GEOCHEMICAL AND TECTONIC IMPLICATIONS OF SOUTH AMERICAN METALLOGENIC PROVINCES*

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The purpose of this paper is to examine the geochemical and tectonic implications of the distribution of ore deposits in South America. The broad questions before us are: Do South American ore deposits exhibit recognizable distribution patterns? If so, what, if any, are their geochemical or tectonic significances?

Specifically, we wish to investigate:

1. if there is a difference between ore deposits in cratonic as opposed to orogenic regions.
2. if the ore deposits in the Andes exhibit chemical variations either along or across the orogenic belt; if so, why?
3. if there is a difference between ore deposits formed in higher as opposed to lower portions of an orogenic belt; if so, why?
4. to what extent the differences between ore deposits reflect magmatic processes in the lower crust or upper mantle and to what extent they are determined by the composition of the geosynclinal prism or by local conditions.
5. if the distribution of ore deposits in an orogenic belt reflects major fracture zones in the geosynclinal prism, in the upper mantle or lower crust, or in adjacent oceanic basins.
6. if the distribution of ore deposits in cratonic areas supports indications of earlier orogenic belts or rifts.
7. if ore deposits in eastern South America support or undermine theories of continental drift.

More detailed background information and references on ore deposits in South America have been presented elsewhere;[46] hence, this paper will focus primarily on geological or geochemical relations and speculations.

Distribution patterns of mineral deposits are revealed best if individual deposit types are analyzed separately. However, it is also instructive to contrast the behavior of one element to that of another. Both approaches are followed in this study.

Political, geographical, climatic, and economic factors have been taken into account, as best as possible, in this evaluation of possible geochemical and tectonic relations of ore deposits.

General Geology

In order to judge the tectonic implications of the ore deposits in South America, it is necessary to review first their regional geological setting. On FIGURE 1 we note:

1. The Andean orogenic belt fringing the western margin of the continent.
2. The cratonic areas: Guiana and the Brazilian and Patagonian shields.
3. The sediments derived from the cordilleran uplift in the Llanos-Amazonas-Acre-Beni-Chaco-Pampas belt and in the Amazon trough.
4. The Tertiary basins of marine sedimentation bordering the continent on all sides.

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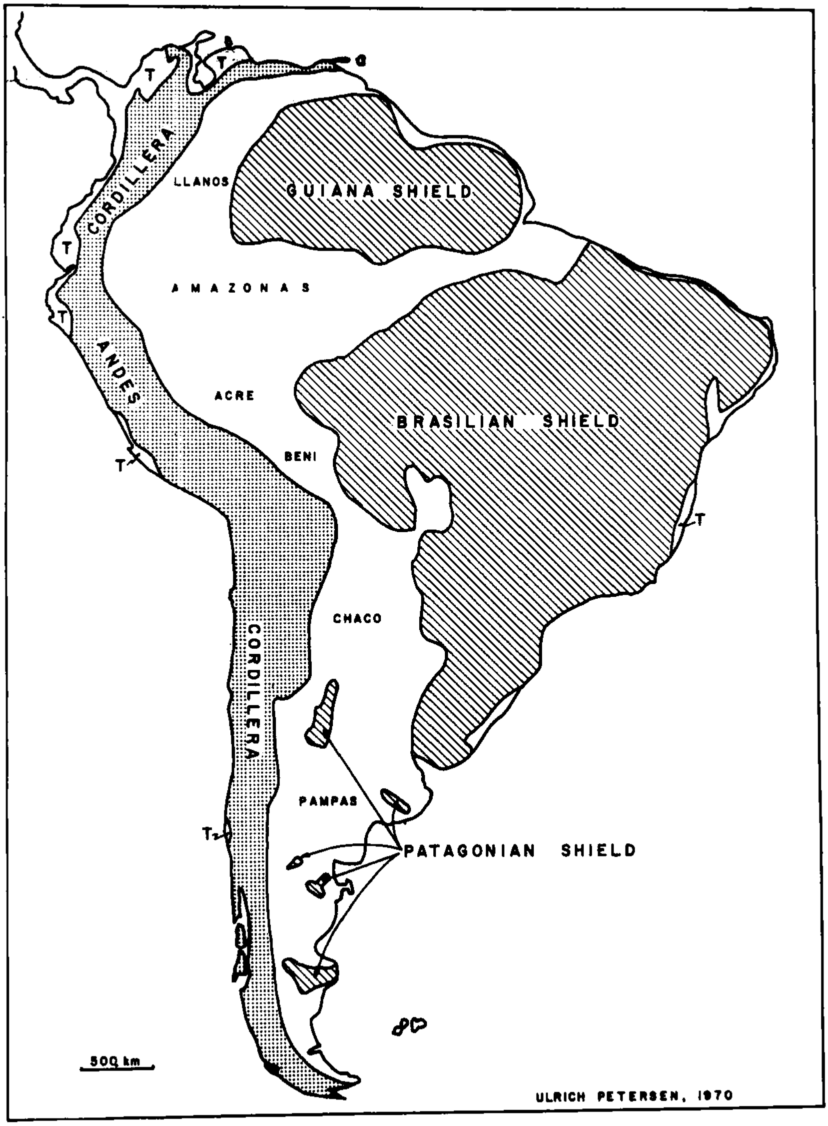

FIGURE 1. Major geologic units of South America. T = Tertiary marine basins on edge of continent.

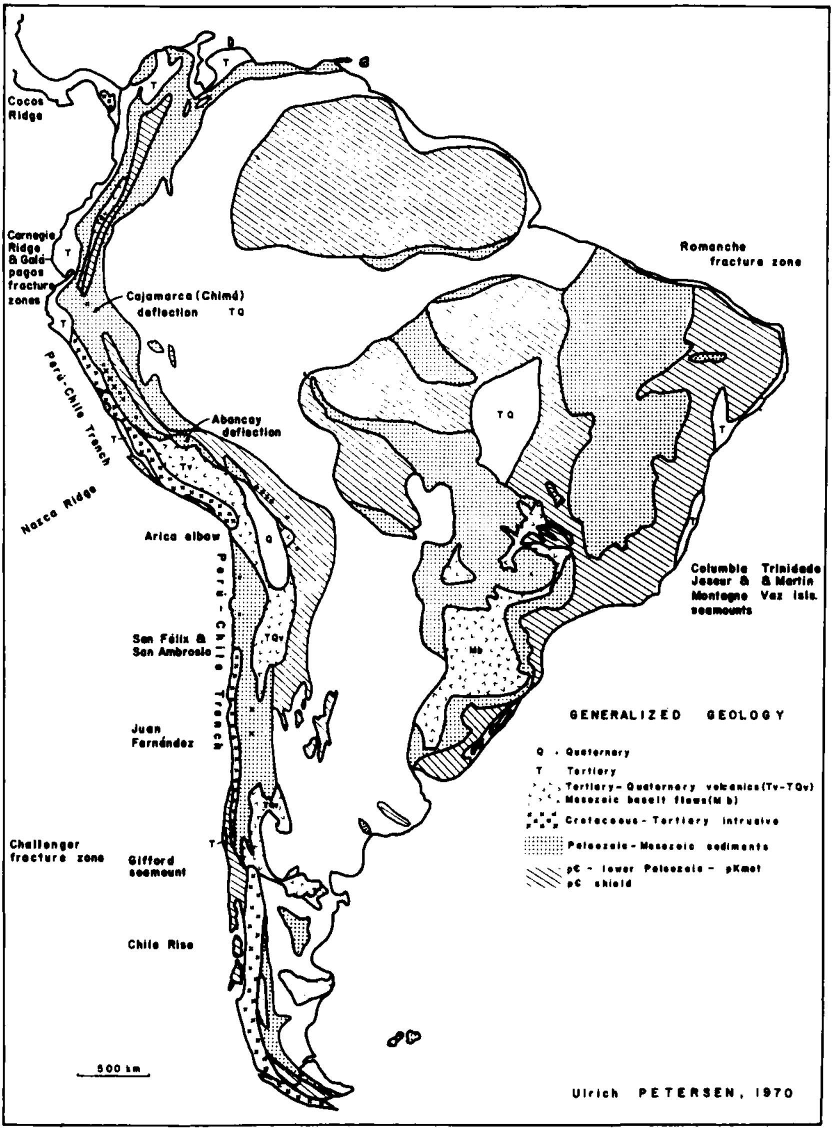

FIGURE 2. Generalized geology of South America and major oceanic structures surrounding the continent.

FIGURE 2 (generalized from the 1:5,000,000-scale geological maps of South America, 1950, 1960) provides additional detail. For the cratonic areas we note:

1. The Guiana shield has the smallest proportion of post-Precambrian cover rocks.
2. Large areas of the Brazilian shield are covered by Paleozoic and Mesozoic sediments, and parts of it are further concealed by Tertiary and Quaternary terrestrial sediments. The Mesozoic Paraná basalt flows overlie a considerable portion of this craton.
3. The Patagonian craton is mostly covered by Tertiary and Quaternary sediments, as well as by patches of Paleozoic and Mesozoic formations. It is the least exposed of the cratons.

Recent radiometric age determinations suggest that the western half of the Brazilian shield (Guaporé craton) may be part of the Guiana shield, whereas the eastern half may correspond to a separate unit, the São Francisco craton;[23, 24] in addition, three orogenic belts are indicated (see FIGURE 12). For the Andean orogen we note:

1. Metamorphosed Precambrian and lower Paleozoic rocks crop out along the center in Colombia and Ecuador; these units occupy an eastern belt in Peru, Bolivia, and northern Argentina; in southern Chile they occur on both sides of extensive batholithic exposures.
2. The predominantly marine Paleozoic and Mesozoic sediments of the Andean geosynclinal complex stretch along most of the Cordillera. In general, eugeosynclinal-type sediments predominate in the western half of the belt, whereas miogeosynclinal sediments predominate in the eastern half. There is, moreover, an unusual abundance of limestone in the central Peruvian section and a conspicuous absence of carbonate sediments in Bolivia (unless they are below the volcanics in the western half of the country), and thick sequences of predominantly andesitic volcanics abound in northern and central Chile. In detail, several basins are recognized and relations are complex.
3. Late Mesozoic – early Tertiary batholithic complexes characterize the coast of Peru, as well as the coasts of central and southern Chile.
4. Late Mesozoic and Tertiary intrusive stocks occur all along the Andes but are more common south of Ecuador. Some form small batholiths (Cordillera Blanca, Peru; Cordillera Real, Bolivia); a few of these stocks appear to be less than 10 million years old.[17, 77]
5. Tertiary and Quaternary volcanics form major expanses in southern Colombia—Ecuador, southern Peru—western Bolivia—northern Chile, and south-central Chile—Argentina. Relations at the edges of these areas and scattered remnants indicate that the volcanic cover was considerably more extensive.
6. Not shown on the accompanying maps are the major longitudinal graben structures closely associated with recent volcanism.[7,16]
7. Two major changes in regional strike are evident on the attached maps: (a) passing from Ecuador into Peru, (b) at the Arica elbow.

Not as evident, but perhaps significant, are the changes in regional strike visible on larger-scale geological maps in northern Peru (7° S, Cajamarca or Chimú deflection) and in the Abancay region (13.5° S, Abancay deflection), as well as the apparent displacement of the coastal batholith of Chile around 39° S. In all three cases the northern side appears displaced westward.

For the adjoining oceanic areas (FIGURE 2, based on 1968 and 1969 National Geographic Magazine maps of the Atlantic Ocean Floor and the Pacific Ocean Floor) we note:

1. To the west, oceanic trenches parallel the Andes. Their deeper portions (Peru and Chile trenches) adjoin the highest parts of the cordillera; they also correlate in part with the major coastal batholiths. West of Colombia, where the Andes are

lower and no major Mesozoic-Tertiary batholith is exposed, the oceanic trench is only half as deep as it is farther south.

2. Structures in the Pacific projecting into South America are the Nazca Ridge, on whose extension the Abancay deflection is located, and the Galapagos fracture zones (both north and south of the Galapagos Islands) and the Carnegie Ridge; in a broad way these structures correlate with the Cajamarca deflection and the Amazon trough.

Not so convincing is the projection of the two dozen other east-west fracture zones emanating from the East Pacific Ridge or Albatross cordillera: one of the larger fracture zones—the Challenger—projects into the area of apparent displacement of the Chilean batholith at 39° S. Perhaps of interest is the fact that the East Pacific Rise is displaced along the Challenger fracture zone in the same sense as the Andean batholith on its extension. The only other major fracture zone—the Easter Islands fracture[38]—appears to die out 1,500 km from the coast; from the Easter Islands it projects to San Felix and San Ambrosio Islands and to the Atacama desert (about 25° S).

3. A case may be made for a belt of volcanic islands parallelling the western margin of South America 750-1,000 km into sea: Cocos Ridge—Galápagos Islands—Nazca Ridge—San Félix and San Ambrosio Islands—Juan Fernandez Islands—Gifford Seamount—Chile Rise. On the South Pacific Ocean Sheet I of the U.S. Naval Oceanographic Office (scale about 1:6,000,000),[61] the evidence is especially suggestive for the 800-km stretch between San Felix and San Ambrosio and Juan Fernandez Islands. The area between this belt and the continent receives predominantly submarine volcanic flows from the west and detrital sediments from the east.

4. On the Atlantic side the Romanche fracture zone projects into the Amazon trough, and the Martin Vaz Islands—Trinidade—Columbia Seamount—Montagne Seamount belt projects just north of Rio de Janeiro toward Belo Horizonte.

Orogenic vs Cratonic Ore Deposits

The most obvious observations regarding the distribution of individual ore deposit types (FIGURES 3—11) are:

1. Several deposit types are largely restricted to the Andean orogenic belt:
   a. Porphyry copper and molybdenum.
   b. Contact-metasomatic (skarn) type copper-zinc-iron.
   c. Zoned copper-zinc-lead-silver.
   d. Red-bed copper-uranium.
   e. Hydrothermal or postmagmatic lead-zinc.
   f. Bolivian-type tin-tungsten-silver-bismuth.
   g. Mercury.
   h. Magmatic iron.
2. Other ore deposit types are confined primarily to the cratonic areas:
   a. Pegmatites (except those of clearly igneous origin, i.e., Casma, on the coast of Peru).
   b. Carbonatites and alkalic complexes.
   c. Diamonds.
   d. Nickel-cobalt-chromite deposits associated to mafic or ultramafic intrusives.
   e. Sedimentary iron and manganese.
   f. Bauxite.
   g. Homestake-type gold.
   h. Witwatersrand-type gold-uranium.
   i. Contact-metasomatic tungsten.
   j. Mississippi Valley-type lead-zinc-fluorite-barite.

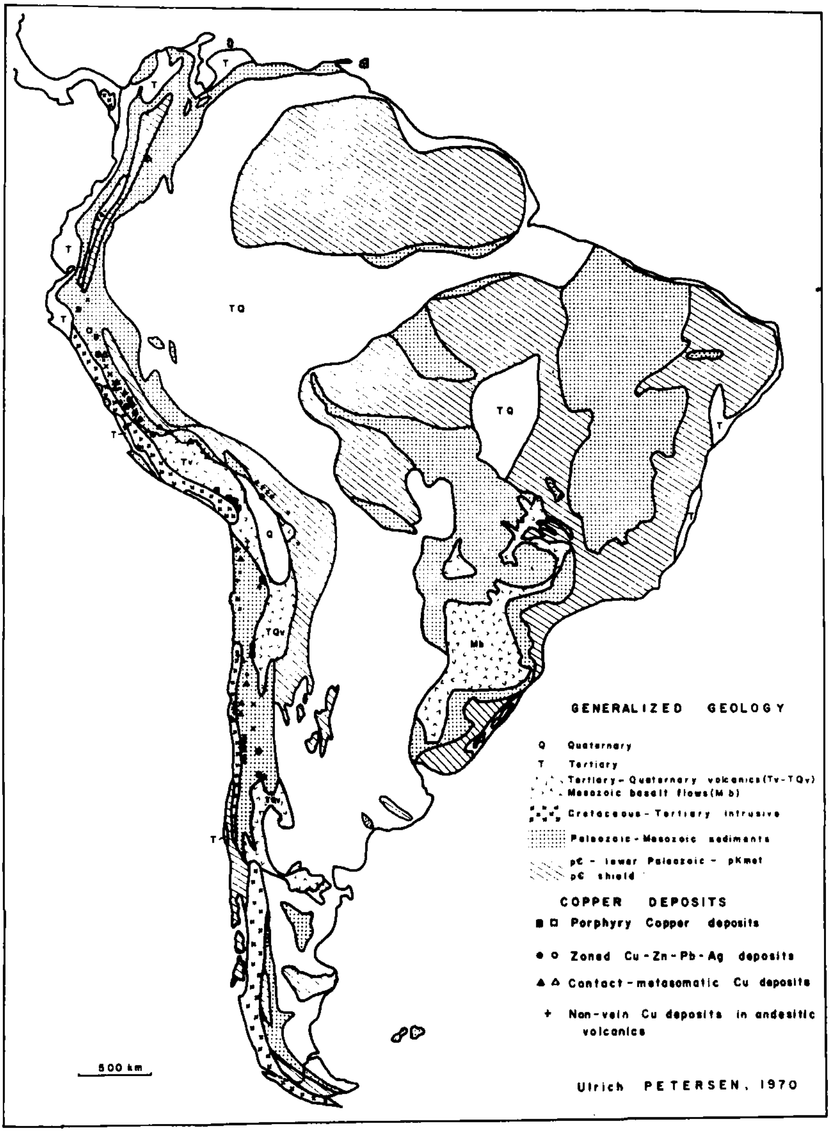

FIGURE 3. Distribution of copper deposits in South America.

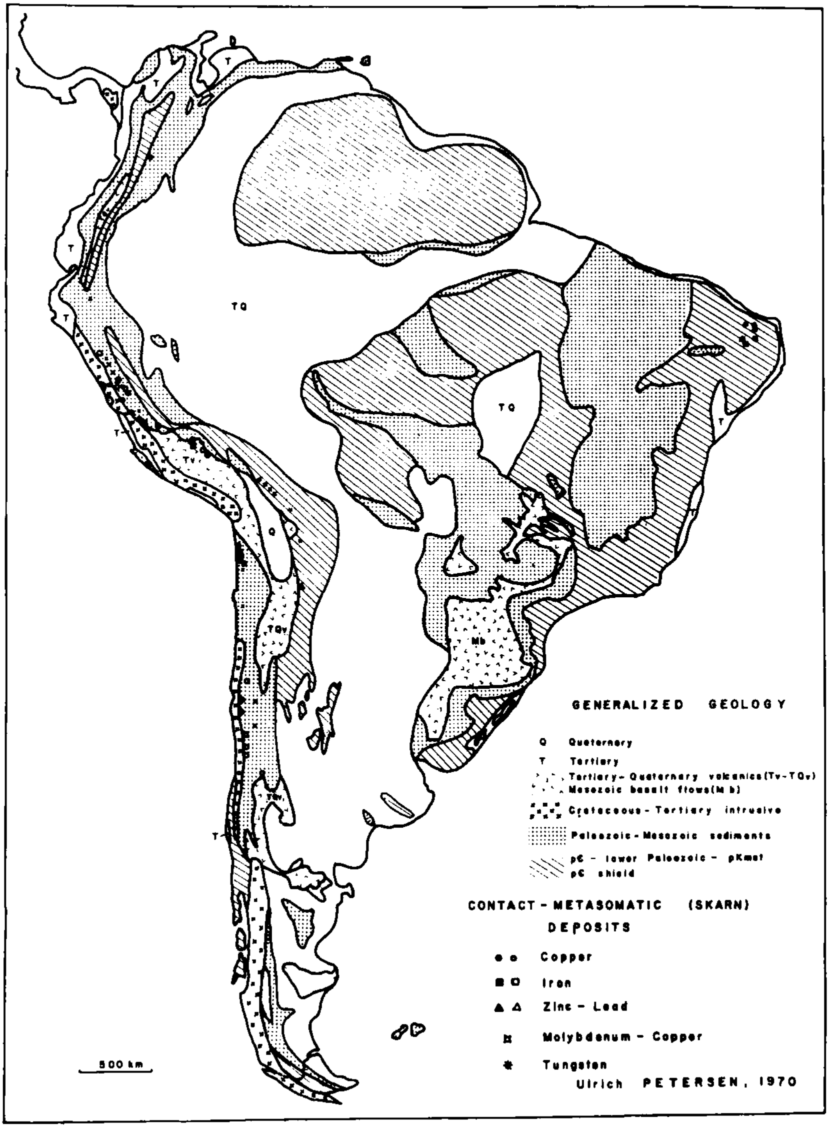

FIGURE 4. Distribution of contact-metasomatic (skarn) deposits in South America.

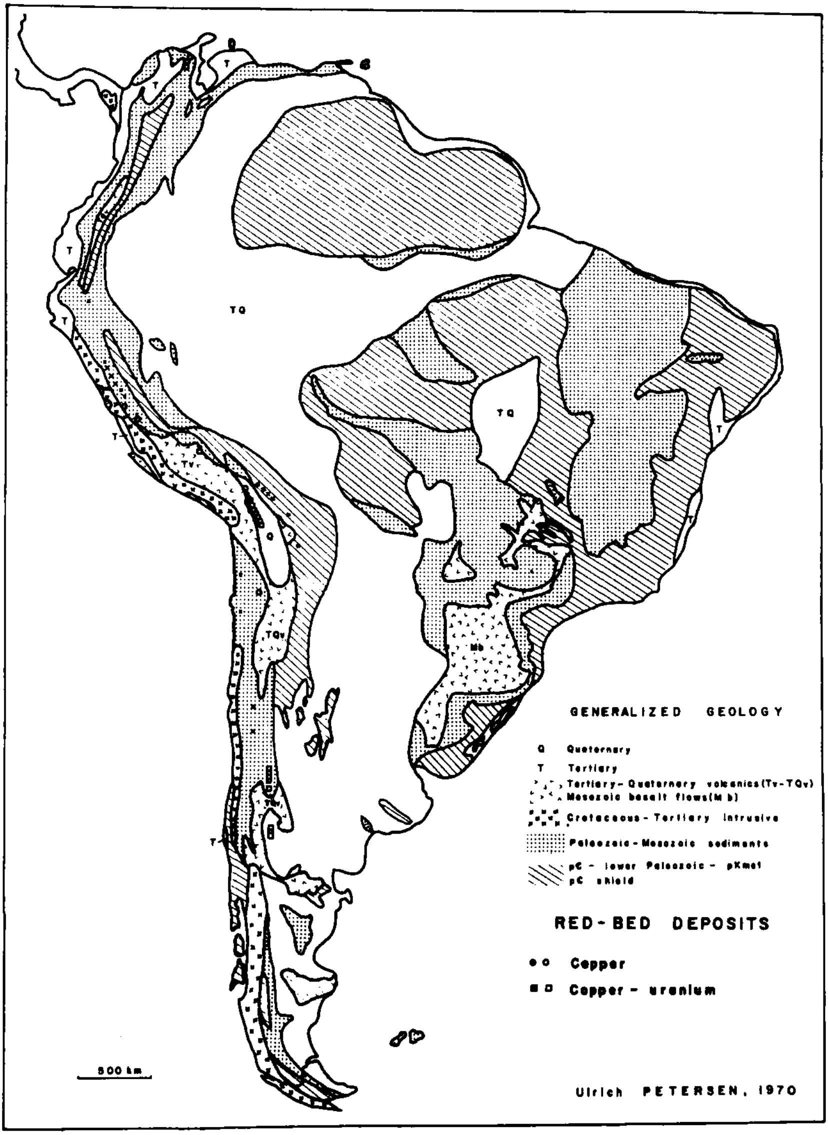

FIGURE 5. Distribution of red-bed copper and uranium deposits in South America.

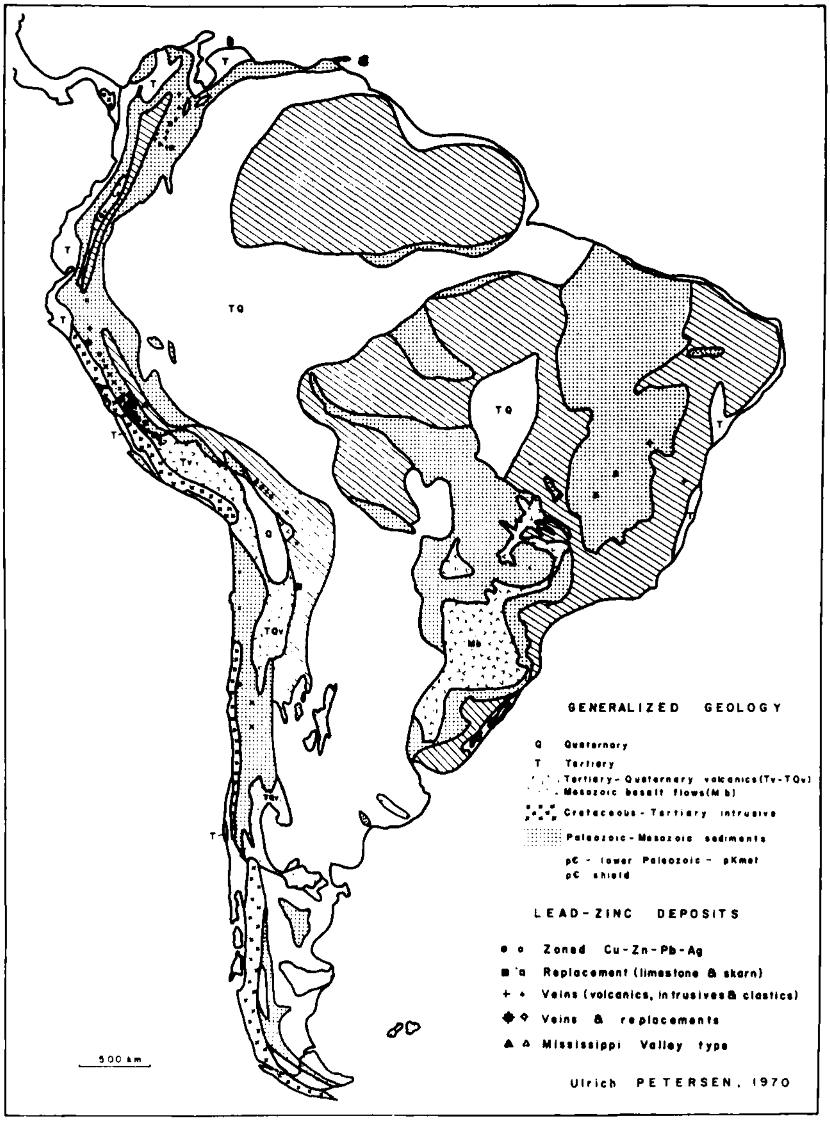

FIGURE 6. Distribution of lead-zinc deposits in South America.

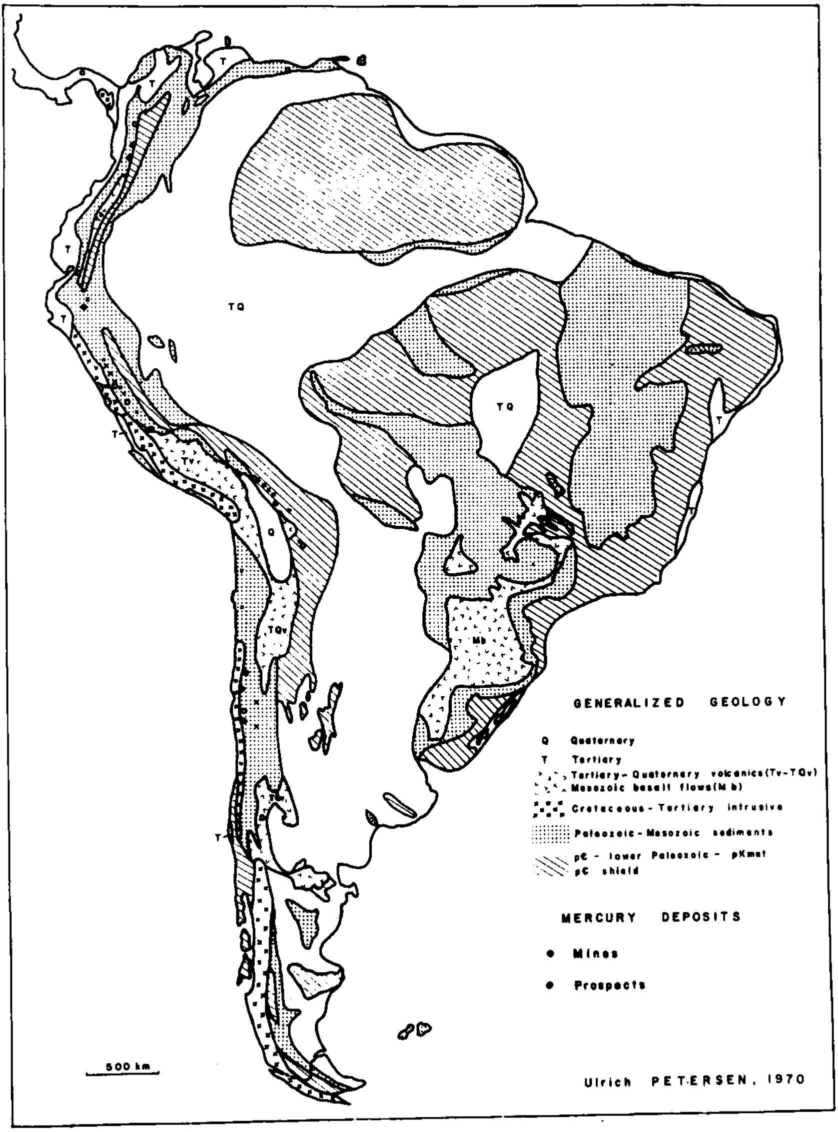

FIGURE 7. Distribution of mercury deposits in South America.

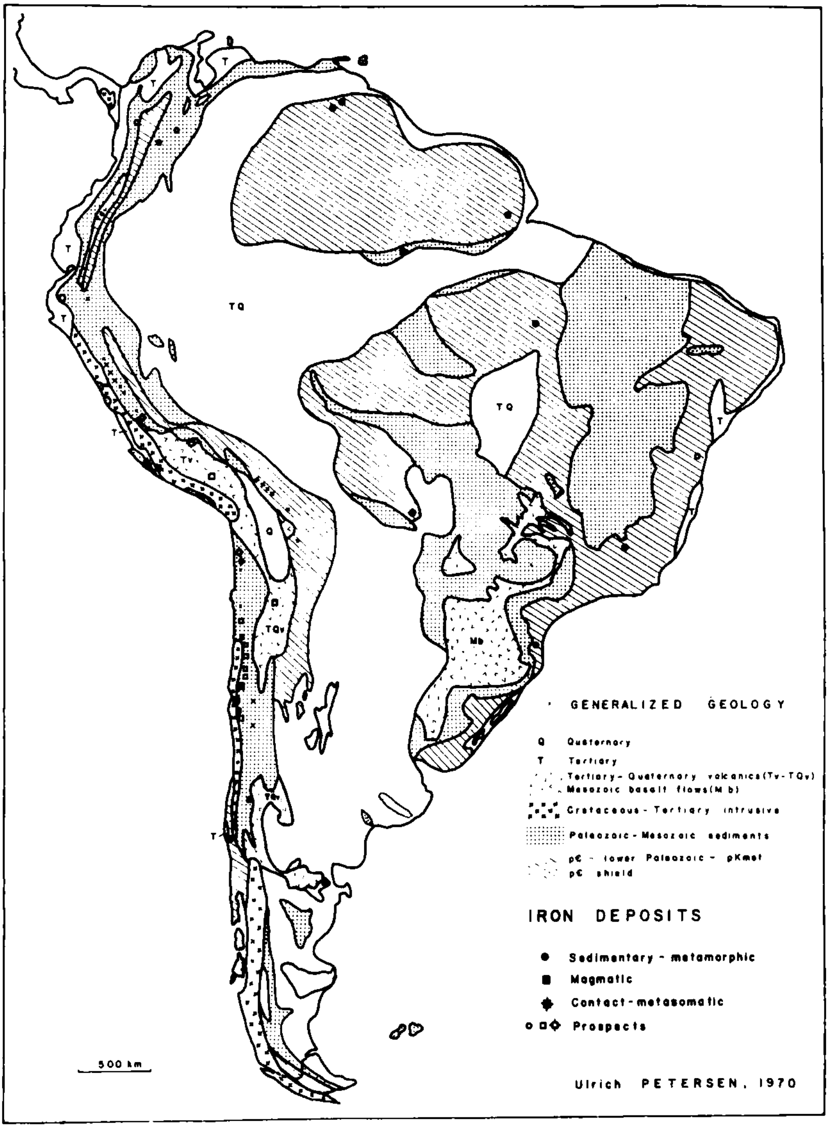

FIGURE 8. Distribution of iron deposits in South America.

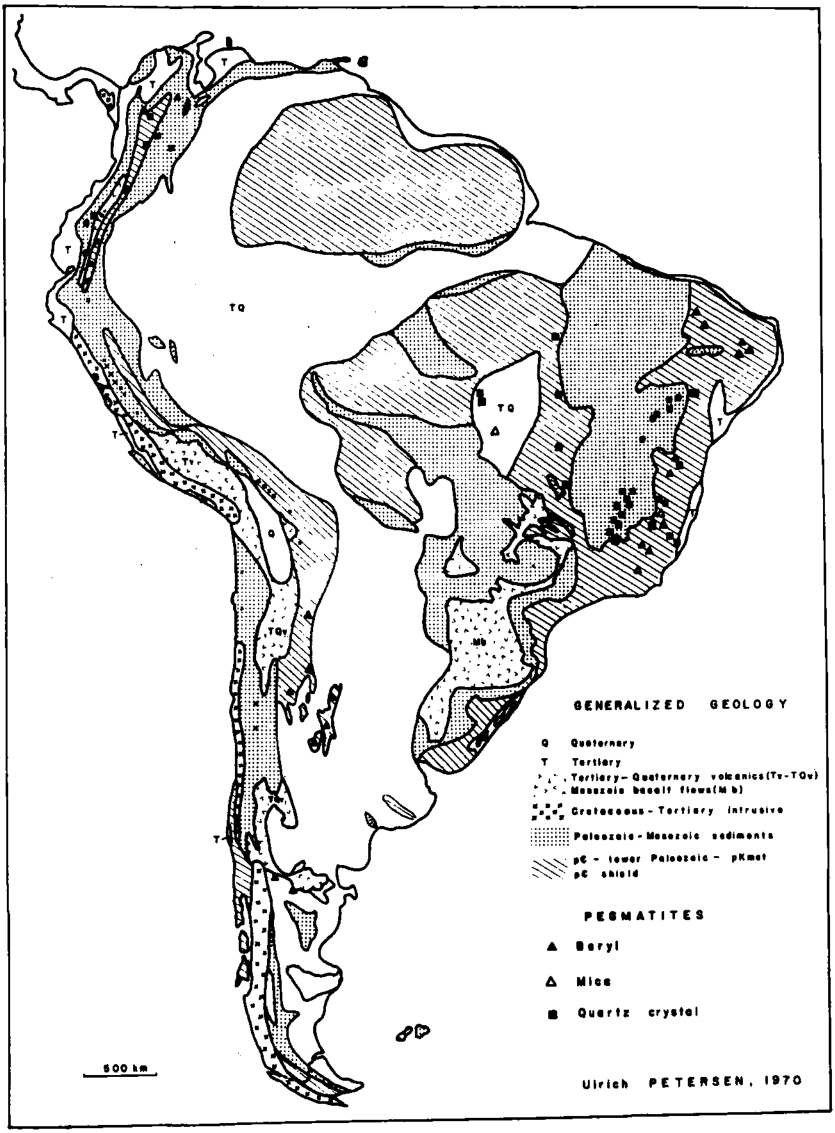

FIGURE 9. Distribution of pegmatites in South America.

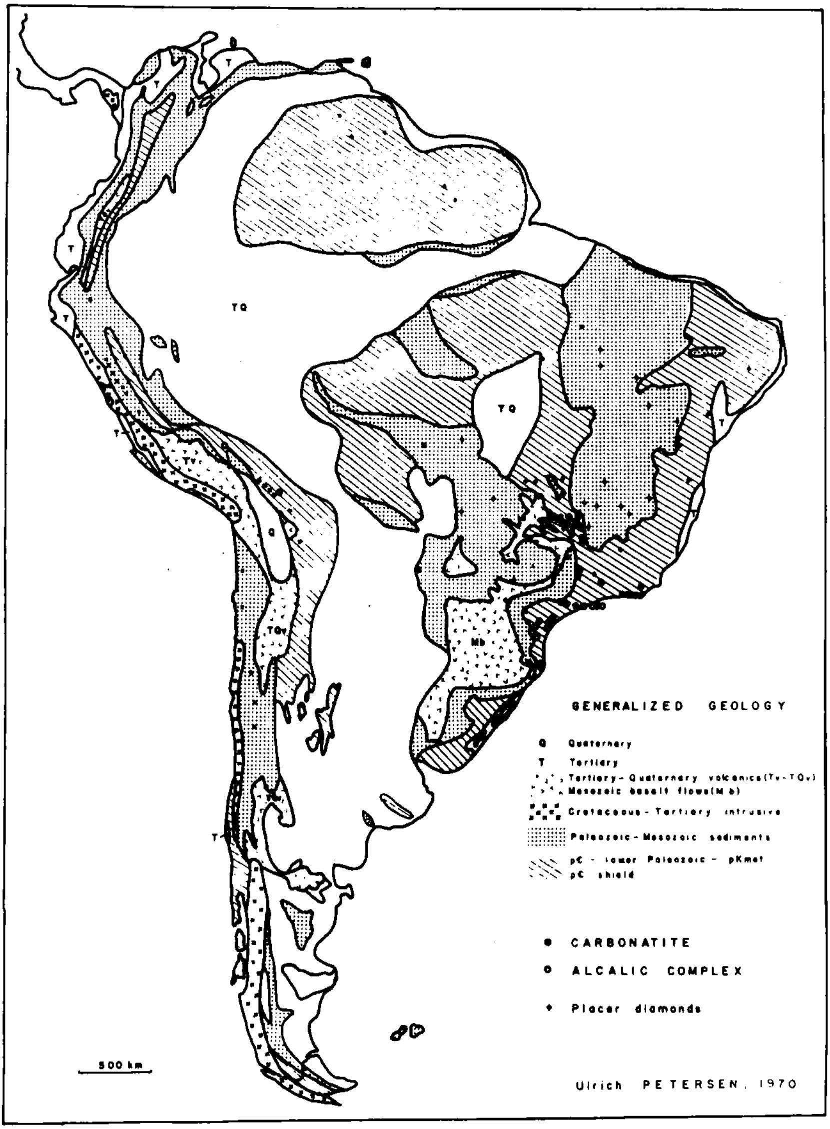

FIGURE 10. Distribution of carbonatites, alkalic complexes and placer diamonds in South America.

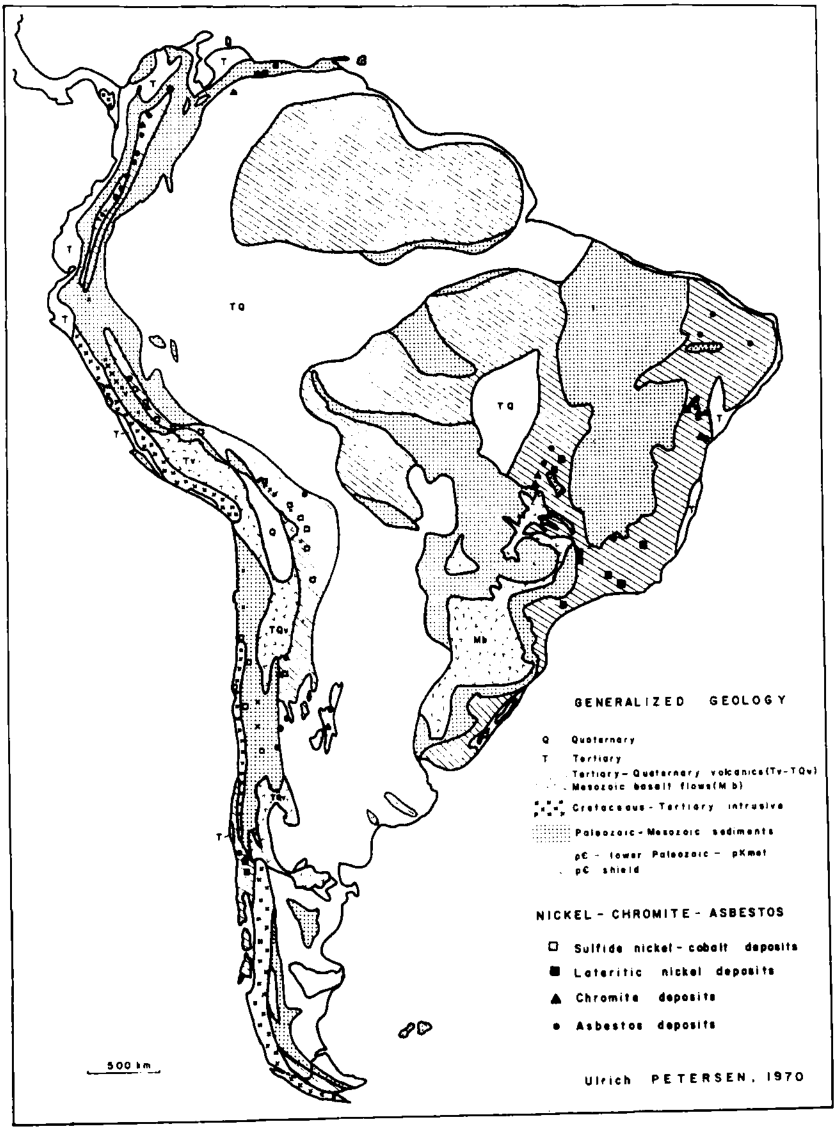

FIGURE 11. Distribution of nickel, cobalt, chromite, and asbestos deposits in South America.

These observations had, of course, been made long ago, both in South America and elsewhere. What perhaps needs emphasizing is that

1. The cratonic deposits are not restricted entirely to the large shield areas as conventionally outlined on generalized maps (FIGURES 1 and 2) but are found also wherever Lower Paleozoic and Precambrian metamorphic rocks are exposed along the cordillera, either in uplifted blocks or in deeply eroded areas. In South America, this is true for pegmatites, nickel-cobalt-chromite deposits associated to ultramafic intrusives, and sedimentary iron deposits.
2. If erosion were to strip more than 2 km off the Andes, almost all "orogenic" deposits would be destroyed; most of the area would consist of Lower Paleozoic and Precambrian metamorphic rocks with an assortment of "cratonic" ore deposits.

Evidently, this is the reason why it is more common to find some "cratonic" deposits along the cordillera as opposed to "orogenic" deposits in the shield areas. It also emphasizes the point that the geosynclinal belt—with its sediments, volcanics, and intrusives—simply overlies a basement that is not significantly different from the rocks exposed in the shield areas.

Longitudinal Belts

Another feature of the distribution patterns is that the orogenic deposits occur in belts that are elongated along the Cordillera and participate in all the regional trend changes of the Andes.

Deposits of some elements, such as mercury (FIGURE 7), occur exclusively within these belts. For other elements, such as iron, copper, lead-zinc, uranium, nickel-cobalt, or tin, belts can be discerned only by considering individual deposit types (FIGURES 3–6, 8 and 11-12). For most of these, the belts can be substantiated without much doubt from northern Peru to central Chile, i.e., over a length of about 4,000 km. The belts are normally 100—150 km wide, although in places they may be narrower or reach 250 km in width. Some deposit types (mercury, contact-metasomatic, red-bed copper, and hydrothermal lead-zinc) can be followed northward into Ecuador and Colombia, so that the total length of the belt comes to about 6,000 km. On the other hand, the Bolivian tin belt is only about 800 km long (unless one wishes to include an isolated example near the Cordillera Blanca in Peru, 800 km farther north). These figures give length-to-width ratios from 6 to 9 for the Bolivian tin belt and 15 to 40 for the other belts.

The fact that the ore deposit belts follow the regional trend is due in large part to the association of many ore deposit types to specific rock units whose outcrop patterns are controlled by the regional structure. Thus, for example, red-bed copper-uranium deposits are bound by definition to (predominantly Permo-Triassic and Tertiary) red-bed sequences; lead-zinc deposits have a distinct preference for limestone; epithermal silver deposits are bound to Tertiary volcanics; contact-metasomatic (skarn) deposits are dependent by definition on the presence of limestone. However, note that

1. Some deposits occur in varied rock types and still follow the regional structural trends, for example mercury and zoned copper-zinc-lead-silver deposits; a similar, but weaker, case may be made for porphyry copper, magmatic iron, and Bolivian-type tin-tungsten-silver-bismuth deposits.
2. There are no statistically significant clusters of deposits forming transverse belts.

There are, though, some puzzling longitudinal variations:

1. The virtual restriction of zoned copper-zinc-lead-silver deposits to Peru (FIGURE 3), in spite of the fact that other deposit types of these four metals

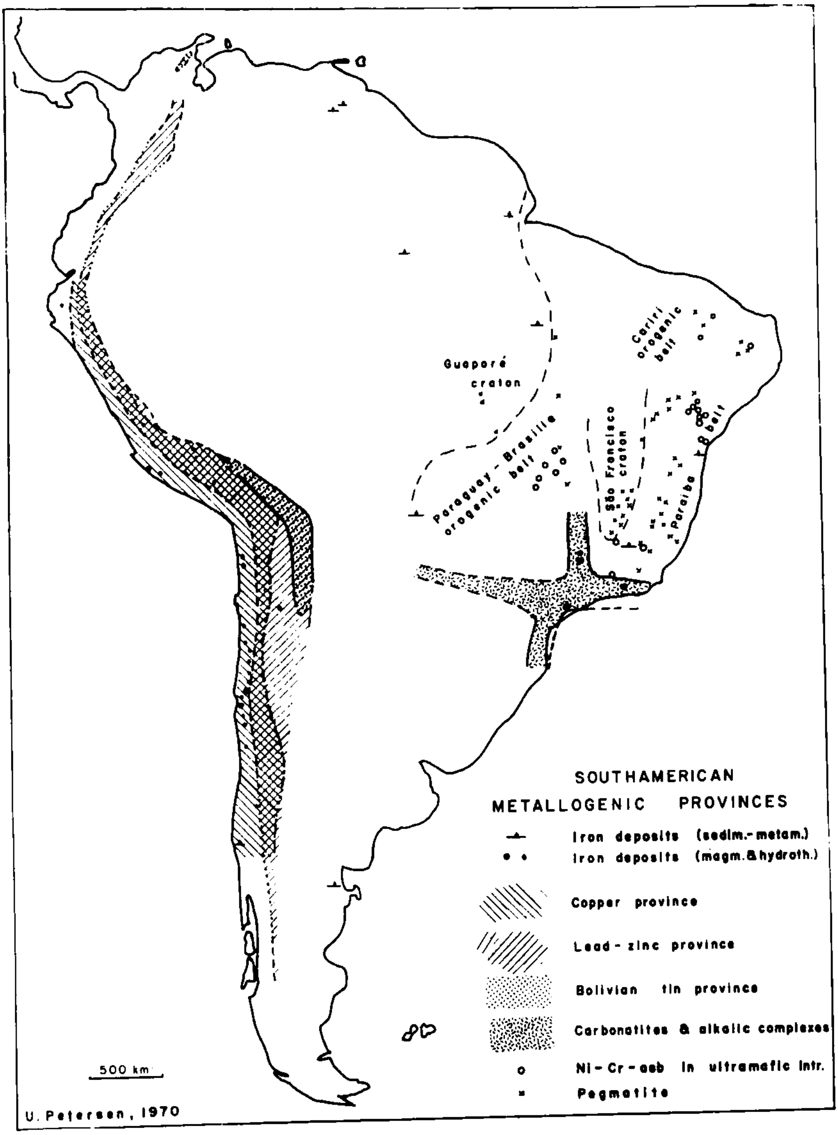

FIGURE 12. Selected South American metallogenic provinces.

occur farther north and south (only one zoned copper-zinc-lead-silver deposit is known from Bolivia: Laurani).

2. The predominance of lead-zinc deposits in Peru (TABLE 1).

3. The restriction of the Bolivian tin belt to that country, with only limited extensions into Argentina and Peru (TABLE 1 and FIGURE 12).

TABLE 1

PRODUCTION FOR 1967*

	Fe	Cu	Pb	Zn	Sn
Chile	60	77	1	—	—
Bolivia	—	1	9	4	93
Argentina	—	—	15	8	7
Peru	40	22	75	88	—

*In percent, recalculated to 100% for the four countries

4. The fact that red-bed deposits (FIGURE 5) contain uranium and copper in Argentina, but generally only copper farther north, and no vanadium (as they commonly do in the Colorado Plateau), in spite of the fact that abundant vanadium-bearing asphaltities exist in central Peru and that Minas Ragra (Peru) was for many years the principal source of vanadium in the world.

Transverse Variation

A change in the chemical character of ore deposits transverse to the Cordillera is revealed in single-ore deposit types by varying proportions of certain elements or by contrasting statistical distributions of all the deposits of major metals.

FIGURE 4 shows that contact-metasomatic (skarn) deposits tend to be primarily of iron on the west coast of South America (only Huacravilca and the Livitaca group are farther inland). Copper deposits in skarn predominate along the Andes but are also present in the coastal region. The only lead-zinc deposit that can be considered to belong to this type is in northern Argentina (Aguilar): no skarn-type lead-zinc deposits formed in Chile, in spite of the availability of limestone and the presence of iron and copper in skarns.

FIGURE 12 summarizes the distribution of magmatic and hydrothermal iron, copper, lead-zinc, and tin deposits in the Andes. The predominance of iron deposits along the coast may reflect the economics of transporting a relatively low-value commodity over rugged terrain; however, the region under consideration is fairly well exposed and explored, so that it is doubtful that many major prospects have been overlooked; hence, it is likely that the distribution of iron mines and prospects shown on the map is statistically significant. It is quite clear that copper deposits tend to occur in the western part of the Cordillera, whereas lead-zinc deposits predominate in the eastern part. There is a central zone of overlap, often referred to as a belt of polymetallic deposits. The Bolivian tin province coincides with the eastern third of the lead-zinc belt. For Peru, a change from iron to copper to polymetallic deposits was described independently by Bellido.[3] These transverse variations are also supported by the production data for 1967 (TABLE 1). Peru spans the whole width of the cordillera and therefore enjoys a more balanced output (excepting tin, either because the tin belt actually ends or because it would continue in the less explored rugged eastern slopes of the Andes).

Hydrothermal gold deposits tend to occur in the western half of the Cordillera, associated either with the coastal batholith (as in Andaray and Alpacay) or with intrusive stocks in the Andes (as in Pataz); their distribution coincides roughly with that of iron and copper deposits. Distinct from these are gold-quartz veins in metamorphic or Lower Paleozoic terrains (Santo Domingo, for example) and their associated placer deposits; the distribution of these deposits mirrors the outcrop areas of their host rocks (in Colombia, eastern Peru, and southern Chile; see Ruiz's FIGURE 6.[56]).

FIGURE 11 shows that sulfide nickel-cobalt deposits occur primarily in two belts: one along the eastern slopes of the Andes, the other in northern and central Chile*; in the first belt nickel generally predominates over cobalt, whereas the reverse is true for the second belt.

It is of interest to compare the aforementioned transverse variations in the Andes with similar changes reported elsewhere. For the southern Appalachian-Piedmont province from Washington, D.C., southward to the coastal plain of Alabama, Pardee and Park[43] discerned the following arrangement:

1. Pyrite-gold: gold zone.
2. Pyrrhotite-pyrite.
3. Pyrrhotite-chalcopyrite: copper zone.
4. Lead-zinc zone.
5. Barite zone.

FIGURE 13 substantiates the sequence gold-copper-lead/zinc from New England to Alabama; it is based on mineral investigations resource maps for gold,[33] copper,[30] lead,[36] and zinc.[37]

FIGURE 14 is a plot of major copper and lead-zinc deposits in the Cordillera of North America. Evidently, the statistical distribution of these deposits is quite similar to that in South America. For a more limited area, such as British Columbia, comparison of distribution maps for deposits of iron,[11] copper,[41] and lead-zinc[14] brings out the succession iron-copper-lead/zinc; Sutherland Brown[6] proposed that the sequence (from west to east) is iron-copper-molybdenum-zinc-lead. For the western U.S., Noble[42] discerns in a broad way the order mercury-copper-gold-silver-tungsten-lead-molybdenum; the same author (p. 1618) interprets unpublished information on Mexico to indicate the order copper-silver-lead (from west to east).

For the Mediterranean area, the maps of Petrascheck[46, 47] suggest a vague transverse variation from copper to lead-zinc deposits. This is especially noticeable in Yugoslavia.[25]

Although tin production in North America is almost negligible, there are a few mines and many prospects. Furthermore, several geochemical investigations deal with the tin content of intrusives, biotites, and chalcopyrite in ore. This information was recently summarized by Sainsbury, Mulligan, and Smith.[57] In addition to the prevailing association with granitic and rhyolitic intrusives of late Mesozoic and Tertiary age, they recognize a reasonably continuous belt from the Seward Peninsula in Alaska to central Mexico (FIGURE 1 in Ref. 57). For three-quarters of its 8,000-km length, namely in Alaska, Yukon, British Columbia, and

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*M. Iberico[78] reports the existence of a prospect in southern Peru that would extend this belt over a 1000 kms farther north than shown on FIGURE 11.

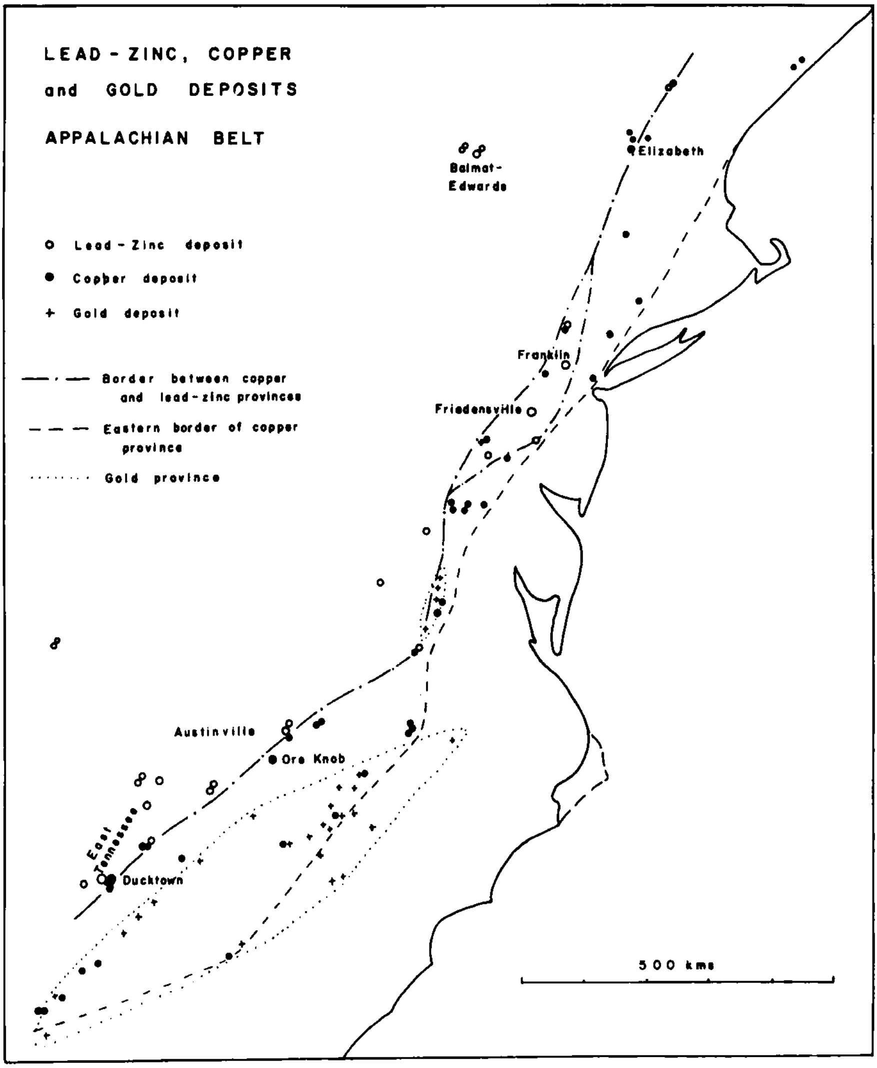

FIGURE 13. Distribution of lead-zinc, copper, and gold deposits in the Appalachians.

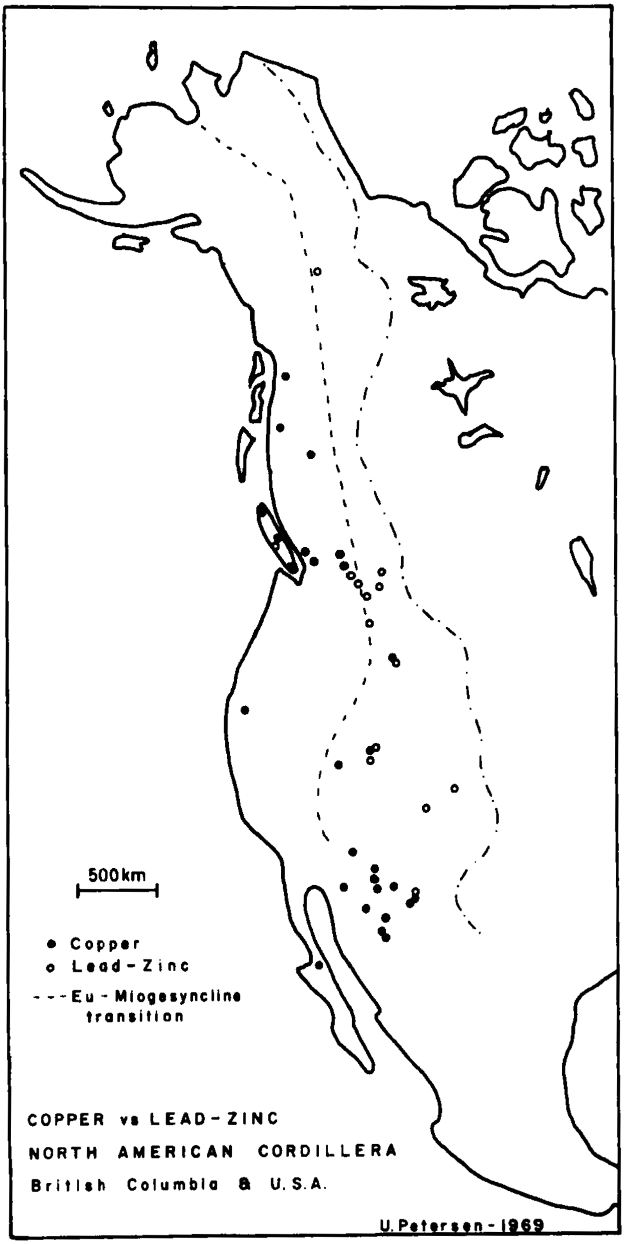

FIGURE 14. Relation of copper and lead-zinc deposits to the eugeo- and miogeosynclinal portions of the North American Cordillera. By permission of the publishers of Geologische Rundschau.[45]

Mexico, the belt does not adjoin the Pacific coast but occupies the eastern (in Alaska, northern) half of the Cordillera, overlapping the belt of lead-zinc deposits in miogeosynclinal sediments. In the western United States, however, this pattern is blurred by tin occurrences across the entire Cordilleran system. In Mexico, the highest content of tin in chalcopyrite is in three areas on the eastern edge of the tin belt; the latter apparently correlates with the older Tertiary volcanic rocks and may be covered by younger volcanics. The relations in Alaska, Canada, and Mexico thus bear many resemblances with those in the Andes south of Peru.

In conclusion, it appears that chemical variations of ore deposits across orogenic belts are quite common but differ somewhat from place to place. The tendency is for copper deposits to occupy one-half of the orogen, lead-zinc deposits the other half, with varying degrees of overlap in the central zone. In those regions where a eugeosyncline-miogeosyncline separation is possible (as the cordilleras of North and South America; Appalachians), copper deposits prefer the eugeosynclinal half, lead-zinc deposits the miogeosynclinal half; in the Americas this also means copper deposits on the oceanic side, lead-zinc towards the continent. Magmatic-hydrothermal iron deposits and gold deposits tend to occur in the copper belts, whereas tin tends to coincide with the lead-zinc belts. Silver seems to prefer the zone of overlap between copper and lead-zinc deposits.

Erosion Levels

It was stated earlier that the distribution maps indicate a reasonably clear-cut separation between orogenic and cratonic deposits, with the latter occurring also in the Andean orogen, wherever denudation has proceeded sufficiently to expose the preorogenic "basement." Erosion down to this level in central Colombia and Ecuador, as well as in the southern third of Chile, explains the relative scarcity of orogenic deposits and abundance of cratonic deposits in these areas, compared with Peru and the northern two-thirds of Chile. The question now is whether various levels within the orogen give rise to different types of ore deposits.

Probably the most obvious example are volcanic sulfur deposits, because these form in the volcanic superstructure close to the surface. In the Cordillera, this type of deposit occurs only where the uppermost portion of the orogen is preserved or is still forming. It is for this reason that, in times of exceptional demand, sulfur is mined from volcanoes along the Chile-Bolivia border and in southern Peru. Ecuador may be another source.

Over extensive areas of central to southern Peru and Bolivia, Tertiary volcanics are preserved, but the near surface portion of them has been eroded. These terrains are devoid of volcanic sulfur deposits. Instead, they harbor a host of silver deposits, especially the traditional epithermal deposits (for example, Sucuitambo, Cailloma, Arcata, Castrovirreyna, and Colqui in Peru). Although much silver is obtained as a byproduct from base metal mines, the association of silver deposits to Tertiary volcanic fields undoubtedly contributes heavily to the fact that Peru and Bolivia are by far the largest producers in South America (Peru about eight times more than Bolivia), and that the five principal world producers are Mexico, Canada, Peru, the U.S.S.R., and the U.S.A.; in Mexico and Peru silver deposits in volcanics provide a major proportion of the total silver mined.

There are a number of ore deposits that appear to form either in the zone of partially eroded Tertiary volcanics or in the geosynclinal prism underlying these volcanics. They include mercury, magmatic iron, and zoned copper-zinc-lead-silver deposits. The most important mercury mine in South America (Santa Barbara) is in Mesozoic quartzite, close to several volcanic necks; the structural setting indicates that it formed just below the Tertiary volcanic flows. Other mercury mines in this district and in a belt extending several kilometers to the south are within the overlying volcanics. In Chile, the magmatic iron deposit of Laco is in Tertiary volcanics, but in most of the producing iron mines, geosynclinal volcanics host both ore and associated intrusives. Among the zoned copper-zinc-lead-silver deposits, some are in Tertiary volcanics (Quiruvilca, Julcani, Laurani are examples), whereas others are in the immediately underlying miogeosynclinal sediments (Cerro de Pasco, Huarón, Colquijirca, Morococha, and Yauricocha are instances).

The contact-metasomatic (skarn) deposits of copper, zinc and iron are restricted — essentially by definition — to the geosynclinal prism, particularly to its limestone-rich miogeosynclinal portion. There are, however, some examples of this type of ore in thin limestone units interbedded with the overlying Tertiary volcanics (as in Felicidad, near Venturosa, Peru) and with the underlying Paleozoic clastic sequences (as in Cobriza, Peru). This distribution is consistent with our expectations from phase equilibria studies, which suggest rather high temperatures of formation at shallow depth for skarn deposits.[65]

The geological environment giving rise to the formation of porphyry copper deposits is a matter of controversy. Relations at Butte (Montana[39]), Chuquicamata (Chile), and Morococha (Peru) suggest that there is a close genetic connection between porphyry copper and zoned copper-zinc-lead-silver deposits, with the former occupying a deeper or more central position relative to the latter. Another argument for a relatively "deeper habitat" for porphyry copper deposits is the location of many of them in British Columbia and in South America within a narrow belt adjoining either side of the cordilleran batholiths or in their immediate roof rocks. However, this argument is not so clear-cut for the cluster of porphyry-copper deposits in southwestern U.S.A. and for the prospects of this type recently discovered in Argentina, all of which are located at considerable distance from clearly defined batholitic masses. It is, of course, possible that a batholith underlies the porphyry-copper deposits in southwestern U.S.A. This speculation is based on the observation that granitic intrusives tend to have higher heat-flow values and that these porphyry-copper deposits are in areas of high heat flow.[5, 8, 55] The Argentinian deposits may not be so relevant because of their relatively low grade and small size. Arguments for a relatively shallow depth of formation are: the common occurence in these deposits of breccia pipes[52], and their general association with volcanic terrains:[79] Perhaps a partial explanation for the contradictory evidence is the comparatively large vertical extent of some porphyry copper deposits,[35] which enables them to span a range of geological conditions. It is also possible that the main control is intrusion of eugeosynclinal sequences at relatively shallow depth: hydrothermal fluids at high temperature (350° — 600° C) would tend to invade limestone and form skarn deposits but would be confined by unreactive rocks, such as volcanics and quartzites, thus forming porphyry copper deposits. Lower temperatures (250° — 400° C), as well as low pH and high pS_2, tend to produce zoned copper-zinc-lead-silver deposits.

The Bolivian tin-tungsten deposits are closely associated with the Cordillera Real batholith in the north and commonly with small igneous stocks in the south. Their genesis has recently been clarified by Kelly and Turneaure.[28, 29] Arguments for a relatively shallow depth of emplacement include:

1. Stratigraphic and structural relations indicating depths at the time of formation between 350 and 2,000 m for the southern deposits and 2—4 km for those in the north.
2. Boiling of fluids as indicated by fluid inclusions, suggesting that even the northern deposits formed at less than 3 km in spite of their plutonic setting.
3. Downward constriction of many stocks (as in Potosi, Oruro, and Llallagua).

Fluid inclusion filling temperatures[28, 29, 34] indicate that cassiterite deposited in the 300° – 500° C range, whereas generally lower temperatures prevailed during the later base-metal sulfide mineralization. The relatively high initial temperatures may well be ascribed to the close association of most of these deposits to igneous stocks. To the south, the Bolivian-type tin-tungsten deposits end in northern Argentina as topography becomes lower and exposes tin-bearing pegmatites. The eastern limit of the Bolivian tin belt coincides with the eastern slopes of the Andes, again a lower erosion level. To the west, the Paleozoic clastic sediments that serve as hosts for the tin-bearing granites and veins are buried by recent alluvials and volcanics. It is also possible, though, that the eastern and western limits are attributable to geochemical changes across the Cordillera, as discussed previously. The reason for the northward termination of the belt in Peru is not clear. One possibility is that the favorable zone projects into the eastern slopes of the Andes, where vegetation, soil cover, and rugged terrain conspire against discovery or where erosion may have proceeded too deeply. An alternative possibility, relating the northern termination to a change in dominant country rock, will be discussed later. However, the latter explanation, whether correct or not, does not detract from the likely importance of relatively shallow intrusion for the formation of Bolivian-type tin-tungsten-bismuth-silver deposits.

By definition, red-bed or sandstone-type copper and uranium deposits occur in arkosic sandstones within red-colored sedimentary groups. In the Andes, two such groups are prominently developed, one of Permo-Triassic age (the Mitu Group in Peru), the other of late Cretaceous—early Tertiary age (viz. Casapalca, Rimac, Puca, Puno, Huanca, Salta, San Pedro, Corocoro, or Guaduas Groups). Sandstone-type copper and uranium deposits occur in both series (FIGURE 5). The late Cretaceous—early Tertiary red beds clearly represent the transition from marine to terrestrial conditions during the final stage of geosynclinal filling, just prior to the onset of plutonic and volcanic activity. It is a matter of speculation whether this is also true for the Permo-Triassic red beds. There is considerable ambiguity as to whether these ore deposits formed almost contemporaneously with the sediments ("syngenetic," "postsyngenetic") or later, from telethermal, ground, or meteoric water. In all cases, however, the depth of formation and burial was shallow.

On the other hand, the hydrothermal gold deposits mentioned earlier are known for their relatively low topographic elevation, both near the coast (as Andaray and Alpacay, Peru) and in Andean valleys (Pataz, Peru among others) suggesting that greater erosion would tend to expose more of them, as well as the gold-quartz veins in metamorphic Paleozoic pelites.

Finally, the metallogenic maps of Peru[48] and Chile[56] clearly show that the central inner portions of large batholitic masses are essentially devoid of metallic ore deposits. It may well be that, in addition to adverse climatic conditions and sparse population, this factor also accounts for the relatively few mineral districts reported for the southern third of Chile.

In conclusion, position within the orogen appears to exert a control on the abundance and nature of ore deposits, and, hence, the erosion level (relative to the orogen) is an important factor deciding which deposit types, if any, are exposed in a given area.

Relation to Igneous Activity

Although some orogenic deposits may be exhalative-sedimentary (for example, some copper deposits in eugeosynclinal volcanics along the coasts of Peru and Chile—Raúl and Condestable, Peru) or formed near surface (such as red-bed copper and uranium deposits), the majority of copper, lead, zinc, silver, mercury, tin, tungsten, and bismuth deposits discussed are epigenetic and hydrothermal in the sense of having formed from hot-water—rich fluids. Regardless of whether the latter are regarded to be magmatic or only ground water that was heated and moved by instrusions, the abundance of ore deposits should be roughly proportional to the pulse of igneous activity. The same should be true for magmatic iron deposits.

It was stated previously that the relative scarcity of orogenic ore deposits in Colombia could be due to the fact that erosion has removed most of them, exposing instead a greater proportion of cratonic deposits.† Another factor contributing to the subordinate number of orogenic deposits in Colombia may be the distinctly fewer intrusives and absence of large batholiths in this stretch of the Cordillera. Unfortunately, no statistical studies are available to substantiate this point.

Structural Controls

The number of epigenetic ore deposits should also be proportional to the number of tectonic events, which may produce channelways and induce large-scale displacements of fluids within the earth's crust. Again, no reliable statistical data are available for the Andes. Hence, we are limited to consider local structural controls and theoretical speculations:

1. Many ore deposits appear to be related to regional longitudinal anticlines (as in Antamina, Cerro de Pasco, Morococha—San Cristobal, and Julcani) and regional longitudinal faults, either singly (as in Antamina, Morococha, Atacocha, and Julcani) or in groups (e.g. Cerro de Pasco—Colquijirca, Chungar—Santander).
2. Not a single group of deposits has convincingly been shown to lie on regional transverse structures, as envisaged in North America by Jerome and Cook,[26] Kanasewich,[27] and Wertz.[64]
3. No significant bunching of ore deposits occurs at the presumed displacement of the Andean batholith around 39° S, nor at the projection of oceanic fractures, as suggested for western United States by Kutina.[32]
4. None of the longitudinal belts widens significantly at the transverse structural trends mentioned under 2 and 3.
5. Of the 16 circles of Rouse and Bisque,[54] parts of two parallel the Andes of Peru and Chile, that is, those stretches of the Cordillera most heavily populated by orogenic deposits. Another one of their circles is perpendicular to the Andes, correlating approximately with the Nazca Rise and the Abancay deflection. However, no significant increase in the number of ore deposits or widening of the belts is noticed in this stretch of the Cordillera, nor at the Chimú deflection.

Lithologic Controls

The broad ore deposit distribution patterns (i.e., longitudinal belts, transverse chemical changes, and vertical range in the orogenic structure) were recognized in spite of the great variety of local structural and geochemical controls. The possible existence of regional lithologic controls, which may account for some of the variations, are reviewed in this section.

In discussion of the environment of porphyry copper deposits it was suggested that the presence of limestone may be an important factor leading to a

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†The larger amount of soil and vegetation cover compared to Peru and Chile should affect both orogenic and cratonic deposits, but not their relative proportion.

skarn deposit instead of a porphyry copper deposit. Similarly, the predominance of limestone in the Mesozoic stratigraphic sequence of Peru probably contributes to the preeminence of this country in lead and zinc production (FIGURE 6 and TABLE 1), as well as to the relatively high number of large contact-metasomatic copper deposits in this portion of the Andes (as in Magistral, Vale un Peru, Antamina, Tintaya, Ferrobamba, and Chalcobamba—FIGURE 4). A survey of lead-zinc deposits throughout the world indicates a preference of these metals for limestone (Dunham,[10] TABLE 3, shows that about 55% of the 114 deposits listed are in carbonate rocks).

The next question is whether the northern termination of the Bolivian tin belt, the virtual restriction of zoned copper-zinc-lead-silver deposits to Peru, the absence of uranium and vanadium in red-bed deposits north of Argentina, and the transverse chemical variations of the ore deposit belts can be ascribed to regional lithological differences. In order to analyze this question it is necessary to discern critical differences between ore deposits and among regional lithologic compositions. Regarding the ore deposits, we note:

1. Temperatures of formation of zoned copper-zinc-lead-silver deposits are in the 250° – 400° C range. This is based on evidence from fluid-inclusion-filling temperatures (Butte,[39] , Julcani[18]), distribution of arsenic and antimony between enargite-famatinite and tennantite-tetrahedrite (Julcani[13]), sulfur isotopic determinations (Julcani[18]), and the predominance of enargite relative to luzonite. This range is probably somewhat lower than the one indicated for porphyry copper and contact-metasomatic deposits by phase equilibria and fluid inclusion studies.[12]

2. Comparing the Bolivian deposits with those in Peru and Chile for similar temperature intervals, we note that in a general way the fugacity of sulfur in hydrothermal solutions may have been lower in the Bolivian tin belt than in Peru and Chile. This is indicated by the following observations:

(a) Careful mineralogical studies by Kelly and Turneaure[29] show that in the typical Bolivian tin ores, the early vein stage is characterized by quartz-cassiterite deposition in the 350°-500° C range; this was followed by a base-metal sulfide stage between 350° and 200° C. Among the sulfides, pyrrhotite is generally early, but later altered to pyrite and marcasite. During the sulfide stage, tin is present in stannite, as opposed to cassiterite, and sphalerite is high-iron (normally over 19 mol percent FeS). The changes from cassiterite to stannite and pyrrhotite to pyrite stability are compatible with a relative increase in activity of sulfur with lowering temperature.

(b) For the 350° - 500° C interval, the proper contrast is with porphyry-copper and contact-metasomatic deposits. The former are notorious for their lack of pyrrhotite, arsenopyrite, or other phases indicative of relatively low sulfur fugacities; to the contrary, a few have phases suggestive of relatively high fugacities of sulfur (such as enargite in Chuquicamata). Skarn deposits have some assemblages indicative of relatively low sulfur fugacities (pyrrhotite and magnetite, occasional arsenopyrite, loellingite, and high-iron sphalerite), but for the most part pyrite predominates over pyrrhotite and iron content of sphalerite is moderate. At this temperature, in the Bolivian ores cassiterite formed instead of stannite and few, if any, sulfides were stable.

(c) For the 350° – 200° C interval, the pertinent comparison is with zoned copper-zinc-lead-silver deposits. The latter have enargite-chalcocite-pyrite as opposed to chalcopyrite-pyrrhotite-pyrite in the Bolivian deposits. A relatively low activity of sulfur is also indiciated for the Bolivian deposits by the common occurrence in them of aresenopyrite, pyrrhotite, native bismuth, and high-iron sphalerite. (See FIGURE 46 of Ahlfeld and Schneider-Scherbina[1]).

(d) In Peru, tin is sometimes present in ore deposits as stannite but seldom as cassiterite.

3. A relatively high acidity is indicated for the hydrothermal solutions that formed the zoned copper-zinc-lead-silver, porphyry copper, and Bolivian tin deposits. Thus, alunite occurs in several of these deposits (Cerro de Pasco, Cerro Verde, Potosi, Oruro, and other Bolivian areas of tin deposits), and, according to Hemley and colleagues,[67] the stability field of this mineral is in the low pH range. Also, the prominent wall-rock alteration of zoned copper-zinc-lead-silver and porphyry copper deposits can be explained best by hydrogen metasomatism in response to a low pH in the ore fluid.[66]

4. Variations in the content of uranium, vanadium, and copper in red-bed deposits are likely to be related to the different geochemical behavior of these elements, as summarized on Eh-pH coordinates by Garrels and Christ, FIGURES 7.27 and 11.8, REF. 15). To be transported, uranium and vanadium require somewhat more acid groundwaters than copper (at 25° C, a pH difference of 3).

Regarding the regional lithological variations, we note:

1. The predominant transverse change is from eugeosynclinal to miogeosynclinal sequences. In general, this means shales and andesitic volcanics in the western half and limestone in the eastern half of the geosynclinal prism. Sandstone is present in both sequences.

2. Upon these transverse changes are superimposed:

a. A higher proportion of volcanics to shales in northern Chile and southern Peru than in central and northern Peru.

b. A virtual absence of limestone in Bolivia compared to Peru.

c. Paleozoic saline deposits in Peru (in the region of zoned copper-zinc-lead-silver deposits), west of the Bolivian tin belt (in the general vicinity of Laurani) and in Venezuela, near Lake Maracaibo.[4] Post-Paleozoic saline deposits are more widely distributed along the Andes.

Changes in dominant host rock could affect the supply of elements to be concentrated into ore deposits; the ability of solutions to transport certain elements to suitable sites for deposition; or the mechanism of deposition, favoring certain elements over others and thus influencing the type of deposit formed.

Let us examine first the possible effect of regional host rock character on the supply of elements. TABLE 2 gives the abundance of selected elements by lithologic category. TABLES 3 and 4 list the ratio of the abundance of an element in basic igneous rocks‡ or in shale to its abundance in carbonates. In general, the elements under consideration are more abundant in basic igneous rocks and shales than in limestone, with the exception of sulfur and of lead in basic igneous rocks. However, the relative enrichment (TABLE 3) varies for different elements:

1. Copper is distinctly more concentrated than lead and zinc in eugeosynclinal sediments, correlating with the broad-scale distribution of their ore deposits.

2. Iron is more concentrated than lead and zinc in basic igneous rocks compared with limestone, but its concentration in shales is comparable to lead and zinc relative to limestone. This correlates with the abundance of iron deposits in northern Chile and the coast of southern Peru, relative to central and northern Peru (where there is only one major deposit, Tambo Grande).

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‡Abundances for "basic igneous rocks" are used as a first approximation for andesite in the absence of detailed information on minor elements in this rock type. Siegers, Pichler, and Zeil[69] give trace element abundances for Cenozoic andesites in northern Chile, but these are not the eugeosynclinal volcanics referred to in this section. The arithmetic average of their 24 samples gives 62,000 ppm Fe, 47 ppm Cu, 50 ppm Ni, and 22 ppm Co. The corresponding big/c ratios in TABLE 3 would be Fe = 8, Cu = 12, Ni = 4 and Co = 220. The use of these values as a first approximation does not materially affect the arguments presented in this section; in fact, they corroborate the conclusions based on general averages.

TABLE 2

ELEMENTAL ABUNDANCES BY LITHOLOGIC CATEGORY*

(parts per million)

	(1)† basic ig	(2)† acid ig	(3)‡ ig	(4)‡ sh	(5)‡ ss	(6)‡ carb
Fe	86,000	22,000	42,000	39,000	19,000	8,000
Cu	90	6	98	45	15	4
Zn	110	50	80	130	16	16
Pb	6	20	16	80	14	16
Ni	145	10	94	29	3	13
Co	45	4	23	8	.3	.1
Sn	1.5	3	2	4	.1	.2
As	2	1.5	2	9	1	2
Sb	.2	.2	.5	.8	.01	.2
S	300	300	400	1,900	900	4,600

†Average after Miyake,[40] Rösler and Lange,[53] and Wedepohl.[63]
‡From Horn and Adams.[22]
*Key: ig = igneous rock; ss = sandstones; sh = shales; carb = carbonate rocks.

TABLE 3

ABUNDANCE RATIOS COMPUTED FROM TABLE 2*

	big/c	sh/c
Fe	11	5
Cu	22	11
Zn	7	8
Pb	0.4	5
Ni	11	2
Co	450	80
Sn	8	20
As	1	4
Sb	1	4
S	0.07	0.4

*Key: big = basic igneous rocks; sh = shale; c = carbonate.

TABLE 4

AVERAGE ABUNDANCE RATIOS BY LITHOLOGIC CATEGORY*

	Basic ig	Acid ig	sh	Carb	Comments
Fe/Cu	$1x10^3$		$1x10^3$	$2x10^3$	Same order of magnitude
Fe/Pb	$1.5x10^4$		$5x10^2$	$4x10^2$	Fe with andesites
Cu/Pb	15		.6	.2	Cu in eugeosyncline Pb in miogeosyncline
Fe/Sn	$6x10^4$	$.7x10^4$	$1x10^4$	$4x10^4$	
Cu/Sn	60	2	10	20	Sn in shales and acid igneous rocks
Zn/Sn	75	20	30	80	
Cu/As	45		5	2	As and Sb in miogeosyncline
Cu/Sb	450		50	20	

*Key: ig = igneous rock; sh = shales; carb = carbonate rocks.

3. The greater concentration of tin in shales and acid igneous rocks correlates well with the general country rocks in Bolivia and the few tin mines in Peru (Tambillo, Condoriquiña, Quenamari). For several regions of the U.S.S.R., Radkevich[50] stressed the association of tin deposits with shales and sandstones, contrasting them with polymetallic deposits in limestone-rich provinces.

4. The virtual restriction of zoned copper-zinc-lead-silver districts to the central Andes of Peru correlates with a more abundant sulfur supply from carbonates and Paleozoic evaporites. The isotopic composition of their sulfides in a narrow range near the meteoritic value is consistent with temperatures of formation around 300° – 400° C in equilibrium with sedimentary sulfates if the proportion deposited as sulfide is small relative to available sulfate or if the sedimentary sulfur provides only the excess that distinguishes this group of deposits.

5. The lower content of sulfur in shales than in limestones may account for the relatively short supply of this element in Bolivian tin deposits. For Russia, Radkevich[50] noted that where tin-bearing granites pass from underlying shales to overlying limestone, tin usually precipitates as stannite. The situation may be analogous for Peru.

6. The abundance data in TABLE 2 do not account for the relative position of the belts in which nickel or cobalt predominates. However, note that in the eastern belt, in which nickel predominates over cobalt in ores, many deposits are related to ultramafic intrusives. The environment of northern Chile, where cobalt predominates in ores over nickel, is characterized by andesitic and rhyolitic volcanics. Abundances tabulated by Rössler and Lange[53] show that in ultramafic rocks, nickel is over 10 times as abundant as cobalt, whereas in basic and acid igneous rocks this ratio is 2:1 to 3:1.

7. Although arsenic is about 10 times as abundant as antimony in the rock types under consideration, both are similarly concentrated in eugeosynclinal rather than miogeosynclinal sediments but show a smaller preference for basic igneous rocks and shales than does copper, iron, or zinc. This correlates with the fact that sulfosalt-bearing ores occur mainly along the central Andes.

The foregoing observations refer only to the availability of minor elements in rocks but say nothing of their extractability or of distribution coefficients between hot rocks and water. Nor do they bear on their possible effects on precipitation of certain ores. Thus, for example, the following additional factors may be involved:

1. Near surface intrusion with boiling and/or oxidation may well provide the mechanism for development of acid solutions (as postulated by Raymahashay,[61] to explain nearby acid and alkaline hot springs at Yellowstone National Park). This would enhance an already relatively low pH inherited from the conversion of clays to feldspars by metamorphism or anatexis[59] or from oxidation of organic carbon,[80] in the pre-Mesozoic shales. A rather low pH of the hydrothermal solutions is consistent not only with the wall-rock alteration observed but also with the relatively large tonnage of base metals in zoned copper-zinc-lead-silver deposits and in porphyry copper deposits. Comparison of the Eh-pH diagram for tin (REF. 49, pp. 478-479) with those for other metals (REF. 15, FIGURES 7.22, 7.26, and 7.27) suggests that unusually acid solutions may be required to transport tin.

2. The relatively low sulfur fugacity indicated for the Bolivian tin deposits may not be due to a short supply of this element but rather to a regional buffering effect exercised by the ubiquitous graphite and magnetite in the country-rocks. The reason for this can be seen on diagrams by Holland (REF. 21, FIGURES 17, 26, 27, 32, and 34) and expressed by the equation

$$8C + 6Fe_3O_4 + 5S_2 = 8FeCO_3 + 10FeS$$

Alternatively, note that in the system C-O-S-Fe the tie-line siderite-pyrrhotite conflicts with the plane carbon (graphite)-magnetite-pyrite for the temperature-pressure range of interest:

$$4FeCO_3 + 10FeS = 4C + 3Fe_3O_4 + 5FeS_2$$

3. Organic carbon and magnetite in the shales of Bolivia may also contribute to a relatively low oxidation potential of the hydrothermal solutions. If the relations for 25°C (REF. 49, p. 480) hold qualitatively for higher temperatures, this should favor the solubility of tin. It remains to be seen to what degree the greater transport of tin is to be attributed to relatively high temperatures, lower sulfur and oxygen fugacities, or greater acidity of hydrothermal solutions.

4. It is possible that in Peru the prevalence of limestone and calcite cement in many red-beds raises the pH of surface and ground waters to the point where effective transport of uranium and vanadium is inhibited, thus preventing its subsequent enrichment at favorable locations within the red beds. In Argentina, more acid ground waters may be responsible for greater transport and redeposition of uranium. It is, of course, also possible that uranium is so scarce in the Andes north of Argentina that it doesn't find its way into red-bed deposits. Another possibility is that vanadium is so firmly locked in organometallic complexes in the Peruvian asphaltites that it doesn't enter into solution in ground waters and hence is prevented from enriching in red beds.

Cratonic Ore Deposits:
General Observations and Lithologic Associations.

Regarding the cratonic ore deposits of South America, we note:

1. The common enrichment of Precambrian sedimentary iron formations to form iron ore deposits (as in Quadrilatero Ferrifero, Minas Gerais; Cerro Bolivar—El Pao, Venezuela).
2. The association of Homestake-type gold deposits with Precambrian iron formations (Morro Velho-Raposos).
3. Rand-type gold-uranium deposits in conglomerates (Jacobina).
4. Scheelite-bearing contact-metasomatic (skarn) deposits in limestone horizons within Paleozoic schists (Brejui).

5. Sedimentary manganese deposits resulting from metamorphism and weathering of manganese-rich sediments, commonly in the same general regions with sedimentary iron formations.
6. *Alkalic complexes with carbonatites.*
7. Nickel, chromite, and asbestos deposits in mafic-ultramafic intrusives.

In the postcratonic cover, a few lead-zinc deposits have been discovered. They are large enough to make Brazil the third-largest lead producer in South America, but, comparing with the midcontinent deposits in North America, one is struck by a vast contrast in tonnage. Some of the Brazilian lead deposits may be of the Mississippi Valley type, but why have not more been discovered? Is it because of soil-vegetation cover and political conditions, or are they indeed less common? A rough appraisal of the volume of limestone in various basins suggests that there is a good chance that additional Mississippi Valley type lead-zinc deposits will be discovered in Brazil.[81]

A comparison with other cratonic areas in the world reveals a number of other puzzling absences, such as of Zambian-type copper deposits; layered intrusives with nickel, copper, chromium and platinum ores (such as the Bushveld, Great Dyke, and Sudbury); ilmenite-magnetite ores in anorthosites; and diamond pipes (in spite of the common occurrence of placer diamonds).

This is a relatively long list of absentees. The most likely explanation for it is insufficient exploration because of the aforementioned politico-geographic factors. Obviously, this poses serious limitations to the recognition of meaningful patterns and their interpretation.

Orogenic Belts, Metamorphism, and Structural Controls:

The Precambrian structure of the South American cratonic areas is poorly known. Hurley and Rand[24] vaguely outline three orogenic belts: Paraguay—Brasilia; Paraiba; and Cariri. These orogenic belts fringe the São Francisco and Guaporé cratons and the Guayana shield (FIGURE 12). As far as this generalized pattern goes, the following ore-deposit types appear to correlate with the aforementioned orogenic belts or with the fringes of the Guayana shield:

1. Precambrian metamorphosed sedimentary iron deposits.
2. Precambrian metamorphic manganese deposits.
3. Homestake-type gold deposits.
4. Rand-type gold-uranium deposits.
5. Nickel-chromite-asbestos deposits associated to ultramaphic intrusives.
6. Alkalic complexes and carbonatites.
7. Pegmatites.

No systematic variations or statistically significant relations have been reported so far for these deposits from South America except that the first three groups of deposits are commonly found to be associated. For example, it would be of interest to know if some of the previously mentioned deposits occupy a specific position in the orogenic belts or if regional metamorphic isograds can be related to pegmatite districts. Are the nickel-chromite-asbestos—bearing ultramafic intrusives related to orogenic belts or to regional fractures? Are the alkaline complexes and carbonatites related to the Paraná basalts, as advocated by Beurlen,[70] or to orogenic belts and regional fractures, as suggested by Petersen?[46] Will diamond-bearing kimberlite pipes be found eventually in the orogenic belts or along major fracture zones? Answers to these questions must await the results of more detailed investigations than are available to date.

Continental Drift

The recent revival of theories of continental drift spurred examination of other lines of evidence. Thus, Schuiling[58] pointed out a correlation of tin provinces between Rio Grande do Norte and Nigeria, and between Rio Grande do Sul and northern Southwest Africa. Petrascheck[75] visualized in addition a correlation of gold, tungsten, tantalum, niobium, and beryl deposits between South America and Africa. Predrift reconstructions indicating a consistent pattern for anorthosite belts were presented by Herz[20] as well as by Smith and Hallam.[60] Furthermore, Adams[68] pointed out the remarkable correlation between the Cretaceous potash deposits at Sergipe in Brazil and those in Gabon (Africa) if the continents are fitted to a predrift position. To this we may add the apparent alignment of many alkaline complexes and carbonatites (FIGURES 10 and 12) in an east-west belt through Rio de Janeiro: its seaward projection is just south of a series of islands and seamounts (Montagne, Jaseur, Columbia, Trinidade, and Martin Vaz) and in a predrift reconstruction of South America and Africa it would project to a group of five carbonatite bodies in Angola.

Discussion and Conclusions

Statistically significant patterns can be recognized in the distribution of ore deposits despite the diversity caused by local structural and lithologic controls. The predominance of deposits of certain metals — notably iron, copper, lead, zinc, tin, nickel, and cobalt — in belts following the changing trends of the Cordillera suggests that ore-deposit genesis is intimately related to orogeny in its broadest sense—geosynclinal deposition, as well as magmatic and tectonic activity. On the other hand, the lack of groupings and belts across the Andes indicates that the location of ore deposits was not significantly influenced by major transverse fractures in the pre-Upper Paleozoic basement rocks. Neither do we see any evidence that Andean ore deposits may be related to extensions of structures recognized in the Pacific ocean. Furthermore, the longitudinal belts and systematic transverse changes provide no support for the suggestion that metallogenic provinces may reflect inhomogeneities in the earth's mantle or crust resulting from accretion and meteoritic impacts in its early history.

The reasonably good correlation in the Cordillera of North and South America of orogenic ore deposits with zones of magmatic activity and with high-heat flow[5, 8, 55] can be interpreted in several ways. It may mean that hydrothermal solutions, including their metal and sulfur content, are juvenile — or at least magmatic. It may also be due to the fact that intrusions are likely to fracture their host rocks, thus providing for increased permeability, and set into motion heated groundwaters capable of dissolving sufficient amounts of metals. On this basis, whether metals and/or sulfur are derived from magmas or are dissolved from country rocks by heated waters (of whatever origin) remains an open question.

Clearly, a more sophisticated analysis is required. For discussion purposes let us, therefore, consider that the chemical changes among ore deposits are due to differences in the supply of metals, in their host rocks, or in temperature and pressure at the site of deposition.

As far as the *supply of metals* is concerned, we can distinguish the following possible sources:

Upper mantle or lower crust; basement rocks — lower Paleozoic and Precambrian rocks; cover rocks — the stratigraphic column after the middle Paleozoic.

A systematic variation in the major components of igneous rocks across an orogenic belt appears to be well documented for several parts of the world.[2, 19, 31, 71-74] To explain this, it has been argued that magmas are generated in the upper mantle or lower crust at varying depths along Benioff zones.[9, 19, 31, 71, 76] One would logically expect concomitant minor element variations in these magmas. This could account for the asymmetric transverse chemical changes among ore deposits. A test of this possibility would be provided by a geochemical survey showing a correlation of metals in intrusives (and volcanics[62]) with ore deposits across the Andes.

The evidence presented in the section on lithologic controls of orogenic ore deposits suggests that the metals and sulfur are derived from the cover rocks. Inasmuch as the field relations are such as to make it improbable that intrusives would have resulted from anatexis of the cover rocks, or would have been substantially modified by them, it follows that groundwaters must have leached the metals from the country rocks. The amount they picked up would have been roughly proportional to the availability of the various elements. A test of this possibility would be provided by a comprehensive geochemical survey across the Andes that showed a correlation of metals in country rocks and ore deposits.

The basement rocks can act as a supply of metals in two ways. First, their metal content can be incorporated in magmas by anatexis or by contamination. Alternatively, their metals may be dissolved by deeply circulating groundwaters. In either case, the observed distribution of ore deposits would require chemical changes in the basement rocks correlating approximately with the cover rocks. Surprisingly, the paleogeographic maps of Harrington[82] do indicate marine deposition during the lower Paleozoic in a belt roughly coinciding with the present outline of the Andes, and the Permian red beds and volcanics (Mitu formation and Catalina volcanics in Central Peru) suggest an orogeny at the end of the Paleozoic. This would mean that two orogenic cycles are superimposed along the Andes. The main differences are that the Lower Paleozoic geosynclinal sequence contains little or no volcanics or limestone (it consists predominantly of pelites) and most of the late orogenic volcanics of the first cycle have not been preserved. A test of this possibility would require a more careful and comprehensive study of the pre-Upper Paleozoic rocks.

It is also possible that the proportions of metals in the source rocks is relatively unimportant, but that variations in ore deposits result from *chemical differences among the host rocks.* These could, for example, influence the proportions of metals deposited from hydrothermal solutions. They could also affect the proportions of metals dissolved by groundwaters from the cover rocks or from the basement. Obvious possibilities are the control of pH, Eh, and pS_2 of hydrothermal solutions by country rocks, particularly by limestone or shales. The observed variations in country rocks could thus correlate with the metal changes in ore deposits. This thesis would be reinforced by theoretical and experimental studies explaining the reasons for specific relations, like the preference of lead-zinc ores for limestone, tin deposits with shales, and the absence of uranium and vanadium in red-bed deposits north of Argentina. Also, more such relations would have to be observed.

Finally, the crucial factors may be *temperature* and *pressure* at the site of ore deposition. The arguments presented in the section on erosion levels suggest that these parameters have at least some influence on the type of ore deposit formed. However, many more geothermometric and barometric determinations are necessary to ascertain the importance of these variables. If temperature and pressure during ore deposition are controlled by plutonic activity or by depth of burial of the geosynclinal prism, then we should observe a symmetric distribution of metals as *postulated* for the southern Appalachians by Park and MacDiarmid.[44] The asymmetric distribution in belts *observed* there and in the Cordilleras of North and South America suggests that regional temperature and pressure gradients cannot account for the distribution of metals in ore deposits. These parameters modify only the element proportions inherited by the hydrothermal solutions from the country rocks or from their parent magmas.

As far as the *cratonic areas* are concerned, the available information supports a correlation of the main ore deposit types with Precambrian orogenic belts, with the possible exception of carbonatites and alkalic complexes, which may be controlled by regional fractures. The distribution of tin prospects, gold and potash deposits, anorthosites, alkaline rock complexes, and carbonatites in South America and Africa lends some support to theories of continental drift.

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