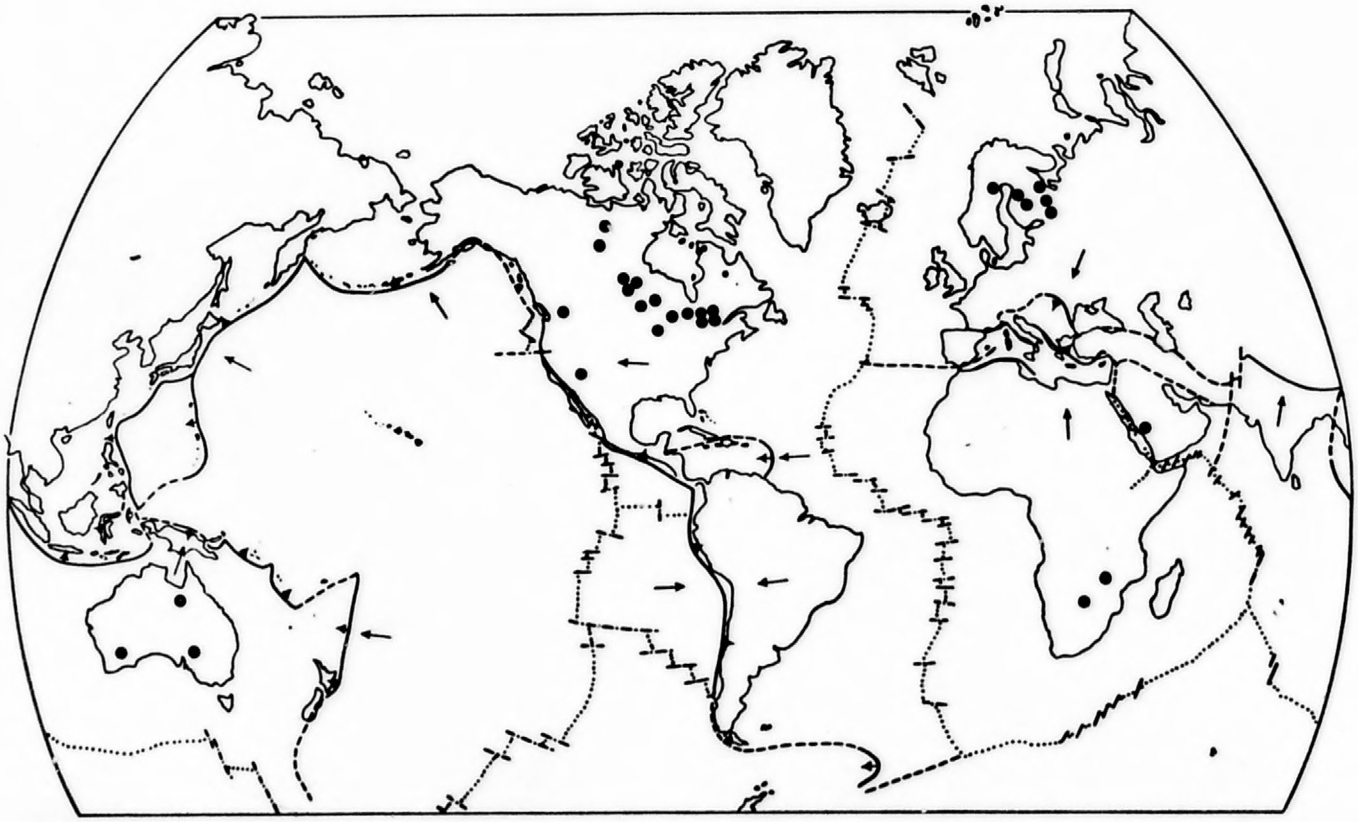

Fig. 7. Massive sulfide deposits of Early Precambrian age.