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METALLOGENIC PROVINCES OF THE SOUTHEASTERN PACIFIC REGION

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by

dward, 1920-
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U. S. Geological Survey

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METALLOGENIC PROVINCES OF THE SOUTHEASTERN PACIFIC REGION

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ABSTRACT

Metalliferous mineral deposits of the southeastern Pacific region include: (1) hydrothermal, magmatic, and sedimentary deposits of the Andean region, one of the great mineral belts of the world; 2) Scattered hydrothermal mineral occurrences in the Antarctic Peninsula; and 3) metal-enriched pelagic sediments, ferromanganese nodules, and volcanic rocks(?) in the southeast Pacific basin. Andean metalliferous deposits, the chief concern of this report, are for the most part spatially and genetically related to calc-alkaline plutons, sub-volcanic intrusions, and volcanic rocks emplaced during the Andean orogeny of Late Triassic to Quaternary age. These deposits are components of a single metallogenic province superimposed on two or more pre-Andean metallogenic provinces that are indicated by scattered deposits of Paleozoic and Precambrian(?) age. Occurrences in the Antarctic Peninsula are of age and origin similar to the deposits in the Andes and are considered to belong to the Andean province.

The Andean metallogenic province may be divided into several subprovinces, each parallel to the Andes and the continental margin and each having a dominant metal or suite of metals. The central Andes of Peru, northern Chile, and Bolivia, which contain the greatest concentration of exploitable deposits and the greatest variety of ore types,

have as many as five linear partly overlapping subprovinces. These subprovinces, from west to east (Pacific coast to the eastern Andean front), are characterized, respectively, by deposits of : 1) iron; 2) copper, with or without associated gold; 3) polymetallic base metals (zinc, lead, copper), generally containing silver; 4) tin; and 5) gold. Iron deposits chiefly are near the coast in central to northern Chile and in southern Peru. The copper and polymetallic provinces are characterized by abundant deposits in the central Andean region but comparatively few scattered deposits in the north (Ecuador, Colombia, and Venezuela) and in southern Chile and Argentina. Scattered gold-rich veins and placers occur along the western Andean front and coastal region, the general area of the copper province, from central Chile to northern Colombia. Similar deposits occur along a discontinuous belt in the eastern Andes from Bolivia to Ecuador and in the central Andes of Colombia. Tin deposits are almost wholly restricted to the eastern Andes of Bolivia.

The position and age distribution of plutonic and volcanic rocks and associated metalliferous deposits of the Andes indicate presence of an active subduction zone in this region since at least Late Triassic time. Magmas of the calc-alkaline igneous rocks are believed to have formed chiefly by partial melting of mantle, oceanic sediments, and oceanic crust along the Benioff zone at depths of 100 to 200 km. Plutonic and volcanic rocks show a general though nonuniform progression of decreasing age from west to east. Rocks of Jurassic and Cretaceous age are most abundant near the coast, whereas those of Tertiary and Quaternary age dominate in the Andes. Locally, intrusive rocks and ore deposits of widely different ages are juxtaposed. Metals of the ore deposits associated

with the calc-alkaline rocks were supplied by the source rocks in the Benioff zone, some of which probably had been previously enriched in certain metals at the ancestral East Pacific Rise and were mobilized or assimilated from metal-rich zones in the overlying mantle and continental crust by magmas rising from the Benioff zone.

INTRODUCTION

This paper presents summary information about the distribution and environment of mineral deposits of three major subdivisions of the southeastern Pacific: The Andean region, marginal lands of northwestern Antarctica (including the Antarctic Peninsula and Scotia Arc), and the ocean basin. It will be concerned chiefly with the Andean region and will only touch upon mineral deposits of Antarctica and seabed resources of the southeastern Pacific.

The Andean region, which is considered to include the coastal mountains and lowlands of westernmost South America as well as the Andean Highlands and low eastern foothills, can be divided into several physiographic provinces (Fig. 1), each of which tends to show distinctive geologic features and characteristic types of mineral deposits. The region constitutes the longest active orogenic belt in the world, stretching nearly 9,000 km (5,600 mi) from Venezuela to Tierra del Fuego. Mineral deposits, chiefly those containing the base metals copper, lead, and zinc, with or without recoverable gold and silver, are found throughout the Andes but are by far the most numerous in the latitudes between northern Peru and central Chile. Within this region are thousands of mining districts and deposits, a concentration of exploitable mineral deposits as great as or greater than any other comparable area on earth.

Figure 1. Physiographic provinces of the Andean region. Heavy dashed line marks approximate eastern limit of Andes. Interpreted from U. S. Air Force Operational Navigation Charts supplemented by data of Aubouin and others (1973), Irving (1971), Goossens (1969), and Bellido and Montreuil (1972).

The future of mining in the Andean region is bright, although many of the richest deposits have been mined out, and some metals such as silver, bismuth, and antimony now are produced largely as byproducts of polymetallic base-metal and tin ores. Copper has by far the greatest potential for large future production, and even though the region has been a major source of copper since the latter part of the 19th century, total production has been only a fraction of potentially exploitable resources. Most of the copper now is extracted from five porphyry copper deposits, one in Peru and four in Chile; a sixth deposit at Potrerillos in northern Chile was mined out and closed in the late 1950's. At least an equal number of porphyry copper deposits are known to contain reserves and grades sufficient to sustain large-scale production comparable with that of deposits now being exploited, and many others that have not yet been adequately explored are present. Tin production, mostly from Bolivia, has decreased in recent years; most of the tin has been mined. The richest tungsten ores of Bolivia and Peru have been largely depleted. Production of lead and zinc, chiefly from Peru but including important quantities also from Bolivia and Argentina, has increased since World War II, and current production will be sustained or even show a moderate increase over the next several decades. Current high prices for gold should stimulate exploration of this metal from both veins and placers. The possibility for greatly increased gold production is excellent, particularly in the eastern Andes of Peru and Bolivia and the central Andes of Colombia.

A report of this kind, dealing with a wide variety of mineral resources and geologic environments of a large area of the earth's surface, must of necessity deal with these resources in general terms only.

The information presented and conclusions drawn are based on many published and unpublished reports in addition to my own investigations of mineral deposits in the Andes, chiefly in Chile and Peru, which began in 1948. The most recent summary reports and maps on Andean metallogeny and metallogenic provinces are as follows: Bellizia (1973), Hollister (1973), Sillitoe (1972a, b; 1973b), Bellido and others (1972), Bellido and de Montreuil (1972), Goossens (1969, 1972), Turneaure (1960, 1971), Kelly and Turneaure (1970), Petersen (1965, 1970), Angelelli and others (1970), United Nations Development Programme (1968, 1970), Bolivia Servicio Geol., Div. Technologia Minera (1968), de las Casas (1969), Ruiz and Ericksen (1962), Ruiz and others (1965), Stoll (1965), Ahlfeld and Schneider-Scherbina (1964). Summary information about mineral deposits of Antarctica has been given by Wright and Williams (1974).

REGIONAL TECTONIC SETTING

The mineral deposits of the southeastern Pacific reflect the nature of the local geologic environment at the time of deposition as well as regional or global processes such as orogeny, plutonism, and volcanism, best explained by plate tectonic theory. Mineral deposits of the Andes formed during the recent past, when plate configurations were similar to those of today, and back in time to the Mesozoic, the beginning of Andean orogeny, when configurations were different (Herron, 1972; Larson and Pitman, 1972). In this report it is assumed that most Andean mineral deposits are genetically related to calc-alkaline magmas that were generated by partial fusion along the upper margin (Benioff zone) of a subducting oceanic plate at depths of more than 100 km (Dewey and Bird, 1970). To judge from distribution of earthquake foci and present and

recent past (Pliocene-Pleistocene) plutonism and volcanism, calc-alkaline magmas formed on the Benioff zone at depths of 100-200 km and distances on the order of 200-400 km from the axis of the Peru-Chile trench.

The southeastern Pacific region now comprises three major plates--South American, Nazca, and Antarctic--and the small Cocos plate, which are separated by seismically active accreting or consuming margins. The East Pacific Rise (Fig. 2), which marks the western margin of the Cocos and Nazca plates and western margin of the Antarctic plate north of lat 60° S., is an accreting plate margin or axis of spreading where new oceanic crust is now forming. Eastward spreading along this axis is as much as 8.3 cm per year (Rea and others, 1973, p. 228). The Galapagos Rift, just north of the Carnegie Ridge (Fig. 2), and the Chile Ridge, which mark the north and south boundaries of the Nazca plate, also are active accreting plate margins. The juncture of the Nazca and South American plates is a consuming margin where the oceanic crust is being subducted beneath the continental crust. As can be seen in figure 2, this boundary is marked by a trench that is interrupted by the Nazca Ridge and by the Carnegie Ridge, neither of which is now an active spreading ridge, although they may have been sites of spreading in the past. A similar trench extends along the north boundary of the Cocos plate, the northernmost trench segment shown in figure 2. All these trench-plate boundaries are marked by shallow earthquakes (<70 km depth), which in the Andean region tend to become progressively deeper eastward to a maximum of about 300 km, indicating a Benioff zone inclination of about 30°. Deep-focus earthquakes (500-700 km) occur in isolated areas just east of the Andes and are attributed to movement on the deepest and easternmost part of the subduction zone.

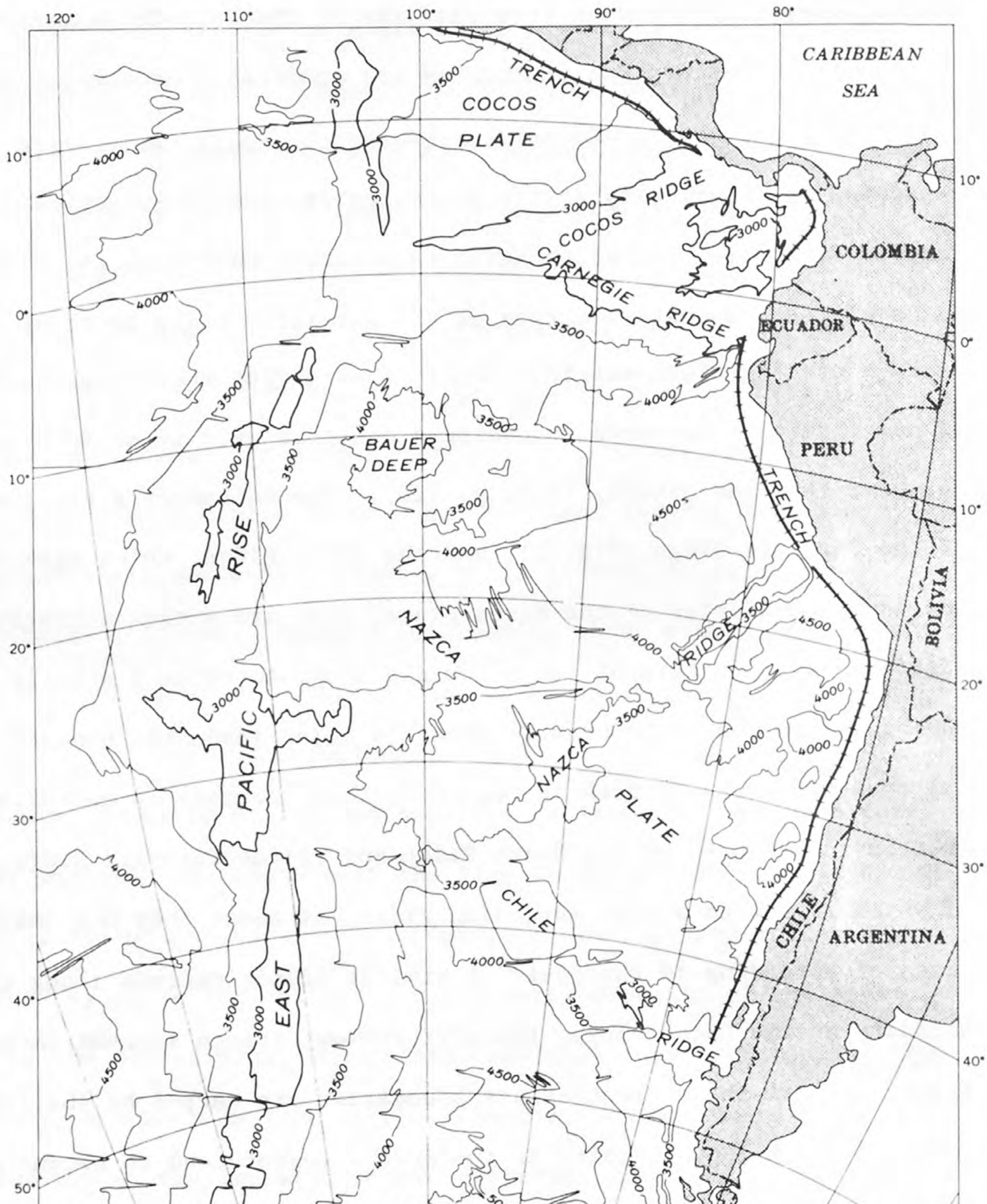

Figure 2. Bathymetric map of the southeastern Pacific. Isobaths in meters. From unpublished 1:10,000,000-scale map compiled by the U. S. Geological Survey for the Circum-Pacific Map project and based on 1:6,500,000 scale maps published by Scripps Institution of Oceanography and the Institute of Marine Resources, University of California.

The northernmost and southernmost Andes and connecting island-arc systems owe their complex tectonic framework to a different style of plate convergence from that affecting the north-trending main Andes. A discussion of the tectonics of these regions is beyond the scope of this paper, but it should be noted that the relative paucity of metallic mineral deposits may in part be due to this difference in style, particularly in regard to variation in position, inclination, and rate of convergence of plates.

The magnetic pattern in the southeastern Pacific basin indicates that spreading on the East Pacific Rise began more than 50 m.y. ago at lat 55° S. and progressed northward; spreading started at 20 m.y. B.P. at 35° S., and at less than 10 m.y. at lat 10° S.-10° N. (Herron, 1972, p. 1671). Prior to 10 m.y.-20 m.y. ago, the accreting margin of the ancestral Nazca plate was to the east along a northwest-trending ridge extending across the present Nazca plate; the Chile Ridge is a still active remnant of this ridge. Herron also suggested that this older spreading axis was active at least as far back in time as Late Cretaceous. Tectonic features and metallogeny of the central Andean region indicate a consuming margin similar in configuration and direction of convergences to that between the present Nazca and South American plates; the configuration of this consuming margin has been similar at least since Late Cretaceous.

Prior to Late Cretaceous time, the oceanic plates west of South America had a still different configuration, and the continental margin may have been marked by island-arc systems in the north and extreme south. Larson and Pitman (1972, p. 3654) interpreted magnetic anomalies on the sea floor of the southeastern Pacific as indicating the existence of

two major plates during the Jurassic and Early Cretaceous (180 m.y.-110 m.y.), separated by a spreading axis of which the presently inactive Nazca Ridge (Fig. 2) is a remnant. Goossens (1974) suggested that the tholeiitic basalt flows and mafic to ultramafic intrusions, which are widespread along the western front of the Cordillera Occidental and in the coastal region of Ecuador and Colombia, were formed at either an upper Mesozoic island arc or oceanic ridge. Dalziel and others (1973, p. 589) described mafic rocks of the southernmost Andes (lat 51^{o}-56^{o} S.) as being the oceanic floor of and Upper Jurassic-Lower Cretaceous marginal continental basin bounded on the west by an andesitic island arc and on the east by the stable continent. During the middle Cretaceous, the basin was closed, and rocks in it were deformed by relative eastward movement of the arc against the continent. The huge batholithic mass in the southernmost Andes (Fig. 4) represents the root of the former island arc.

Seismic data indicate that the South American lithospheric plate beneath the Andes is 200 to 300 km thick, whereas the Nazca plate is only 50-60 km thick near its juncture with South America (James, 1971, p. 3329). Simatic oceanic crust on the Nazca plate is probably less than 10 km thick, and sialic continental crust beneath the Andes ranges from 45 to 70 km in maxiumum thickness. A maximum crustal thickness of about 70 km was determined by seismic refraction studies in the altiplano of southern Peru and northern Bolivia (Ocola and others, 1970, p. 233). The crust beneath the Andes thins to the north and south to a probable maximum thickness of 45 km in the Andes of southern Colombia. James (1971, p. 3332) reported that crustal thickness across the central Andes (latitude of Bolivia) ranges from 11 km (including water) off the coast to 30 km along the coast,

and is more than 70 km beneath the Bolivian altiplano, and 50 km beneath the eastern Andes. The gravity anomaly map (Fig. 3) indicates relative crustal thickness in the Andean region. High negative anomalies are over thinner crust.

GEOLOGIC SETTING OF ANDEAN MINERAL DEPOSITS

Structures of Paleozoic and younger rocks of the Andes--folds, faults, elongate plutons--are more or less parallel to the Andes and the western coast of South America from Colombia to southern Chile. They also are parallel to the mineral belts or metallogenic subprovinces. Major breaks or bends in the structural pattern occur at several places: 1) in Colombia, where the Andes split into three divergent ranges; 2) in northern Peru and southern Ecuador, where a major break in the structure, referred to as the Huancabamba deflection, is marked by deflection and intersection of north-northeast-trending structures of the northern Andes and north-western structures of Peru (Gansser, 1973, p. 104); and 3) in Bolivia, where the north-trending structures of Chile and Argentina bend north-westward parallel to the Peruvian coast. Furthermore, two sharp westward bends in the structure occur in Peru; one, the Cajamarca virgation, is between lat 7° and 8° S. and the other, the Abancay virgation, is between lat 13° and 14° S. (Audebaud and others, 1973, p. 90). The extreme north and south ends of the Andes also show curving trends. In the north, the easterly structural trends in Venezuela bend northward into the Lesser Antilles and then westward into the Greater Antilles; in the south, the structural grain follows the Scotia Arc into the Antarctic Peninsula.

Structures in metamorphosed Paleozoic and Precambrian rocks may show considerable deviation from the above trends, and such structures are related to orogenesis that predates Andean orogeny.

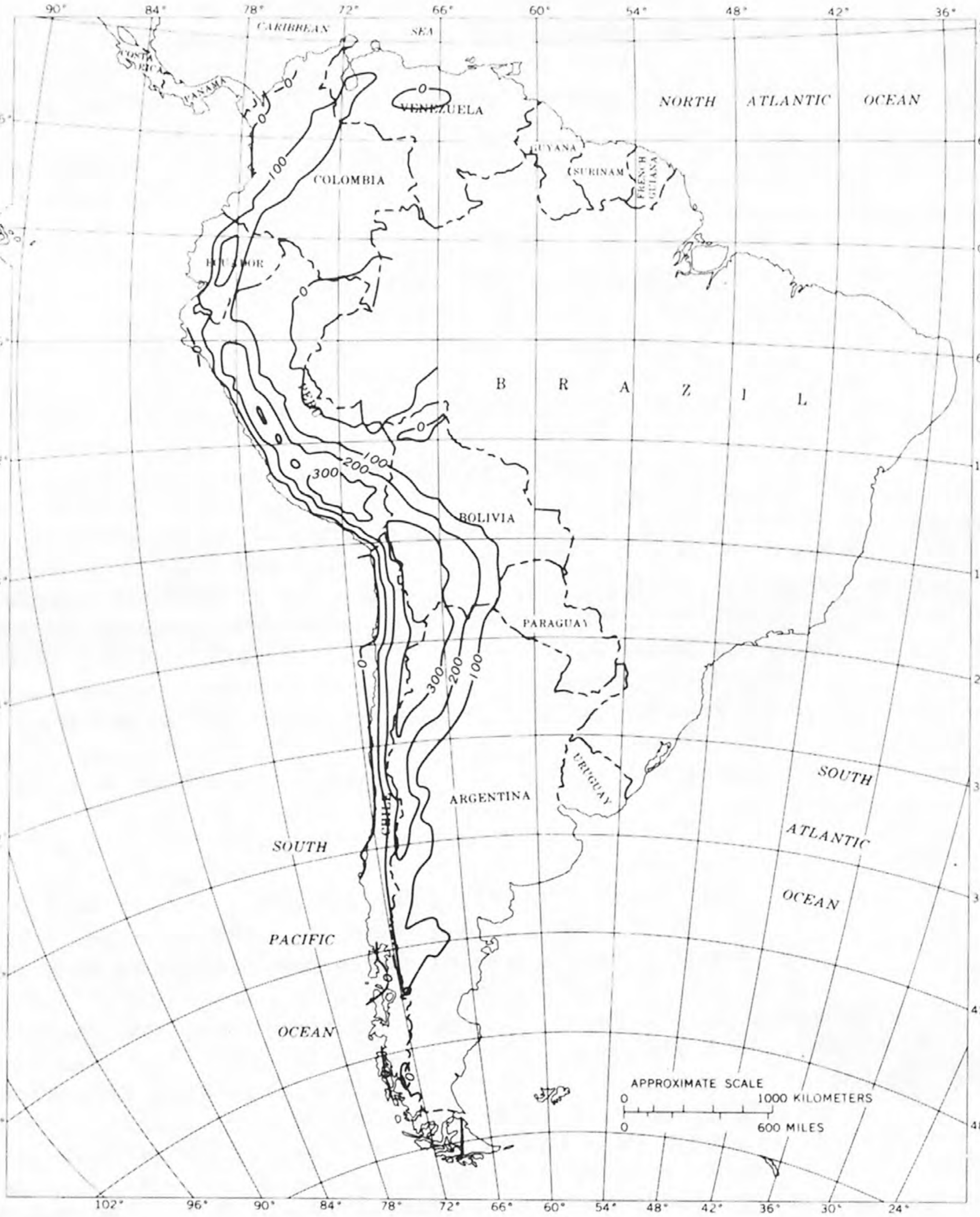

Figure 3. Bouguer gravity anomaly map of the Andean region. Isomagnetic contour interval, 100 mgal; number values are negative. From Breville and others (1973).

Structural controls of mineralization include local fault zones, favorable stratigraphic horizons, and intrusions, as well as large regional structures such as longitudinal faults, folds, batholiths, and former geosynclines. As a consequence of local structural control, the principal ore deposits consist of: 1) fissure-filling veins, replacement bodies, and disseminations that are associated with faults and fractures; 2) replacement deposits at favorable stratigraphic horizons; 3) contact metasomatic or skarn deposits; and 4) stockwork or disseminated porphyry deposits and breccia pipes related to faults and subvolcanic porphyritic intrusions. In a general way, the copper and polymetallic base-metal provinces extend over the site of the Mesozoic Andean geosyncline, which extended nearly the full length of the western Andes. The copper province (Fig. 7) is in the western part of this geosynclinal belt, where volcanic rocks and clastic sediments predominate, and polymetallic deposits are found to the east where marine limestone is widespread.

A recent study of ERTS imagery for northern Chile and southern Peru by W. C. Carter (in press) shows that porphyry copper deposits in northern Chile (Cerro Colorado and Mocha) and southern Peru (Toquepala area and Cerro Verde) occur within a narrow belt of intensive structural deformation. Continued study of ERTS imagery probably will reveal regional structural controls elsewhere in the Andes. In general, no clear relationship has been shown to exist between distribution of mineral deposits and most other major tectonic features such as deflections or breaks in the structural pattern or major transverse fault or fracture zones, although Goossens (1972, p. 459) considered that some mineral deposits in Ecuador are controlled by major transverse faults. The distribution and character of structure and mineralization of the Andes

appear to be unrelated to projections of sea-floor structures such as ridges, rifts, and transform faults, as would be expected if plate movement caused progressive changes in relative positions of these structures and the continental margin.

The host rocks of most Andean mineral deposits consist chiefly of marine and continental sedimentary rocks, volcanic rocks, subvolcanic intrustions, and plutonic rocks of Jurassic to Tertiary age, and marine sedimentary rocks of Paleozoic age. Most of the plutonic rocks shown in figure 4 are of Jurassic to Tertiary age. Sedimentary and volcanic rocks of similar age crop out in those parts of the Andes not underlain by rocks of pre-Mesozoic age (Fig. 5) or covered by postmineral volcanic rocks and sediments (Fig. 6). Marine sedimentary rocks of Paleozoic age are the chief hosts of deposits of the Bolivian tin belt and of many gold veins in the eastern Andes of Bolivia and Peru; gold deposits in the central Andes of Colombia are in pre-Devonian metamorphic rocks.

Plutonic rocks are more extensive in the Andes than in any other modern mountain system. As can be seen in figure 4, the plutons along the coast of Peru and Chile include a segment in Peru that crops out continuously for about 1,000 km (621 mi); another in central Chile is about 1,500 km (932 mi) long, and still another in southern Chile is 2,200 km (1,367 mi) long. Most of the plutonic rocks along the coast are considered to be part of the Andean Batholith of late Triassic to Tertiary age. Plutonic rocks of Paleozoic age, which occur sporadically in the Andes, are most extensive in the coastal region of southern Chile between lat 34° and 38° S. The only plutons of known Precambrian age are near the coast of southern Peru, and these are late Precambrian in age.

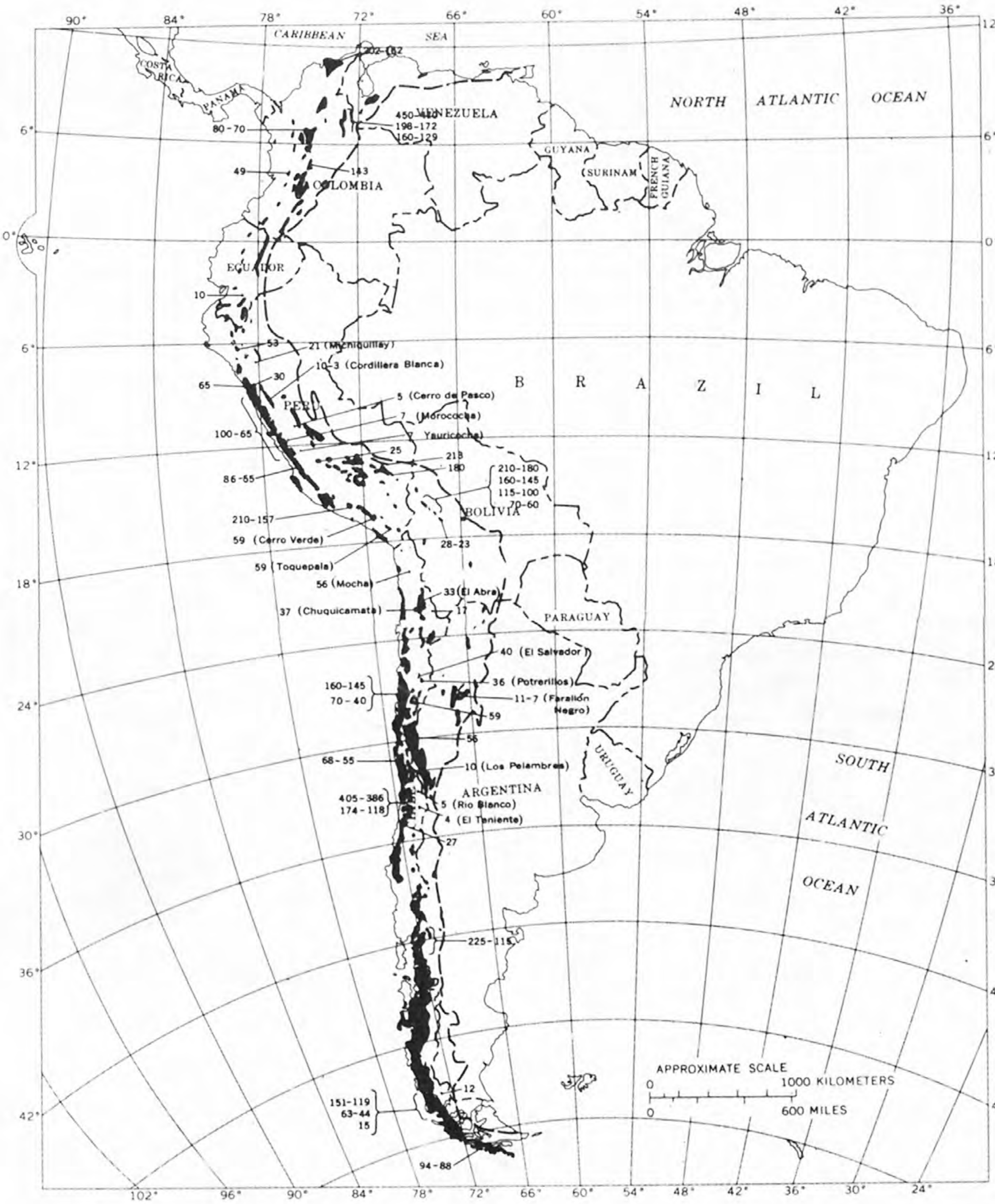

Figure 4. Distribution and selected radiometric ages of plutonic rocks in the Andean region. Heavy dashed line marks approximate eastern limit of Andes. Plutons from unpublished geologic map prepared by G. H. Goudarzi (1973), U. S. Geological Survey. Radiometric ages (in million years) from following sources: 1) Colombia--Goldsmith and others (1971), Irving (1971); 2) Ecuador--Muller-Kahle and Damon (1970); 3) Peru--Steward and others (1974), Alberto Manrique (written communication, 1971), Laughlin and others (1968), Gilletti and Day (1968); 4) Bolivia--Clark and others (1973); 5) Chile--Halpern(1973), Corvalán and Munizaga (1972), Quirt and others (1971), Farrar and others (1970); and 6) Argentina--Clark and others (1973), Caelles and others (1971).

Figure 5. Distribution of Precambrian and Paleozoic sedimentary and metamorphic rocks of the Andean region. Heavy dashed line marks approximate eastern limit of Andes. From unpublished geologic map (1973) by G. H. Goudarzi, U. S. Geological Survey.

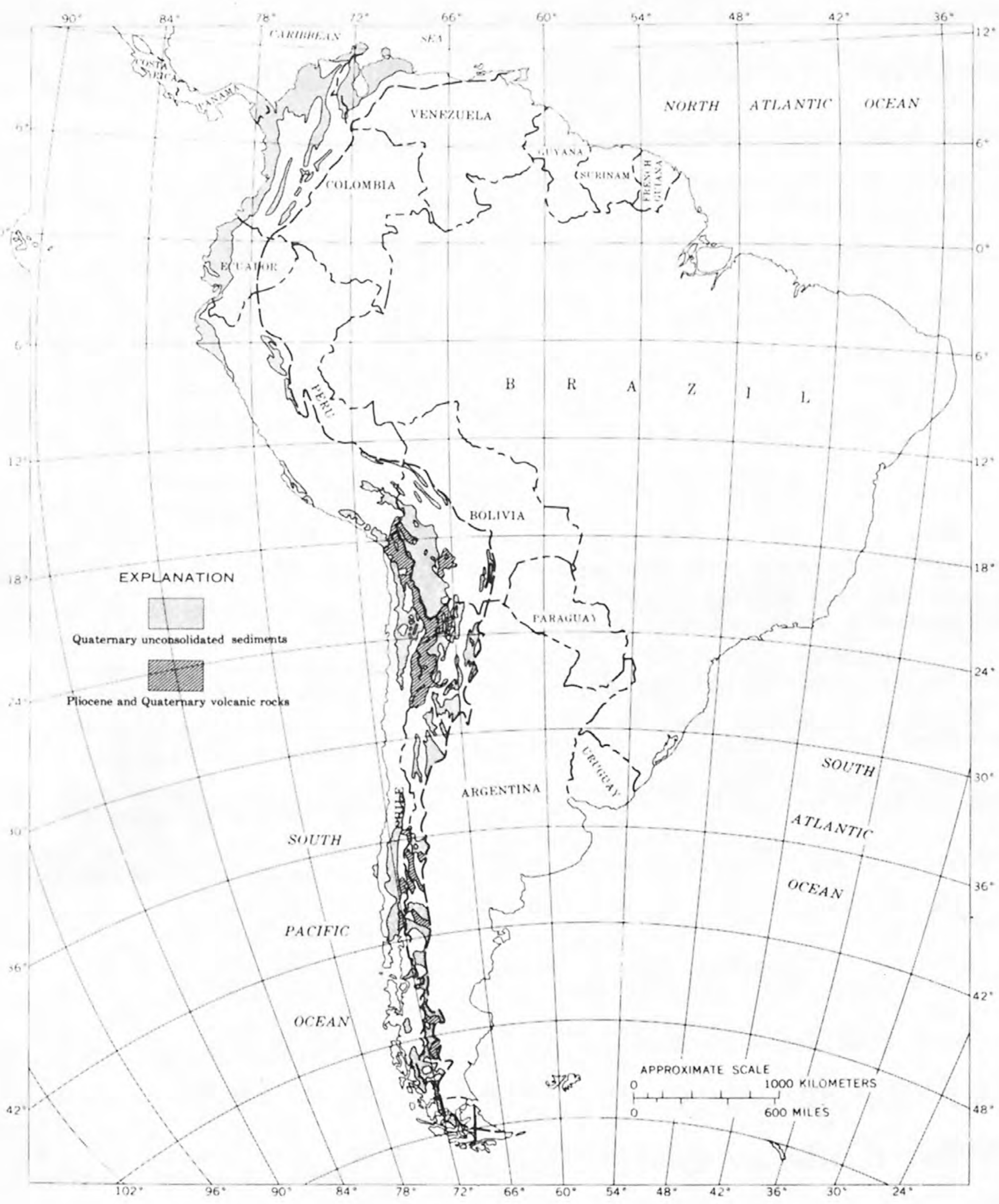

Figure 6. Distribution of volcanic rocks and unconsolidated sediments of Pliocene and Quaternary age, most of which lack mineral deposits; unconsolidated sediments locally contain gold placer deposits. Heavy dashed line marks approximate eastern limit of Andes. From unpublished geologic map (1973) by G. H. Goudarzi, U. S. Geological Survey.

About 500 radiometric age dates for plutonic, volcanic, and metamorphic rocks of the Andes have been published since 1960, giving new insight into Andean orogenesis and metallogenic epochs. Most of these dates are found in the following publications: Stewart and others (1974), Zentilli (1974), Vergara and Munizaga (1974), Clark and others (1968), 1970, 1973), Halpern (1973), Halpern and others (1973), Corvalán and Munizaga (1972), Caellas and others (1971), Quirt and others (1971), Goldsmith and others (1971), Gonzales-Bonorino and Aquirre (1970), Müller-Kahle and Damon (1970), Farrar and others (1970), Giletti and Day (1968), Laughlin and others (1968), Rutland and others (1965), Levi and others (1963), and Ruiz and others (1960). Ages shown in figure 4 for plutonic rocks of the Andes, as well as those in this discussion, have been taken from these reports and from unpublished data of Alberto Manrique (written commun., 1971). The dates shown in figure 4 have been selected to give an idea of patterns and ranges of ages of Andean plutonic rocks. Nearly all the dates in this figure were determined by the K-Ar method. About 30 radiometric ages of Chilean rocks determined by the lead-alpha method (Ruiz and others, 1960; Levi and others, 1963) have not been considered because of the variable accuracy of ages obtained by this method (Corvalán and Munizaga, 1972).

The radiometric ages indicate several stages of major plutonism in the Andean region prior to the Andean orogeny of Late Triassic to Quaternary age, as follows: 1) Late Precambrian (679-642 m.y.); 2) Late Ordovician and Early Silurian (447-421 m.y.); 3) Late Silurian and Early Devonian (405-386 m.y.); 4) Late Devonian and early Carboniferous (346-325 m.y.), and Late Permian (251 m.y.). Plutons of Mesozoic and Tertiary age are

chiefly of Late Triassic to Pliocene age (190-5 m.y.). According to Steward and others (1974, p. 1107), most of the plutonic rocks in Peru were emplaced during the interval of Late Cretaceous to Miocene (100-10 m.y.).

Intrusive rocks of Mesozoic and Tertiary age in the Andes south of Colombia tend to be oldest near the coast (generally Jurassic or Cretaceous) and youngest in the high Andes (Fig. 4). For example, Stewart and others (1974) have shown that the batholith of coastal Peru was emplaced chiefly during the interval Late Triassic (190 m.y.) to middle Oligocene (30 m.y.) time. Oldest rocks tend to occur in the southwestern part of any given segments of this batholith. Farrar and others (1970, p. 60-65) reported four stages of Mesozoic-Tertiary intrusive activity in the coastal region of Copiapó northern Chile (near lat 27° S.): 1) Early Jurassic; 2) middle Cretaceous; 3) early Paleocene, and 4) late Eocene. Magmatic activity here shows an eastward migration with time, so that Jurassic plutons are at or near the coast and upper Eocene plutons are several tens of kilometers inland. Zentilli (written commun., 1975) believes that most of the mineral deposits of the Copiapó region are associated with the Cretaceous intrusions that were emplaced during the interval 120 m.y. to 95 m.y. B. P. Zentilli (1974) reported that migration here ended abruptly in Oligocene time and that by Miocene time, calc-alkaline magmatic activity was taking place simultaneously in several areas over a 250-km-wide belt between lat 26° and 29° S., and east of the above region of Eocene activity. Plutons in the Andean Highlands of Peru appear to be chiefly of Miocene and Pliocene age, but radiometric ages are too scanty to allow conclusions as to geographic age distribution. The easternmost plutons in the Peruvian Andes are older --

Late Triassic and Jurassic--but here also, age data are too scanty to indicate a distribution pattern. In Colombia, in contrast to the Andes to the south, the youngest plutonic rocks tend to occur to the west in the Cordillera Occidental and the oldest, to the east in the Cordilleras Central and Oriental (Figs. 1 and 4).

Plutons and subvolcanic intrusions associated with metalliferous deposits appear to be chiefly of Late Cretaceous to Pliocene age (100 to 5 m.y.). Ages of intrusions associated with certain types of deposits tend to be within a characteristic time span. Thus, deposits of the copper province (Fig. 7) appear to be chiefly Cretaceous (100 m.y.) to Oligocene (30 m.y.) in age. Porphyry copper deposits, most of which are near the eastern margin of the copper province, are Paleocene (60 m.y.) to Pliocene (4 m.y.) in age (Quirt and others, 1971). The polymetallic base-metal deposits in the Andean Highlands of Peru (see Fig. 11) are probably the youngest group of Andean metalliferous deposits, most being within the time span of Miocene and Pliocene (25-3 m.y.). Some of the most important mining districts here (Cerro de Pasco, Morococha, Yauricocha, and many districts in the Cordillera Blanca) are less than 10 m.y. old, and they rank among the world's youngest metalliferous deposits. Clark and others (1973) cited five different ages of tin mineralization in Bolivia: 1) Middle Triassic-Early Jurassic (210-180 m.y.); 2) Middle-Late Jurassic (160-145 m.y.); Late Cretaceous-Paleocene (70-60 m.y.); 4) Oligocene (28-23 m.y.), and 5) Neogene (presumably <20 m. y.). Zentilli (1974) reported six pulses of intrusion and associated mineralization in the Copiapó region of northern Chile (between lat 26° and 29° S.: 1) Early Jurassic; 2) Middle-Late Jurassic; 3) Early-Late Cretaceous; 4) Paleocene; 5) Eocene-early Oligocene, and 6) early Miocene.

MINERAL DEPOSITS

For purpose of discussion, the mineral deposits are divided into those of the Andean region (the Andean metallogenic province and the relatively few pre-Andean deposits) and those of Antarctica and the Pacific basin. The Andean metallogenic province comprises mineral deposits that were formed during the Andean metallogenic epoch of Triassic to Quaternary time. Pre-Andean deposits formed during three or more intervals in Precambrian and Paleozoic time.

Deposits of Andean metallogenic province

At least five linear subprovinces can be distinguished in the Andean metallogenic province (Fig. 7), each characterized by a metal or suite of metals; locally, these subprovinces may be further subdivided into mineral belts, each characterized by a dominant suite of minerals. Such mineral belts also are elongate and trend more or less parallel the subprovinces. Although a certain type of deposit predominates in each subprovince, it is not necessarily the only type present, nor is it restricted to this subprovince.

The geological environment of the major zones of mineralization in the Andes shows abrupt and probably genetically significant changes in terms of types of deposits from west to east. Thus, iron and copper subprovinces (Fig. 7) are in the coastal region and western flanks in the Andes in northern Chile and southern Peru, where relatively deep erosion has exposed huge segments of the Andean Batholith (Fig. 4). The mineral deposits occur chiefly in the plutons, in Upper Cretaceous and lower Tertiary volcanic rocks, and in Jurassic sedimentary and volcanic rocks. The polymetallic base-metals province in Peru, where it is best developed,

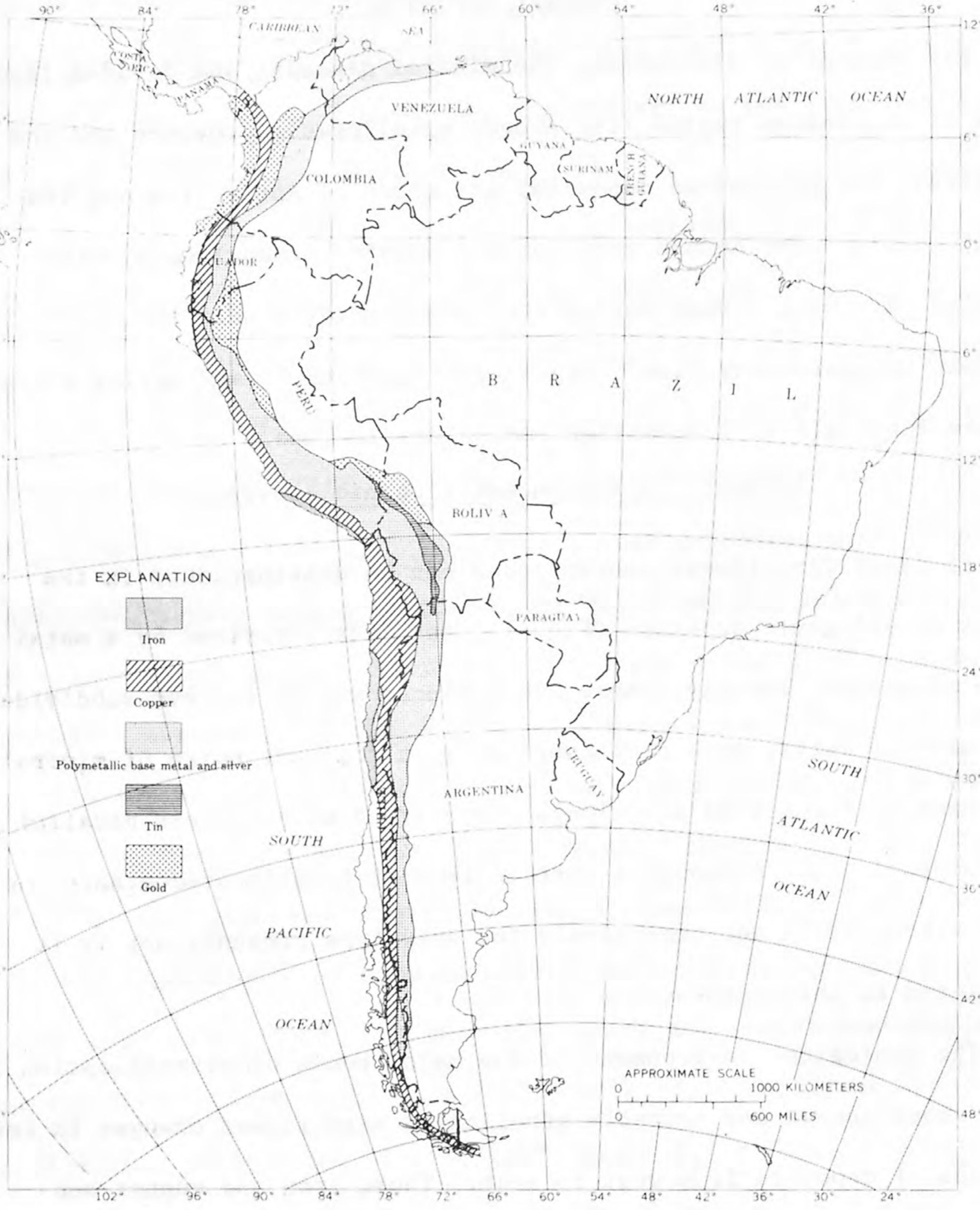

Figure 7. Andean metallogenic province, showing five major subprovinces of 1) iron, 2) copper, 3) polymetallic base metal and silver, 4) tin, and 5) gold.

is in an area where marine limestone of Mesozoic age is widespread and where most intrusions are relatively small. Eastward, the polymetallic base-metal province extends into terrane of dominantly Paleozoic clastic sedimentary rocks and large batholiths of Jurassic and Cretaceous age (Fig. 4). Some copper and iron deposits here are similar in mineralogy and geology to those near the coast. The gold deposits in the eastern Andes of Bolivia and Peru and Cordillera Central of Colombia are chiefly in Paleozoic sedimentary and metamorphic rocks.

By far the greatest number of major Andean mineral deposits are in the region extending from northern Peru to central Chile; elsewhere, deposits tend to be scattered and small. Furthermore, the different types of deposits within this central Andean region tend to be clustered within given segments of the subprovinces (see Fig. 7). For example, most polymetallic base-metal deposits are in Peru, copper deposits in Chile, and tin deposits in Bolivia. More than 90 percent of the value of Andean mineral production has come from the deposits in these three countries, including deposits shown in figures 9-11, as well as many others. The only large production elsewhere in the Andes has been from gold deposits in Colombia and Ecuador and from a single lead-zinc deposit in northernmost Argentina, which may be pre-Andean.

A notable feature of the Andes is the apparent absence of massive sulfide deposits associated with basaltic lavas or ophiolites. Also absent are layered chromite deposits and contact metasomatic scheelite deposits (Petersen, 1970, p. 839). In part, however, the apparent lack of these types of deposits may be due to relative lack of exploration in favorable areas.

Iron.--The discontinuous iron province of the coastal region of northern Chile and southern Peru, which overlaps the copper province, contains several tens of deposits ranging from a few hundred thousand to about 100 million tons of high-grade iron ore (average ~60% Fe). These deposits have been and continue to be the sources of nearly all the iron ore produced in the Andean region, which in the year 1971 was about 11 million metric tons in Chile and 9 million in Peru (U.S. Bur. Mines, 1973, p. 208, 646). Scattered iron deposits are found elsewhere in northern Chile and northwestern Argentina, in the eastern Andes of southern Peru, and in the eastern Andes of Colombia. Of these, only the deposits in Colombia are currently being exploited.

Nearly all the iron deposits are of either contact metasomatic or hydrothermal origin, and most are considered to be of Late Cretaceous age (Ruiz and others, 1965, table 1; Bellido and de Montreuil, 1972). The iron deposits of coastal Chile consist of magnetite bodies and veins in sequences of andesite flows and breccias and continental clastic sediments at or near the contacts of dioritic to granodioritic plutons (Ruiz and others, 1965, p. 147-148). Deposits in southern Peru are similar, but the host rocks in this region are schist, gneiss, and granite of probable Precambrian and early Paleozoic age (Bellido and de Montreuil, 1972, p. 40-41).

The magnetite flows at El Laco (Fig. 8) are a unique type of iron deposit that has not been recognized elsewhere. They have been described by Park (1961) and by Ruiz and others (1965, p. 246-247). The flows occur at five localities on the flanks of an eroded Quaternary volcano, which probably represent the sites of former craters (Sanchez, unpublished report cited by Ruiz and others, 1965, p. 246-247). The flows consist chiefly of magnetite, which probably was the principal magmatic mineral,

Figure 8. Principal zones of sedimentary, magmatic, and placer deposits in the Andean region. Heavy dashed line marks approximate eastern limit of Andes.

and hematite which probably formed largely by hydrothermal alteration of magnetite after the flows had been emplaced. Judging from the information of Sanchez, the five deposits may contain as much as 100 million tons of moderately high grade iron ore. According to Sanchez (Ruiz and others, 1965), the iron-oxide magma that formed the flows originated as magmatic segregations of an andesitic magma. However, Frutos and Oyarzún (Oyarzún, 1974) suggested that itabirite fragments in the iron ore and trace-element content of the magnetite indicate fused iron-formation as the source of magnetite.

Copper.--A copper province can be traced nearly the full length of the Andes from northern Colombia to the southernmost tip of South America (Fig. 7). The deposits are most numerous in the western part of the Andes and coastal region from central Peru to central Chile (Fig. 9). A belt of copper deposits (not shown in Fig. 7) and intermingled polymetallic deposits occurs in southern Peru at the eastern side of the polymetallic base-metal province. The copper deposits in Peru and Chile have yielded most of the copper that has been produced in the Andes. Copper from polymetallic ores of Peru has been small by comparison. Total copper production from Chile for the period 1601-1963 was estimated by Ruiz and others (1965, p. 172) to be about 18 million metric tons, most of which was produced in the present century from three mines, Chuquicamata, Potrerillos, and El Teniente (Fig. 10) which exploited porphyry copper deposits. Chuquicamata and El Teniente are perhaps the largest and highest-grade porphyry coppers in the world. Potrerillos was closed in the late 1950's when ore grade had dropped to a point at which the operation was no longer economic. Historic data about Peruvian copper

Figure 9. Selected major copper deposits, other than porphyry coppers, in the Andean region.

Figure 10. Porphyry copper deposits in the Andean region.

production is not readily available, but inasmuch as large-scale exploitation of a porphyry copper deposit (Toquepala) did not begin until the late 1950's, it is estimated that production is considerably less than that of Chile. Production for the year 1971 from Chile was about 720,000 metric tons of fine copper, whereas that of Peru was 215,000 tons, which includes copper recovered from polymetallic ores (U.S. Bur. Mines, 1973, p. 208, 646).

The seven types of copper deposits exploited in the Andean region are, in order of economic importance: 1) porphyry copper; 2) hydorthermal veins and replacements; 3) stratabound; 4) contact metasomatic; 5) red-bed copper; 6) tourmaline breccia pipes; and 7) fumarolic. The ore of nearly all these copper deposits (except for the red-bed copper) consists of a few dominant primary minerals, generally quartz, pyrite, and chalcopyrite, but some also contain abundant bornite. Many vein deposits are relatively high in gold, and some contain gold as essentially the only exploitable metal in a quartz-pyrite-arsenopyrite gangue.

Only a few of the distinguishing features of the seven types of copper deposits can be mentioned here. Porphyry coppers are similar to those elsewhere, but three of those in Peru--Hualgayoc, Antamina, Morococha deposits (Fig. 10)--are associated with porphyries that have intruded limestone terrane. Disseminated copper minerals occur in the porphyries as well as the associated skarn. Also, these deposits are within the area designated as the polymetallic base-metal province in Figure 7, and are in districts of abundant zonally arranged base-metal and silver deposits. Hydrothermal veins, formed by fissure-filling and replacement, are the most widespread and numerous of all the copper

deposits and have yielded important quantities of copper in Peru and Chile. Veins of this type in Chile have also yielded by-product cobalt, mercury, and tungsten and include the principal gold-bearing deposits. Stratabound deposits occur chiefly in Cretaceous volcanic rocks and associated marine or lagunal sediments of northern Chile (Ruiz and others, 1965, table 1). The typical deposit consists of disseminated chalocopyrite and bornite in vesicular tops of lava flows and in associated volcanic tuff and breccia. Alternatively, these minerals are finely disseminated in interbedded layers of marine or fresh-water limestone. Tourmaline breccia pipes ranging from a few meters to 1,200 meters in diameter occur in a 2,000-km-long belt extending through northern Chile (Sillitoe and Sawkins, 1971, p. 1028). They have yielded relatively small amounts of copper. Small fumarolic copper veins, consisting of covellite associated with native sulfur, occur at the top of Volcan Aucanquilcha, a Holocene volcano near the Bolivian border in northern Chile (northeast of El Abra deposit shown in Fig. 10). The covellite was deposited in open, near-surface fractures during late-stage fumarolic activity; fumarolic sulfur was deposited after the copper. Although the deposit contains comparatively little ore, it is of interest because it shows copper mineralization to be associated with recent volcanic activity. Sillitoe (1973b, p. 811) suggested that this type of deposit forms at the top of a porphyry copper mineralizing system.

Polymetallic base metal and silver.--The most numerous and widespread deposits of the Andean Highlands of Peru and Bolivia are polymetallic deposits having a complex mineralogy characterized by the presence of signifcant quantities of two or more recoverable metals. Those in Peru

that consist of lead, zinc, copper, and varying amounts of silver (Fig. 11) will be discussed here; those in Bolivia that contain tin and tungsten associated with varying amounts of lead, zinc, silver, bismuth, and antimony will be discussed in the section on tin deposits. Polymetallic base-metal deposits are few and small north of Peru; to the south, they occur sporadically in Argentina and Chile, being most numerous in the northern parts of these countries.

Lead and zinc are the dominant metals in the Peruvian deposits, and in 1971 production of these metals were respectively 166,000 metric tons and 318,000 metric tons (U.S. Bur. Mines, 1974). In this same year, production from Bolivia was 20,600 metric tons of lead and 45,000 metric tons of zinc.

Most of the polymetallic deposits of Peru are hydrothermal veins and replacement bodies; fewer are contact metasomatic bodies. The dominant ore minerals are sphalerite, galena, chalcopyrite, tetrahedrite-tennantite, and enargite. Silver occurs chiefly as argentiferous galena and tetrahedrite and more rarely as distinct silver minerals, chiefly argentite, pyrargyrite, and proustite. Small amounts of many other sulfides and sulfosalts of copper, lead, silver, antimony, and bismuth are widespread, and these minerals are major constituents in some veins. Cadmium, indium, gold, selenium, arsenic, and tellurium are recoverable byproducts in many of the ores.

Many polymetallic base-metal deposits and districts show a zonal pattern wherein a copper-rich central zone gives way outward first to a zinc- and lead-rich zone and finally to a marginal zone rich in silver or antimony. Zoned deposits are so widespread in Peru that Peterson

Figure 11. Selected major polymetallic base-metal and silver deposits in the Andean region.

(1970, p. 850) recognized them as a special type of polymetallic base-metal deposit. Zoning reflects the temperature gradient of deposit or district at the time of mineralization, the inner zones being hottest and the outer zones coolest. At many mines and districts, the zonal patterns indicate the position of the plutonic source of the metals.

Tin.--The tin subprovince of Andes, which is almost wholly restricted to the eastern Bolivian Andes (Cordillera Oriental), contains several thousand tin-bearing veins in a region that traverses the length of the Andes from northern to southern Bolivia, a distance of nearly 750 km (466 mi), and ranges from 25 to 80 km (15 to 50 mi) wide (Fig. 7). It extends across the borders into northwestern Argentina and into southern Peru where only a few exploitable deposits are known. Other deposits in northwestern Argentina (Fig. 12) are of Paleozoic age. The Bolivian tin deposits have most recently been described by Turneaure (1971); Kelly and Turneaure (1970); and Ahlfeld and Schneider-Scherbina (1964); these are the sources of the information in the following discussion.

In addition to the tin deposits, which show a wide variation in chemical and mineralogical composition and among which are those rich in silver or bismuth, three other types of deposits can be recognized in the Bolivian tin province: 1) tungsten deposits similar to the tin deposits but containing wolframite in place of cassiterite; 2) lead-zinc deposits having dominant galena and sphalerite and little or no tin; and 3) antimony deposits in which stibnite is the dominant mineral.

The typical tin vein or district has a complex mineralogy and commonly shows a pattern of zoning in which a central tin-rich zone gives way outward to a lead-zinc zone and finally to an antimony-rich zone. Cassiterite is the dominant tin mineral found in nearly all the tin-bearing veins; stannite is found in many veins and is more abundant than cassiterite in a few. Many of the tin deposits of Bolivia contain considerable silver and are classified as tin-silver deposits. Silver occurs in argentiferous galena, lead sulfosalts such as jamesonite, the tin minerals franckeite and cylindrite, tetrahedrite-tennantite, and as native silver and silver sulfides such as argentite, proustite, and pyrargyrite. Some tin veins are high in bismuth, which occurs as native bismuth and bismuthinite.

The grade of tin ore mined in Bolivia has decreased from an average of 12-15 percent during the early part of this century to 1-2 percent, with an upper range of about 3 percent, in the 1960's. Bolivian tin production in 1970 was about 26,000 metric tons, down from a maximum of about 42,000 metric tons in 1945 (U.S. Bur. Mines, 1953, 1973). Clearly the heyday of tin mining in Bolivia is past, and a diminished tin production may be expected in the future.

Bismuth and antimony.--Bismuth and antimony are associated with the polymetallic base-metal ores of Peru and the tin ores of Bolivia, and these deposits have been a major source of the world's bismuth. Production of bismuth in 1970 was 608 metric tons in Bolivia and 806 metric tons in Peru, about a third of world production. In the same year, antimony production was 1,167 metric tons in Peru and 11,766 metric tons in Bolivia.

Small amounts of bismuthinite and, more rarely, native bismuth, emplecitite, matildite, and aramoyoite occur in many of the polymetallic base-metal deposits of Peru, where bismuth is recovered as a byproduct. Among the Peruvian polymetallic deposits that have yielded byproduct bismuth are Cerro de Pasco, Atacocha, Yauricocha, and Morococha (Fig. 11). The amount of bismuth in tin deposits ranges from trace amounts to a dominant metal constituent.

Byproduct antimony is recovered from the polymetallic deposits of Peru, where it occurs in sulfosalt minerals such as tetrahedrite and boulangerite and as stibnite. Scattered high-purity stibnite veins also occur in the polymetallic base-metal and tin subprovinces of Peru and Bolivia.

Gold.--The gold that has been produced from the Andean region has come from three sources, all of which have been important producers: 1) gold-bearing quartz and quartz-pyrite veins, some of which also contain copper; 2) gold-bearing base-metal veins, where gold occurs in the primary ore and is enriched in the oxide capping; and 3) gold placers. The great quantities of gold recovered by the Indians during pre-Columbian time, which contributed greatly to the early wealth of Spain, came chiefly from placers and oxide cappings. Gold-bearing quartz and quartz-pyrite veins and placers are most numerous in the eastern Andes where they occur sporadically from

Ecuador to Bolivia, along the western flank of the Andes and coastal region from Colombia to central Chile (the copper province shown in Figure 7), and in the Cordillera Central of Colombia.

The Minerals Yearbook for 1970 (U. S. Bur. Mines, 1972) shows that the Andean countries of Bolivia, Chile, Colombia, Peru, and Venezuela produced about 400,000 ounces of gold in 1970, of which about half came from Colombia.

Veins and placers in the Cordillera Central of Colombia have yielded the largest amounts of gold of any area in the Andes, and production from this area is probably equal to or greater than that of any other Andean country (Earl Irving, oral commun., 1974). Considerable amounts of gold also have been produced from the oxide cappings of copper deposits in the Atacama desert of northern Chile. In the eastern Andes, gold placers are more numerous and widespread than gold-bearing veins; the gold in these placers may have been derived from various types of veins of diverse ages, perhaps including deposits of Paleozoic and Precambrian age. Veins in the eastern Andes generally contain varying but small amounts of lead, zinc, and copper minerals, in addition to abundant quartz and pyrite. The gold veins on the western side of the Andes occur in the copper subprovince and have a simpler mineralogy, generally containing only chalcopyrite in addition to quartz, pyrite, and arsenopyrite. One of the oldest and largest gold mines in the Andes is the Portovelo

deposit of southern Ecuador (Fig. 11), which is classified as a polymetallic base-metal deposit because the typical ore contains considerable lead, zinc, copper, and silver (Goossens, 1972, p. 460). Other polymetallic base-metal deposits of Peru contain lesser amounts of gold, which is recovered as a byproduct. The gold-bearing veins in the Cordillera Central of Colombia are chiefly quartz veins that contain varying though generally small amounts of the sulfide minerals pyrite, pyrrhotite, galena, sphalerite, and chalcopyrite (Singewald, 1950, p. 122-139)

Manganese.--Sedimentary manganese deposits of Early Cretaceous age, which crop out sporadically over an area of several hundred square kilometers in central Chile (Fig. 8), have been the chief source of manganese ore in the Andean region. They consist of layers of manganese minerals, chiefly braunite and psilomelane, in a sequence of thin-bedded volcanic sandstone and tuff, shale,and impure limestone. Deposition probably took place in shallow marine water along the former continental margin, and the apparent source of the manganese was thermal springs associated with nearby volcanoes. Similar but smaller, lower grade, and generally noncommercial manganese deposits of Quaternary age occur in the high Andes of northernmost Chile (Fig. 8). These deposits consist of manganese oxide as layers in unconsolidated lacustrine sediments and as filling and cementing material in fractures and breccias. Cruzat (1970, p. 689) suggested that the manganese was supplied by thermal springs associated with Quaternary volcanism.

Scattered manganese deposits consisting of veins and replacements of manganese oxides have been exploited in northwestern Argentina, particularly as the result of development of the national steel industry in the late 1950's (Angelelli and others, 1970, p. 93).

Hydrothermal manganese minerals, rhodonite and rhodochrosite, occur as gangue in many of the polymetallic base-metal deposits but not in recoverable amounts. An exception is the beautiful banded rhodochrosite of the Capillitas mine in northern Argentina (Fig. 10), which has been mined as ornamental and semi-precious stone.

In 1970, Chilean production of manganese ore and concentrates was 26,723 metric tons, and that of Argentina was 31,613 metric tons (U. S. Bur. Mines, 1973).

Nickel and cobalt.--Nickel and cobalt occur separately and in distinctively different deposits in the Andes. Nickeliferous laterites overlying serpentinites at two localities, one in the coastal plain of northern Colombia and the other in northern Venezuela, are potentially commercial nickel deposits (Earl Irving, oral commun., 1974). Recoverable cobalt is associated with copper-bearing veins and replacement bodies in the Vallenar-Copiapo region of northern Chile. The principal cobalt-bearing minerals are cobaltite, danaite, and loellingite. Run-of-the-mine ore contains as much as 1 percent cobalt, and copper concentrates commonly contain 4-5 percent cobalt (Ruiz and others, 1965, p. 291-292). Small amounts of nickel and cobalt occur in veins of the eastern Andes of southern Peru; this is considered to be a favorable prospect area (Bellido and de Montreuil, 1972, p. 33-34).

Tungsten.--In addition to the tungsten deposits of the Bolivian tin belt, tungsten has been mined from several mines in Peru, Chile, and Argentina. The major production in Peru has been from deposits in the northern Cordillera Blanca (Fig. 4), which are fissure-filling veins in which the domiant minerals are wolframite and quartz. Wolframite also has been produced from pyrite-wolframite-quartz veins of the

San Cristobal and other polymetallic deposits in central Peru (Fig. 11). Scattered small copper deposits in northern Chile, chiefly in the provinces of Coquimbo and Atacama (lat 27° to 30° S.), yielded a small production of byproduct tungsten, chiefly as the mineral scheelite, from about 1915 to 1938 (Ruiz and others, 1965, p. 293). Tungsten deposits in northwestern Argentina are probably of Paleozoic age (see p. 52). In 1970, tungsten production from Andean countries was as follows (U. S. Bur. Mines, 1973): Argentina, 178 metric tons; Bolivia, 1,845 metric tons; and Peru, 804 metric tons.

Mercury.-- A few scattered, generally small mercury deposits have been reported in the Andes from Venezuela to central Chile (Petersen, 1970, p. 865), but by far the most important are those in the Huancavelica district of central Peru, which have produced more mercury than any other district in the Western Hemisphere (Yates and others, 1951, p. 21). This district is about 30 km (19 mi) north of the Huachocoplpa mine shown in Figure 11. Most of the mercury came from the Santa Barbara mine during the period 1571-1790 (Yates and others, 1951, p. 21). Moderately large amounts of mercury also have been produced from the Punitaqui district, northern Chile (Fig. 9). In the Huancavelica district, mercury occurs as cinnabar, relatively sparse metacinnabar, and native mercury associated with pyrite, realgar, arsenopyrite, orpiment, and stibnite (Yates and others, 1951, p. 21-22). Deposits in Chile contain cinnabar associated with pyrite, chalcopyrite, and tetrahedrite (Ruiz and Ericksen, 1962, p. 97).

In 1970, mercury production (76-lb flasks) in Peru was 3,196, whereas that of Chile was 388; Colombia produced 215 flasks (U.S. Bur. Mines, 1973).

Pre-Andean deposits

Metalliferous deposits of pre-Andean age (Fig. 12) include: 1) tin-tungsten deposits, beryllium-lithium pegmatites, iron deposits, and certain lead-zinc deposits(?) of northwestern Argentina; 2) gold deposits in the coastal region of southern Chile, and perhaps some of those in the eastern Andes of Argentina to Ecuador and the Cordillera Central of Colombia; and 3) iron and manganese deposits in southern Chile. These deposits are of minor economic importance, except for the Aguilar lead-zinc deposit in northernmost Argentina (Fig. 11), which is of uncertain though probably early Paleozoic age. The Relún and Zapla iron deposits (Fig. 12) may have moderately large tonnages of medium-grade iron ore (Ruiz and others, 1965, p. 244; Angelelli and others, 1970, p. 75). Other pre-Andean deposits apparently are of little or no economic importance.

Metalliferous deposits in northwestern Argentina formed during at least two stages of mineralization in Paleozoic time. For example, granitic rocks to which the tin and tungsten deposits of northwestern Argentina (Fig. 12) appear to be genetically related have been dated radiometrically (Clark and others, 1973, p. 16) as representing two distinct ages: Late Ordovician and Early Silurian (445-425 m.y.) and early Carboniferous (335-325 m.y.). These deposits and the Mesozoic and Tertiary tin and tungsten deposits of Bolivia constitute a tin belt in which deposits were emplaced sporadically over a period of more than 400 million years. The Rondônia tin veins (Fig. 12), which are of Pre-cambrian age, are examples of still earlier tin mineralization in this same belt.

The deposits in northwestern Argentina are the only ones of known or presumed pre-Andean age that have been exploited in the Andean

Figure 12. Principal zones of metalliferous deposits of Precambrian and Paleozoic age in and near the Andean region. Heavy dashed line marks approximate eastern limit of Andes.

region. The Aguilar deposit (Fig. 11), which has been worked on a moderately large scale for several decades, has been the chief source of lead and zinc in Argentina. The U. S. Bureau of Mines (1972) reported that Argentine mines produced 35,588 metric tons of lead and 38,985 metric tons of zinc in 1970. To judge from descriptions of tin and tungsten deposits and the beryllium- and lithium-bearing pegmatites by Angelelli and others (1970), total production of concentrates of these four metals from several tens of mines in the areas shown in Figure 12 could not have been more than 30,000 to 40,000 metric tons of concentrates, of which tungsten concentrates made up more than half. Tungsten and tin occur in the minerals wolframite, scheelite, and cassiterite in quartz veins and as replacements and disseminations in metamorphic and plutonic rocks of Paleozoic age (Angelelli and others, 1970, p. 66).

Beryl, the only beryllium mineral that has been found, occurs widely in pegmatites in the areas shown in Figure 12; spodumene, the principal lithium-bearing mineral, occurs in fewer pegmatites, most of which also contain beryl (Angelelli and others, 1970, p. 39 and 86).

Some of the gold veins in the eastern Andes of Peru and Bolivia and in the Cordillera Central of Colombia may be of Paleozoic or Precambrian age. However, because of the scarcity of radiometric age data for intrusions in these areas and the paucity of detailed information about the deposits here, it is not possible to differentiate between veins formed during the Andean metallogenic epoch and those that might have formed earlier. Ruiz and other (1965, p. 144) suggested that sparse gold occurrences in the Coastal Range of southern Chile (lat 34° -40° S.) are of Precambrian age. They occur as quartz lenses and pods in

schist that subsequent to the report of Ruiz and others (1965) has been dated radiometrically as being of Paleozoic age (González-Bonorino and Aquirre, 1970). Deposits of this type, of little economic importance in themselves, are the sources of gold placers in this area that have been worked sporadically since Colonial times.

The iron-formation at Relún which consists of alternating magnetite-rich and quartz- and silicate-rich layers, and the manganese (rhodonite-bearing) deposits of the Valdivia area, Chile (Fig. 12), are within a sequence of metamorphic rocks that have been dated radiometrically (K-Ar method) as being early Carboniferous in age (González-Bonorino and Aguirre, 1970, p. 989). This age, however, only dates the thermal event that caused the metamorphism, and the rocks are still older, probably early Paleozoic. The iron-formation is clearly a metamorphosed sedimentary rock. The manganese deposits are lenticular and parallel to foliation of the enclosing schist; they may be metamorphosed sedimentary manganese layers. A few small veins or lenses of stibnite and quartz, which occur in foliated rocks in the Valdivia area, also may be of Paleozoic age.

Angelelli and others (1970, p. 73-74) reported that the sedimentary iron deposits of the Zapla region in northwestern Argentina (Fig. 12) are of Ordovician age. They estimated that these and nearby similar deposits contained about 100 million tons of iron ore averaging 40-50 percent Fe.

Mineral occurrences in Antarctica

Within the Antarctic region, which in this report is considered to include the islands of the Scotia Arc, the Antarctic Peninsula, and the Pacific margin of the continent, only a few metallic occurrences

are known, none of which appears to be exploitable. Undoubtedly, future exploration in these areas will reveal other deposits, some of which may prove exploitable, but on the whole it seems unlikely that either numerous or very large deposits will be found in ice-free areas here where they could be exploited under current technology and economic conditions. The paucity of deposits here and in island of the Scotia Arc may be in keeping with the mineralization pattern of the southern Andes where relatively few and small deposits are known. Marginal lands of the Amundsen and Bellingshausen Seas (Fig. 13) are less well known and perhaps are more favorable for mineral deposits than the Antarctic Peninsula. Elsewhere in Antarctica, exploration is too scanty to allow an evaluation of the mineral-resource potential, and ice cover of about 95 percent will inhibit exploration for the forseeable future. Even if deposits could be found beneath the ice cover, it is unlikely that they could be exploited unless the ice were thin and easily removed, or access gained by shafts and tunnels from nearby ice-free areas. Nevertheless, as pointed out by Wade (1974), the search for minerals in Antarctica has only begun, and inasmuch as this continent does not differ greatly geologically from others, it should have important mineral resources, as do the other continents.

Available information about mineral resources of Antarctica was summarized by Wright and Williams (1974), who gave the following information about eight mineral occurences in the Antarctic Peninsula and nearby islands. The most widespread metals are copper, gold, and silver; chromium, nickel, and cobalt occur at one locality. Copper occurs as chalcopyrite in small pods and veinlets in dioritic to

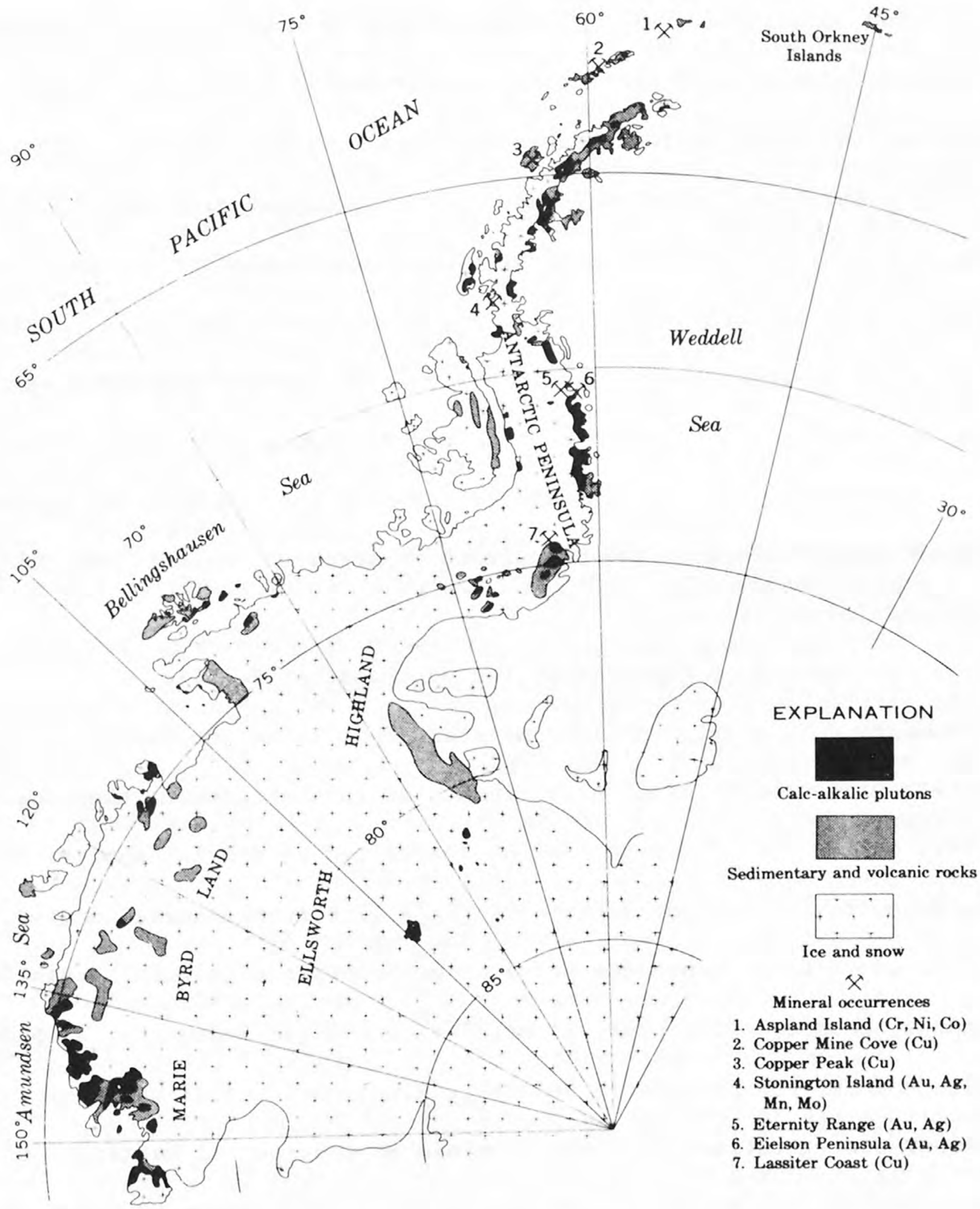

Figure 13. Generalized geology and metallic mineral occurrences of the Antarctic Peninsula and the Pacific margin of Antarctica. Geology from Craddock (1970); mineral occurrences from Wright and Williams (1974).

quartz monzonititc plutons of middle Cretaceous to early Tertiary age. In addition, malachite and chrysocolla stains from weathering of copper sulfides have been found at these and other localities in the Antarctic Peninsula, indicating rather widespread copper mineralization. Two veins 1 to 1.5 m thick on Greenwich Island (near the Copper Mine Cove locality shown in Fig. 13) contain as much as 0.8 percent chalcopyrite, the richest copper-bearing material yet reported in the Antarctic Peninsula. Gold and silver occur in trace quantities in pyrite-rich igneous and metamorphic rocks at three localities on the Antarctic Peninsula (Fig. 13). Gold values range from 0.3 to 2 ppm, and silver from 1 to 10 ppm. Wright and Williams did not describe the occurrence of chromium, nickel, and cobalt on Aspland Island (Fig. 13).

Sea-floor deposits of the southeastern Pacific

Summary data about sea-floor mineral deposits in the Pacific basin have been presented by other participants of the conference; therefore, the information included here will be restricted to a brief summary of these deposits. Sea-floor deposits include 1) ferromanganese nodules, which in addition to manganese and iron may contain significant quantities of copper, cobalt, and nickel; 2) metal-rich pelagic sediments; 3) phosphorite nodules and phosphatic sediments along continental margins; and 4) placer concentrations of heavy minerals at continental margins. Of these deposits, all except placer concentrations are known to exist on the sea floor in the southeastern Pacific, and even deposits of this type, particularly gold placer, may yet be found on the continental shelf of western South America.

The presence of metal-rich sediments on the East Pacific Rise suggests the possibility of underlying metal-rich volcanic rocks, which, like the sediments, contain metals deposited by hydrothermal solutions associated with volcanism at the ridge crest or along transform faults on its flanks. Although disseminated or massive sulfide deposits have not yet been found on the sea floor, it seems reasonable to assume that such deposits do exist and that they formed along active spreading ridges (Dewey and Bird, 19741; Sillitoe, 1972c; Guild, 1972). Such deposits that formed at former spreading ridges in the southeastern Pacific may have contributed metals to calc-alkaline plutons generated in the Benioff zone beneath the Andes, as suggested by Sillitoe (1972a,b).

In the southeastern Pacific, metal-rich pelagic sediments have been found along the East Pacific Rise and in the Bauer Deep (Fig. 2). Bostrom and Peterson (1966) reported unusually high concentrations of manganese, zinc, nickel, and lead as well as other elements in sediments from the East Pacific Rise. Dasch and others (1971, p. 176) reported that a sediment from the rise at lat 9^{o} S. contained 178 ppm lead, and that the lead-isotope ratios indicate a magmatic source. They concluded that the concentrated metals in the iron-rich sediments of the rise, including the lead, originated as precipitates from hydrothermal solutions injected into sea water. Dymond and others (in press) reported that seven samples of sea-floor sediments from the Bauer Deep contained an average of 910 ppm copper, 820 ppm nickel, and 330 ppm zinc. These values are considerable higher than averages for rocks and sediments and indicate metal enrichment, also probably by precipitation from hydrothermal solutions.

At present, the deep-sea metalliferous deposits being most intensively studied are the ferromanganese nodules and crusts at or near the sea-floor surface, which on a worldwide basis constitute a major mineral resource. Experimental techniques for recovery of nodules are now being tested, and exploitation will, no doubt, become a reality within the next decade. Although manganese nodules and crusts are found on the sea floor thourhout the world's oceans, those that are of potential commercial value, in terms of nodule abundance and content of manganese, copper, cobalt, and nickel, are in a relatively few large areas. Perhaps the greatest concentration of ferromagnesium nodules having high metal content are in a band in the east Pacific Ocean just north of the Equator (Horn and others, 1972, p. 13; Cronan, 1972, p. 23). High concentrations of nodules also have been found along the southern margin of the equatorial belt, but these have a relatively low content of copper and nickel (Hammond, 1974, p. 502).

CONCLUSIONS

The southern Pacific region--the Pacific basin and marginal lands of South America and Antarctica--shows a wide variety of metalliferous deposits of diverse origins, but those of greatest economic importance are hydrothermal deposits of the central Andean region. By far the most important deposits in terms of world resources are the porphyry copper deposits; other types of copper deposits, polymetallic base-metal and silver deposits, and tin deposits also are important sources of metals. Exploitable metallic mineral deposits have not yet been found in the Antarctic Peninsula or on the Pacific margin of Antarctica, and it seems unlikely that either numerous or large deposits will be found in ice-free parts of these regions. Ferromanganese nodules are widespread

in the southeastern Pacific and may some day be exploited. However, nodules here are generally less abundant and have a lower recoverable metal content than nodules in extensive areas of the north Pacific Ocean.

The Andean region, which probably has been the site of relatively constant rates of plate convergence and subduction at least since the Late Cretaceous (70 m.y.) presents a comparatively simple plate tectonic model for testing theories of metallogenesis. As yet, however, pertinent information about critical parameters such as age distribution and geochemical character of Andean mineral deposits and their host rocks are too scanty to give unqualified support to theories concerning the relationship between subduction and metallogeny. Nevertheless, available information, gathered chiefly during the past decade, is now sufficient to lend support to limiting factors of this relationship, if the basic assumption is made that the calc-alkaline magmas, with which most Andean mineral deposits are genetically related, formed along the Benioff zone at depths of 100 to 200 km. If this basic assumption is correct, the following factors were important to the formation of Andean mineral deposits: 1) the metals of the deposits had a multiple source; 2) the inclination, position relative to the present-day continental margin, and subduction rate of the subduction zone varied with time, although generally over any given interval of a few million to several tens of millions of years these variations were small; and 3) calc-alkaline plutonic and volcanic rocks of the Andean orogen show no significant systematic time change in most major and minor elements, including the metals now found in the mineral deposits.

The metals of Andean ore deposits were original constituents of magmas that formed at the Benioff zone, augmented by metals that were mobilized or incorporated by the magma as it rose through the overlying mantle and continental crust. Possible metal-rich source rocks are as follows: 1) Oceanic crust and pelagic sediments in the Benioff zone (Sillitoe, 1972a; Mitchell, 1973), which formed chiefly at or near the crust of the East Pacific Rise and its precursory spreading ridges; 2) longitudinal zones or layers in the South American lithospheric plate above the Benioff zone that are rich in certain metals such as tin (Clark and others, 1973); and 3) rocks in deeper parts of the continental crust in which metals may have been concentrated during an early stage of crustal development. In the absence of any significant age or geographic variation in the metal content of exposed Andean plutonic, volcanic, and sedimentary rocks of Mesozoic age, it is unlikely that these rocks or their near-surface counterparts contributed any significant quantities of metals to the deposits by hydrothermal leaching or low-grade metamorphism, a source suggested by Sutherland-Brown (1974) for deposits in western Canada. On the other hand, the high incidence of metalliferous deposits in latitudes of the central Andes where the continental crust is thickest (see p. 10) suggest a deep crustal source for at least part of the metals.

The age and geographic distribution of magmatism and mineral belts in part was probably influenced by position, inclination, and subduction rate of the oceanic lithospheric plate. Thus, the gradual eastward age migration (see p. 13) of plutonism and associated mineralization was due to: 1) slow eastward migration of the subduction zone relative to the continental margin; or 2) generation of plutons at progressively

deeper levels in the Benioff zone; or 3) slow decrease in inclination of the subducting slab; or 4) combinations of these factors. Changes in rates of subduction would influence these factors and could account for anomalies in the normal age-distribution pattern. It is not yet possible to evaluate the relative importance of each of the above factors in magmatic evolution in the Andes as a whole. However, Zentilli (1974) suggested that chemical data for volcanic rocks in the Copiapó region of northern Chile (lat 26°-29°S.) indicate a progressively deeper magmatic source during Mesozoic and early to middle Tertiary time. He suggested that magmatic activity of Miocene age, which extended over an east-trending belt about 250 km (155 mi.) wide, indicates a decrease in inclination of the subducting plate. Distribution of potassium values in post-Miocene igneous rocks of this region correspond to those that would be predicted for the present-day Benioff zone, as indicated by seismic activity (Zentilli, 1974).

Andean mineral deposits also show affinities for certain rock types or geologic environments, and Petersen (1970, p. 888) suggested that a major control of Andean mineralization was the gross lithology of the host rocks. Thus, the copper province tends to be spacially related to the western part of the Mesozoic Andean geosyncline, where calc-alkaline igneous rocks and marine to continental clastic sedimentary ocks are the chief hosts of the mineral deposits. Porphyry copper deposits in northern Chile occur chiefly in a narrow belt along the eastern margin of the geosyncline. Polymetallic base-metal deposits of Peru are associated with a marine sedimentary sequence of Mesozoic age

having abundant limestone, as they are in the eastern Andes of Colombia. The tin province of Bolivia is an area underlain chiefly by clastic marine sedimentary rocks of Ordovician and Devonian age (Ahlfeld and Schneider-Scherbina, 1964, p. 7).

The boundary between the copper and polymetallic subprovinces of the Andes corresponds to the copper-lead line of Wilson (1967, p. 227), which in many of the major mineralized areas of the world separates domains of dominantly high copper values from those of high lead values. Wilson and Laznicka (1972) pointed out that in geosynclinal fold belts, the copper-lead line marks the boundary between the eugeosyncline and miogeosyncline, and that the former is the copper domain and the latter, the lead domain. In the Andes, the relationship between the copper-lead line and geosynclinal sediments is evident only in Peru and Colombia where the line marks an approximate western limit of abundant limestone that was deposited in the Andean geosyncline. Eugeosynclinal clastic sedimentary rocks are found west of this line in Colombia (Irving, 1971), but the sequence of interbedded volcanic and marine to continental clastic sedimentary rocks and local limestone west of the line in Peru is not representative of an eugeosynclinal environment. Elsewhere in the Andes, the copper-lead line appears to be unrelated to geosynclinal rock types.

The metal subprovinces or mineral belts of the central Andean region show a type of zoning that is suggestive of a vertical temperature gradient. In part, this apparent zoning is related to depth of

erosion (Petersen, 1970, p. 888). Thus, relatively old high-temperature deposits of simple mineralogy--copper, iron, and gold--tend to occur on the deeply eroded flanks of the Andes, and young, low-temperature deposits of complex mineralogy--polymetallic base metals--in the Andean Highland where erosion since their formation has been less. The coastal region of Peru and Chile clearly illustrates deep erosion to expose huge segments of the Andean batholith and related copper and gold deposits. Polymetallic deposits probably either once existed in the coastal region and have since been eroded away, or did not form originally because of the paucity of lead and zinc in mineralizing solutions or of a favorable limestone terrane. In any event, the composition of mineralizing solutions was probably not sufficiently varied to account wholly for the distribution of the different types of deposits that characterize each mineral belt.

Goossens (1972, p. 463-465) recognized a vertical metal zoning in the Cordillera Occidental of Ecuador, wherein metals occur in deposits at the following altitudes: 1) Au and Cu-Mo below 2,000 m; 2) Pb and Zn in association with Au, Ag, Cu, and Cd between 1,500 and 3,000 m; and 3) high-grade Ag and Hg veins between 2,500 and 4,000 m. Such a uniform vertical zoning cannot be recognized elsewhere in the Andes, and it is probably due to happenstance positioning of the relatively sparse deposits in Ecuador. Nevertheless, the general distribution of gold and copper deposits at relatively low altitudes and polymetallic base-metal and silver deposits at high altitudes is consistent with observed distribution of similar deposits in the Andean region to the south, and with variations in levels of erosion.

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