ANDEAN MINERALIZATION: A MODEL FOR THE METALLOGENY OF CONVERGENT PLATE MARGINS

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Reprint from

THE GEOLOGICAL ASSOCIATION OF CANADA SPECIAL PAPER NUMBER 14

GEOLOGICAL ASSOCIATION OF CANADA, SPECIAL PAPER NUMBER 14, 1976

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ABSTRACT

The post-Palaeozoic, central Andean orogen provides the most complete and best-exposed example of metallogeny at a convergent plate margin. Ore types temporally, spatially and genetically related to intrusive and extrusive magmatism in the central Andes include, eastwards from the coast, contact-metasomatic Fe deposits, Cu-Au and Ag veins, manto-type Cu deposits, stratiform Mn deposits, Cu-bearing breccia pipes, porphyry Cu-Mo deposits, Cu-Pb-Zn-Ag deposits of vein and contact-metasomatic types, a volcanogenic Fe deposit, Sn-W and Sn-Ag veins, and porphyry Sn deposits. There are also red-bed Cu and U deposits. The magmatogene ore types are assigned to clearly-defined, longitudinal belts dominated from west to east by: Fe, Cu-(Au-Mo), Cu-Pb-Zn-Ag, and Sn-(W-Ag-Bi). Belts terminate, or their characteristics change, at transverse tectonic boundaries, believed to represent divisions between discrete segments of the underlying subduction zone. Magmatism and mineralization in the Fe and Cu belts migrated progressively eastwards from the early Jurassic to the mid-Tertiary, but about 15 m.y. ago a sudden eastward expansion of magmatism occurred giving rise to the Cu-Pb-Zn-Ag belt. Magmatism along the eastern margin of the central part of the orogen took place, probably episodically, from the Triassic to the late Tertiary to produce a composite Sn belt. Belts are believed to be caused by progressive liberation of the various metal combinations with depth on a "stable", shallow-dipping subduction zone, with Sn being produced at its down-dip extremity at about 300 km, the present landward limit of intermediate-focus earthquakes.

RÉSUMÉ

L'orogène post-paléozoïque des Andes centrales nous fournit l'exemple le plus complet et le mieux exposé de métallogénie aux marges d'une plaque convergente. Les types de minerais apparentés dans le temps, l'espace et la génèse au magmatisme intrusif et extrusif des Andes centrales sont, de l'Ouest à l'Est, des dépôts de fer de métasomatisme de contact, des filons de cuivre-or et d'argent, des dépôts de cuivre de type manto, des dépôts stratiformes de manganèse, des brèches de pipes contenant du cuivre, des dépôts de cuivre-molybdène de type porphyrique, des dépôts de cuivre-plomb-zinc-argent de type veine et de métasomatisme de contact, un dépôt de fer volcanogénique, des filons d'étain-tungstène et d'étain-argent et des dépôts d'étain de type porphyrique. On y trouve aussi des dépôts de cuivre et d'uranium de type « red bed ». Les minerais magmatogènes se rangent dans des ceintures longitudinales clairement définies et dominées de l'Ouest à l'Est par: fer, cuivre-(or-molybdène), cuivre-plomb-zinc-argent, et étain-(tungstêne-argent-bismuth). Les ceintures se terminent ou leurs caractéristiques changent, aux limites tectoniques transversales que l'on croit représenter les divisions entre les différents segments de la zone de subduction sous-jacente. Du Jurassique Inférieur au Tertiaire Moyen, le magmatisme et la minéralisation des ceintures de fer et cuivre ont migré progressivement vers l'Est, mais, il y a environ 15 m.a., une expansion soudaine du magmatisme vers l'Est s'est produite, donnant naissance à la ceinture de cuivre-plomb-zinc-argent. Le magmatisme le long de la marge Est de la partie centrale de l'orogène s'est manifestée de façon probablement épisodique, du Trias au Tertiaire Supérieur, pour engendrer une ceinture d'étain composite. On croit que les ceintures sont dérivées d'une libération progressive des combinaisons de métaux, différentes avec la profondeur, le long d'une zone de subduction « stable » et de faible inclinaison, l'étain étant produit à l'extrémité inférieure à une profondeur d'environ 300 km, limite présente des tremblements de terre de profondeur moyenne.

INTRODUCTION

The central Andes is a volcano-plutonic orogen constructed along a convergent, or consuming, plate margin between the overriding continental edge of the Americas plate and the subducting, suboceanic Nazca plate (Fig. 1). Descent into the mantle of the Nazca plate eastward from the Peru-Chile trench is presently active at a rate of some 6 cm/yr., and consumption of eastern Pacific plates appears to have taken place since at least Permo-Triassic times. A variety of relatively well known and economically important base- and precious-metal ore deposits are widespread in the central Andes from lat. 5°-35°S (Fig. 1). Rock exposure is extensive and the geological evolution of the region seems to have been more straightforward than that in any comparable orogen. These factors clearly distinguish the central Andes as the type area for continental margin metallogeny along a convergent plate boundary and, although many problems remain and our understanding is still far from complete, the metallogenic features exhibited by the central Andes should aid in deciphering the metallogeny and geological history of more complex orogens in which plate consumption has played a part, such as the Appalachian-Caledonian system of eastern North America and Europe, the Cordilleran system of western North America and the Malaysian-Indonesian system.

This abbreviated account of central Andean metallogeny in the context of plate tectonic theory should be treated as a preliminary statement which attempts to highlight some of the more obvious features and problems. Several workers are currently involved in geological and metallogenic investigations in the region, so we can look forward to further information to up-date and modify this account. Recent compilations of data on mineral deposits in Chile (Ruiz *et al.*, 1965), Argentina (Angelelli *et al.*, 1970), Bolivia (Ahlfeld and Schneider-Scherbina, 1964) and Peru (Bellido and de Montreuil, 1972), metallogenic syntheses of various parts of the region under con-

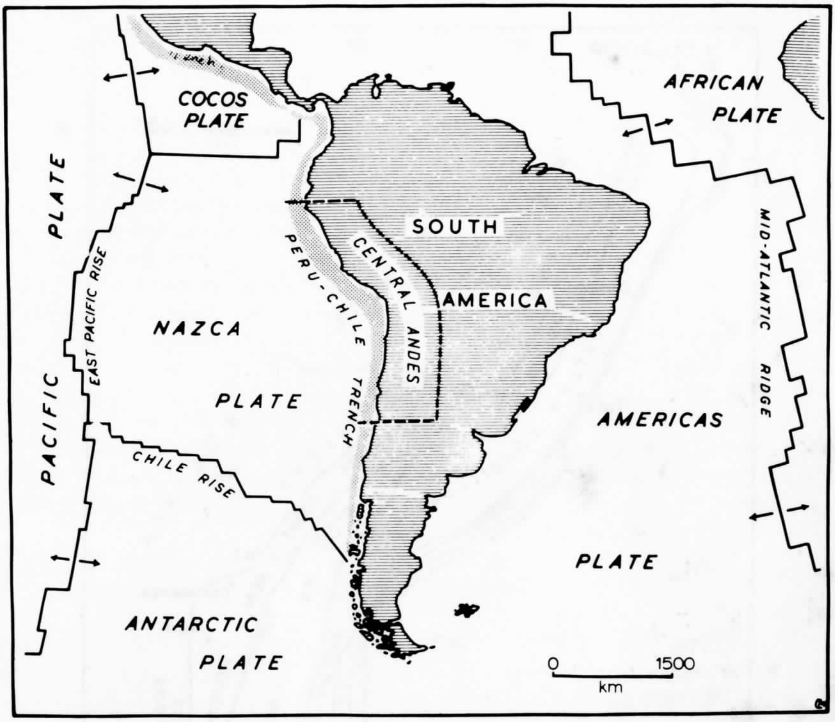

Figure 1. The position of the central Andes in relation to the plate configuration in the southern parts of the Atlantic and Pacific oceans.

sideration (e.g. Ahlfeld, 1967; Gabelman, 1961; Petersen, 1970; Ruiz and Ericksen, 1962; Stoll, 1964, 1965; Turneaure, 1971), and my own work in the central Andes during the last decade provide the basis for this summary.

In 1970, plate tectonic theory was first applied to analysis of mineral deposits in the Andes (Sillitoe, 1970) and, subsequently, a preliminary attempt was made to relate the metallogenic zonation of the Andes to processes operative at a convergent plate margin (Sillitoe, 1972a). These and other studies (Sawkins, 1972) show that plate tectonic theory is a powerful tool for use in understanding the genesis and distribution of Andean mineral deposits.

SALIENT GEOLOGICAL FEATURES OF THE CENTRAL ANDES

Restricted space and the aims of the paper prohibit a detailed consideration of the geology of the central Andes and its analysis in terms of plate tectonic theory; accounts by James (1971b, 1973) should be consulted for more details. With the metallogeny of the region in mind, this summary highlights several significant aspects in the context of plate tectonic theory. Physiographic features may be located by reference to Fig. 2.

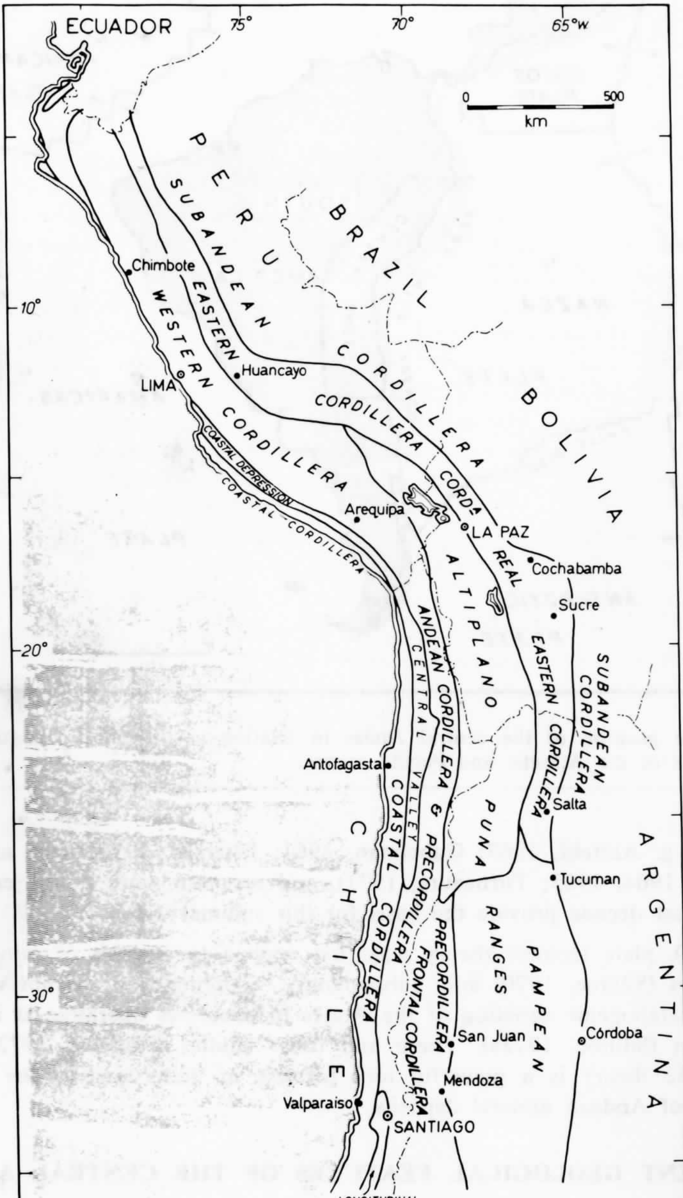

Figure 2. Location map of the central Andes showing the principal physiographic divisions of the region.

Pre-Permian Development

During the Palaeozoic a 10-15 km thick sedimentary succession of flysch type was deposited on the continental margin of western South America at least partly overlying a Precambrian basement (Mégard *et al.*, 1971). The Palaeozoic rocks now crop out principally in the Eastern Cordilleras of Peru, Bolivia and Argentina. The Palaeozoic continental margin may have been similar in character, at least at times, to the present inactive eastern margin of South America, which lies *within* the Americas plate (Fig. 1), although it should be emphasized that large volumes of calc-alkaline intrusive rocks were emplaced at several times during the Palaeozoic era, especially in the eastern part of the orogen in Argentina (Halpern *et al.*, 1970; Gonzalez *et al.*, 1971), Peru (Stewart *et al.*, 1974), and further west; these intrusive rocks and their associated mineralization may well have been generated during Palaeozoic episodes of subduction.

A point of paramount importance when considering geological models of the central Andes is that the Mesozoic-Caenozoic magmatic arc has been constructed upon Precambrian (and, of course, Palaeozoic) continental crust (Cobbing and Pitcher, 1972a). These old rocks appear as inliers throughout the orogen, particularly on its eastern side where the volcanic cover is scanty, but even along the coast as in the Coastal Cordillera of southern Peru (Fig. 2). Radiometric ages in excess of 640 m.y. were obtained from regionally metamorphosed rocks caught up in the Arequipa batholith (Fig. 3) of southern Peru (Stewart *et al.*, 1974). Much of the 50-70 km thick continental crust beneath the central Andes (James, 1971a), therefore must consist of Precambrian-Palaeozoic basement (Cobbing and Pitcher, 1972a).

Permo-Triassic and Later Development

The Mesozoic-Caenozoic orogen may be considered to have first become active in the Permo-Triassic when calc-alkaline intrusive and extrusive rocks were emplaced, especially in belts away from the present Pacific littoral, in Peru (Mitu Group; Bellido, 1969), Chile (Ruiz *et al.*, 1965) and western Argentina (Serie Porfirítica; D.N.G.M., 1964), at the same time as continental red bed sedimentation. From that time until the present the formation of calc-alkaline intrusives and extrusives has dominated the geological record in the central Andes. The development of a convergent plate margin along western South America in Permo-Triassic times was probably due to the inception of a predecessor of the present East Pacific Ridge, as a by-product of the incipient disruption of the supercontinent of Pangaea.

In the early post-Permian stages of construction of the magmatic arc, especially in the Jurassic, andesitic volcanism was, at least partly, submarine in coastal Peru and northern Chile (Bellido, 1969; Ruiz *et al.*, 1965), and shallow water marine sediments, both calcareous and clastic, were deposited within and east of the coastal volcanic arcs during the Jurassic and Lower Cretaceous. From the Middle or Upper Cretaceous onward, however, volcanism and associated clastic sedimentation was dominantly subaerial, although local deposition in land-locked lagoons undoubtedly occurred. Once the magmatic arc was appreciably above sea level, from the Upper Cretaceous onward, continental, molasse-type sediments were deposited in the eastern part of the Andes in tectonic grabens, particularly in the Altiplano and its southern extension, the Puna (Fig. 2), and further east in the Subandean Ranges; some 20 km of molasse accumulated on the Bolivian Altiplano in late Mesozoic and Caenozoic times. Lesser amounts of coarse, clastic sediments were also deposited in the late Caenozoic in the Central and Longitudinal Valleys (grabens) of western Chile (Fig. 2), within the arc-trench gap.

Structure

The post-Palaeozoic structure throughout the central Andes is dominated by a longitudinal, tensional fault system giving rise to horsts and grabens, with many of the faults of high-angle, reverse type (Ahlfeld, 1970; Schwab, 1970; Thomas, 1970). The over-all structural regime, including the folding of Meso-Caenozoic and Palaeozoic formations, and the vast uplift of the Andes, particularly in the Caenozoic, can be understood in terms of the distension of the continental crust produced by the injection of enormous volumes of calc-alkaline magma (James 1971b; Gough, 1973). It should be pointed out, however, that other related styles of dislocation play a part in the structural makeup of the central Andes. On the eastern border of the Andes from Ecuador southwards to Argentina a belt of eastward-directed, intracontinental, high-angle thrusting is present (Ham and Herrera, 1969) which may reflect the incipient development of an opposed subduction zone at the rear of the magmatic arc, as in the Rocky Mountains, on the eastern border of the Cordilleran orogen in the western United States (Misch, 1971). In coastal northern Chile (lat. 24°-26°S), the Atacama fault system underwent a few tens of km of transcurrent motion, possibly in the Mesozoic (Arabasz and Allen, 1972) that may be attributed to an oblique component in the interaction of the Americas plate with an east Pacific plate. In addition to the longitudinal thrust belt and minor transcurrent faulting, a number of ill-defined transverse lineaments of continental dimensions are present. Those in Chile, Peru and Argentina mapped by Ricci and Figueroa (United Nations, 1973) and Segerstrom (1971) may represent basement structures and are certain to become better understood with fuller utilization of the ERTS imagery.

Additional Comment

On the broad scale the post-Palaeozoic development of the central Andes has been relatively simple when compared with some other convergent plate margins, with no change in the polarity of subduction and consequent magmatism. The absence of Mesozoic-Caenozoic ophiolitic sutures from the central Andes suggests that marginal ocean basin development including back-arc spreading (Karig, 1971) and the collision of island arcs or microcontinents with the continental margin have not occurred. It should be noted that although the early stages of magmatic-arc construction were characterized by calc-alkaline volcanism along a string of coastal islands similar to that in island-arcs, these islands apparently represented the early basal parts of the post-Palaeozoic magmatic pile and were never separated from the continental margin by an actively-spreading marginal ocean basin. Either the relatively great thickness (200-300 km) of the Americas plate (James, 1971b) or the fact that both the Americas and Nazca plates are in motion in opposing directions (Wilson and Burke, 1972) would seem to have precluded the development of marginal ocean basins along the central Andes.

Further north from the Gulf of Guayaquil in Ecuador, however, a belt of ophiolitic rocks is present in the Coastal and Western Cordilleras (Gansser, 1973; Goossens and Rose, 1973) which may represent Pacific oceanic crust accreted to the inner wall of the Peru-Chile trench and subsequently uplifted. If such accretion of ophiolitic or mélange belts has taken place in the central Andes, it seems likely to have been on a smaller scale and the materials are presently beneath sea level.

At the time when the Americas plate began to be rafted westwards by spreading at the Mid-Atlantic Ridge in the early Cretaceous (Le Pichon and Hayes, 1971) no profound changes were noted in the central Andes, although the volume of calc-alkaline magma emplaced on and in the upper crust apparently increased at around this time. Unlike the situation in western North America, control of the geological development of the central Andes seems to be unrelated to the motion pattern (fairly constant) of the Americas plate (Coney, 1971), but is more closely related to changes in spreading rate and direction in the east-central Pacific.

DETAILS OF MESOZOIC-CAENOZOIC MAGMATISM

In view of the fact that most Andean ore deposits are spatially, temporally and genetically related to intrusive and extrusive rocks of calc-alkaline affinity, the magmatic development of the central Andean orogen is outlined in more detail.

Source of Magma

Calc-alkaline magmatism in the central Andes although episodic in nature seems to have been essentially continuous from Permo-Triassic to the present. The huge amounts of magma emplaced within and upon the continental crust during this time are almost certainly derived in large part from partial fusion by shear heating (Oxburgh and Turcotte, 1970), and by conductive heat transfer from the overlying mantle, of the upper parts of the subducted oceanic plate, in particular of thin layer-1 sediments and of layer-2 basaltic volcanics (transformed to eclogite), as discussed by many workers (e.g. Ringwood, 1969; Boettcher, 1973). As remarked by James (1971b), the great volume of magma emplaced during the Mesozoic-Caenozoic effectively precludes any principal source for the magmas other than the oceanic plate, some 5000 km of which were underthrust beneath South America since the Cretaceous (Larson and Pitman, 1972). Additional subsidiary sources of magma may include both the continental crust and the wedge of mantle above the subduction zone, but island-arc tholeiites that are probably derived by partial fusion of that mantle wedge (Nicholls and Ringwood, 1972) have not yet been described from the Andes. The role of continental crust in Andean magmatism is believed to be restricted to the provision of minor amounts of contaminant to subcrustal magmas, and to the provision of a site for the differentiation of such magmas. It is to be expected that a water-charged, subcrustal magma body will rise with little reaction through the continental crust (Modreski and Boettcher, 1973).

Few initial Sr^{87}/Sr^{86} ratios have been published for Andean magmatic rocks, but those from the coastal batholith of Peru (0.704 and 0.705; Stewart *et al.*, 1974), from andesitic volcanics in northern Chile (0.705-0.707; Pichler and Zeil, 1972), and from intrusive and volcanic rocks from lat. 26°-29°S. (0.702-0.707; McNutt *et al.*, 1973), suggest a subcrustal source with only limited, but variable, contamination by continental crustal rocks. (It should be noted, however, that Pichler and Zeil (1972) proposed an origin of the volcanic rocks by partial fusion of the lower continental crust).

Volcanic-Plutonic Relationships

Following the concept of Hamilton and Myers (1967), Hamilton (1969) and Dickinson (1970), intrusive rocks in the central Andes are believed to have underlain and in part to have intruded their cogenetic volcanic rocks, and to have formed the roots of the magmatic arcs; intrusive and extrusive rocks may therefore be considered as comagmatic. Support for such a contention comes from recent attempts at constructing profiles through Andean porphyry copper deposits (Sillitoe, 1973a) and from regional studies of the coastal batholith of Peru (Cobbing and Pitcher, 1972b). It may thus be concluded that present distribution of the intrusive and extrusive equivalents depends to a large extent on erosion level (Sillitoe, 1972b), and older magmatic belts are of course likely to exhibit a greater proportion of intrusive material. A corollary of this proposal is that recent volcanic arcs are underlain by intrusive equivalents (Hamilton, 1969).

Distribution of Magmatism in Space and Time

In the central Andes the generalization seems valid that the locus of magmatic activity in the western part of the orogen moved progressively eastward with time from the late Triassic or early Jurassic onward (Fig. 3). Permian, and possibly Lower Triassic, magmatism appears to have occurred east of the coastal belt prior to the initiation of this system of migrating magmatic arcs. At any one time, the products of partial melting on the subduction zone constructed an intrusive volcanic belt that possessed a considerable longitudinal continuity but was only some 10-30 km wide. In central and northern Chile, such belts are commonly parallel but separated (Ruiz *et al.*, 1965; Farrar *et al.*, 1970), whereas in northern and central Peru they overlap to form the huge Coastal batholith (Cobbing and Pitcher, 1972b; Stewart *et al.*, 1974). Nevertheless, radiometric dating does support an eastward younging of Cretaceous-Tertiary intrusive events in the Peruvian coastal batholith (Stewart *et al.*, 1974, and Fig. 3), thus rendering it comparable with the Coast Range batholith of British Columbia (Hutchinson, 1970).

From data compiled by Ruiz *et al.* (1965), Farrar *et al.* (1970) and Stewart *et al.* (1974) it can be concluded that late Triassic-Jurassic intrusives occur in the Coastal Cordillera of southern Peru and in the western part of the Coastal Cordillera farther

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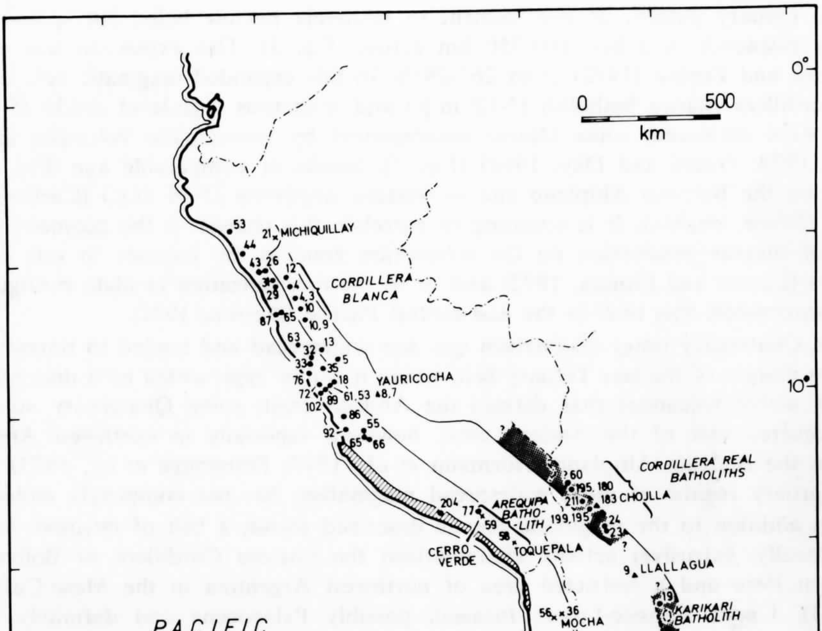
Figure 3. The most reliable radiometric ages of post-Palaeozoic intrusive rocks and associated ore deposits in the central Andes determined by the K-Ar and Rb-Sr methods (to the nearest m.y.). Using the small amount of reliable data, the regions in which Triassic-Jurassic, Cretaceous-mid-Tertiary, late Tertiary (15 m.y. onwards) and the eastern Triassic-late Tertiary intrusives are located are approximated; the effects of tectonic boundaries on the positions of the limits of the intrusive belts are omitted, as are the minor alkaline stocks along the extreme east of the orogen. This figure is meant to create only an over-all impression and is liable to profound modification as new data become available.
Sources: Ages for Peru: Giletti and Day, 1968; Laughlin *et al.*, 1968; Evernden and Kistler, 1970; Stewart *et al.*, 1974; for Bolivia: Evernden and Cordani (summarized by Clark and Farrar, 1973); for Chile: Farrar *et al.* 1970; Quirt *et al.*, 1971; for Argentina: Caelles *et al.*, 1971; Halpern and Latorre, 1973; Sillitoe (unpub.).
The limit of Triassic-Jurassic intrusives in Chile was located using data given by Ruiz *et al.*, 1965.


0 500
km
0°
10°
20°
30°
80°
70°
60°
PACIFIC
OCEAN
53
21 MICHIQUILLAY
44
43 26
12
31
29
4
4.3
10
87
65
10.9
CORDILLERA BLANCA
63
32
13
5
33
35
76
18
YAURICOCHA
72
89
61.53
8.7
102
86
92
55
65
66
?60
195.180
CORDILLERA REAL BATHOLITHS
211
183 CHOJLLA
204
77
AREQUIPA BATHO-LITH
199.195
24
23
59
58
?
CERRO VERDE
TOQUEPALA
9 LLALLAGUA
19
KARIKARI BATHOLITH
56
36
MOCHA
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33
29.37
CHUQUICAMATA
AGUILAR
123.130.133
123.129
16
188
40
EL SALVADOR
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8 FARALLON
7 NEGRO DISTRICT
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59
60
67
63
87
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LOS PELAMBRES
10
4 RIO BLANCO
EL TENIENTE
5
● Intrusive rock
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▲ Other ore deposit
TRIASSIC-JURASSIC
LATE TERTIARY
CRETACEOUS-MID-TERTIARY
TRIASSIC-MID-TERTIARY

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south, and are flanked to the east by a series of progressively younger belts of intrusives of Cretaceous and Tertiary age throughout Chile and Peru (Fig. 3).

About 15 m.y. ago magmatism in the central Andes did not continue the Mesozoic to mid-Tertiary pattern of confinement to relatively narrow belts, but spread much farther eastwards in a belt 100-350 km across (Fig. 3). This expansion was charted by Clark and Zentilli (1972) from 26°-29°S. In this expanded magmatic belt in Peru, the Cordillera Blanca batholith (3-12 m.y.) and numerous high-level stocks (5 and 7 m.y.) were emplaced, some clearly accompanied by comagmatic volcanics (Stewart *et al.*, 1974; Giletti and Day, 1968) (Fig. 3). Stocks of comparable age (Fig. 3) are found on the Bolivian Altiplano and in western Argentina (7-16 m.y.) (Caelles *et al.*, 1971; Sillitoe, unpub.). It is tempting to correlate this change in the geometry of the zone of magma production on the subduction zone to the increase in rate of subduction (Larson and Pitman, 1972) and/or to the reorganization in plate configuration at approximately this time in the east-central Pacific (Herron, 1972).

In Quaternary times magmatism was less widespread and tended to retreat to the western margin of the late Tertiary belt, where it is now represented by a discontinuous line of active volcanoes that defines the Andean crest; some Quaternary volcanism has occurred east of the Andean crest, however, especially in northwest Argentina and on the Bolivian Altiplano (Hörmann *et al.*, 1973; Fernandez *et al.*, 1973) so the late Tertiary regime of more widespread magmatism has not completely ended.

In addition to the magmatic regime described above, a belt of intrusive (and, at least locally, extrusive) activity characterized the Eastern Cordillera of Bolivia and southern Peru and a restricted area of northwest Argentina in the Meso-Caenozoic (Fig. 3). Upper Triassic-Lower Jurassic, possibly Palaeocene and definitely Lower Miocene magmatism in the Cordillera Real has been identified by preliminary radiometric dating by Evernden and Cordani (summarized by Clark and Farrar, 1973). Furthermore, I believe that Upper Jurassic and Cretaceous ages could be revealed by further dating because two granites have been dated as Cretaceous on the eastern border of the orogen in northwest Argentina (Halpern and Latorre, 1973). Stewart *et al.* (1974) recorded possible late Triassic and Jurassic intrusives ages from the Eastern Cordillera of Peru, as well as from the Coastal Cordillera. Besides the many stocks of Upper Miocene-Pliocene age (e.g. Llallagua, 9 m.y.) in the southern part of the Eastern Cordillera of Bolivia and northwest Argentina, the Karikari batholith (or an andesite plug to the north), lying on the eastern extremity of the belt, has been preliminarily dated at 19 m.y. (Evernden, reported by Clark and Farrar, 1973 and Fig. 3).

It appears, therefore, that there have been two distinct intervals of magma generation on the subduction zone, from the beginning of the Mesozoic era, one in the west that gradually moved east at a rate depending on its latitudinal position, and one in the east generating much smaller volumes of magma, that approximately maintained its position for a remarkably long period, particularly in the Cordillera Real. If an analogy can be drawn with the situation at present, then the eastern magmatic arc was constructed above the deepest down-dip extension of the continuous subduction zone, now some 300 km beneath surface (James, 1971b; Stauder, 1973). The broadening of the zone of active magmatism some 15 m.y. ago had the effect of uniting the eastern and western magmatic belts from lat. 16°-24°S.

In the latitudinal range from 26°-29°S, sufficient radiometric dating has been carried out (Farrar *et al.*, 1970; Clark and Zentilli, 1972) to indicate that the pulses of intrusive activity are separated by quiescent intervals. This pulse-like nature of magmatism in volcano-plutonic orogens is apparently widespread and the midpoints of discrete pulses are commonly separated by intervals of 20-35 m.y. (Dickinson, 1970; 1972). Unfortunately documation of the same episodic pattern of intrusion throughout all the central Andes is lacking, although available evidence strongly supports its occurrence.

Although this pattern is a fair generalization of the magmatic activity in the central Andes, it should be stressed that local irregularities do occur. For instance in northern Chile between lat. 18° and 19°S. an early Quaternary belt of andesitic volcanoes is located to the west of both late Tertiary and late Quaternary magmatic belts, and in the northward extension of this latter region, in southern Peru, late Quaternary strato-volcanoes coincide with the eastern margin of the Arequipa batholith.

Nature of Magmatism

The late Triassic to early or mid-Tertiary magmatic belts are now dominated by batholiths, from which the cogenetic volcanics presumably have largely been stripped by erosion. The Coastal and Arequipa batholiths of central and southern Peru (102-26 m.y.; Stewart *et al.*, 1974) are typical and are constructed of multiple, steep-sided plutons amongst which tonalites predominante, granodiorites and adamellites occur in significant amounts, and minor early gabbros and late granites are also present (Jenks and Harris, 1953; Stewart, 1968; Cobbing and Pitcher, 1972b). Coeval andesitic volcanics are still present in some areas and constitute the wallrocks to the batholiths. The submarine origin of the Jurassic volcanics has aided in their preservation. Late Cretaceous-early Tertiary magmatic products include particularly large volumes of andesitic volcanics with some ignimbrite flows in parts (e.g. lat. 27°-28°S; Segerstrom, 1967). In Chile, early to mid-Tertiary plutons are generally of smaller dimensions than those further west. The batholiths in the Cordillera Real tend to have a similar composition to those in the coastal belt although they are much smaller; granodiorite and adamellite predominate (Turneaure and Welker, 1947). Volcanics are generally thought to be absent from the Cordillera Real but restricted areas of andesites were identified on the western flank of the Illimani batholith (Turneaure and Welker, 1947; Sillitoe, unpub.), and may once have been more widespread. Exposed late Tertiary magmatic products are dominated by volcanics that range from andesitic in the west to andesitic, dacitic and quartz latitic in the east. At this time, ignimbrite flows, ranging from rhyolitic to rhyodacitic in composition, were particularly abundant in northern Chile (Zeil and Pichler, 1967), Bolivia, southern Peru and northwest Argentina, and may represent the erupted, differentiated tops of underlying batholiths. It is noteworthy that the period of eruption of large volumes of ignimbritic material (3-19 m.y.; Ruiz *et al.*, 1965) approximately corresponded to the time when magmatism prevailed over a greater width of the central Andes. Most of the high-level, subvolcanic stocks in the Andes are late Tertiary and possess compositions comparable to those of the batholithic rocks. Two batholiths, the Cordillera Blanca in central Peru (Egeler and de Booy, 1958) and the Karikari in southern Bolivia (Fig. 3) are also Miocene or later in age (Stewart *et al.*, 1974; Evernden, in Clark and Farrar, 1973).

Further east from the magmatic belt of the Eastern Cordilleras (Fig. 3), minor high-level stocks and volcanics of peralkaline type and late Tertiary age (4-5 m.y. in eastern Peru) are known (Stewart, 1971; Ahlfeld and Schneider-Scherbina, 1964), that might have been generated by incipient partial fusion of the very deepest, continuous part of the subducted slab (cf. Stewart, 1971). No magmatism seems to overlie the detached part of the subducted slab, now at depths greater than 550 km (Isacks and Molnar, 1971).

In the Quaternary, ignimbrite eruption declined markedly and the visible products of magmatism are principally andesitic to dacitic strato-volcanoes (Pichler and Zeil, 1969).

Segmentation of Magmatic Belts

Preliminary data suggest that the magmatic arcs do not possess longitudinal continuity throughout the central Andes, but extend for only a few hundred km or less in a north-south sense (northwest-southeast in Peru) before terminating at transverse boundaries. It is believed that these transverse boundaries (Fig. 4), commonly distinguished at surface by changes in geology and geomorphology, represent divisions between discrete segments of the subduction zone that descend eastward independently) of adjoining segments (Carr *et al.*, 1973; Sillitoe, 1974 b). It is believed that transverse boundaries are zones of geological transition rather than regional faults or megalineaments. An examination of the distribution pattern of recent volcanoes helps to define these transverse segments, but does not indicate the duration of their activity. Although geophysical verification of such segmentation of the central Andes has not yet been carried out, it is believed that studies of intermediate and deep-focus earthquakes, such as those recently undertaken in Japan (Carr *et al.*, 1973), will supply confirmation. Segmentation of a subduction zone is probably caused by stresses created during underthrusting, although subduction of transform faults that divide the ocean floor into a series of transverse strips may also be an influence.

It must be expected, therefore, that magmatic belts will only exist in individual segments, to be replaced both to the north and south by a distinct regime exhibiting a different episodicity. A clear example of this behaviour is provided by the present day absence of Quaternary volcanoes from lat. 27°-33°S, an interval which appears to have an extended history as a series of highly individual segments. This transverse segmentation is an important control of Andean metallogeny.

Controls to Loci of Magmatism

Dickinson (1973) has recently concluded that a progressive down-dip (retrograde) migration of the locus of magma generation on a subduction zone is a characteristic feature of magmatic arcs if prograding of the inner wall of the oceanic trench by accretion of mélanges and ophiolitic material does not occur. Retrograde migration results in an expansion of the arc-trench gap with time (Dickinson, 1973). Rutland (1971) suggested that eastward migration of magmatism in the central Andes was due to abrasion of the overriding continental plate at the inner wall of the trench, but it seems more likely that the dominant factor is a progressive change in the conditions controlling magma generation on the subduction zone beneath the arc, perhaps involving a depression of the isotherms in the vicinity of the contact

TABLE I

Magmatogene ore deposits marked on Fig. 4 and referred to in the text

	Contact-metasomatic Fe deposits
1	Tambo Grande ?
2	Marcona
3	Acarí
4	Algarrobo
5	El Tofo
6	Romeral
	Cu-Au and Ag vein deposits
7	Acarí ?
8	Tocopilla district
9	Carrizal Alto
10	La Higuera
11	Brillador
12	Tamaya
13	La Africana
14	Punta del Cobre district
15	Huantajaya
16	Caracoles
17	Tres Puntas-Chimberos
18	Chañarcillo
19	Arqueros
	Manto-type Cu deposits
20	Raúl and Condestable ?
21	Buena Esperanza
22	El Venado
23	Panulcillo
24	El Salado
	Stratiform Mn deposits
25	Corral Quemado
	Cu-bearing breccia pipes
26	Turmalina
27	San Pedro de Cachiyuyo
28	Cabeza de Vaca
29	Disputada
	Porphyry Cu-Mo deposits
30	Hualgayoc
31	Michiquillay
32	Morococha – Toromocho
33	Cerro Verde
34	Cuajone
35	Quellaveco
36	Toquepala
37	El Abra
38	Chuquicamata
39	Farallón Negro-Mi Vida district
40	El Salvador
41	Potrerillos
42	Los Pelambres
43	El Teniente
44	Paramillos district
45	Los Loros
46	Mo-rich prospect
47	Mo-rich prospect
48	Compaccha
	Cu-Pb-Zn-Ag vein and contact-metasomatic types
49	Quiruvilca
50	Mundo Nuevo-Pasto Bueno districts (W deposits)
51	Antamina
52	Cerro de Pasco
53	Atacocha
54	Janchiscocha (Mo deposit)
55	Casapalca
56	Yauricocha
57	Julcani
58	Ferrobamba
59	Tintaya
60	Matilde
61	Laurani
62	La Joya
63	San Cristóbal (? porphyry type)
64	San Antonio de Lípez
65	Aguilar
66	La Concordia
67	Famatina
68	El Tontal
	Volcanogenic Fe deposit
69	El Laco
	Sn-W and Sn-Ag veins
70	Milluni
71	Chojlla
72	Araca
73	Caracoles
74	Morococala
75	Huanuni
76	Avicaya
77	Colquechaca
78	Tasna
79	Pirquitas
	Porphyry Sn deposits
80	Oruro
81	Llallagua
82	Potosí
83	Chocaya

of the two plates, which would result in magma generation at progressively greater depths with time (James, 1971b; Dickinson, 1973). The essentially fixed locus of magmatism in the Eastern Cordillera is the product of a second deeper locus of partial fusion of the descending lithosphere, probably corresponding to the attainment of a critical set of higher P-T conditions; it also reflects more constant thermal conditions through time at depth on the subduction zone. It should be mentioned, however, that this eastern belt of magmatic activity could conceivably not be due to partial melting on the subduction zone but to some related mantle or crustal perturbation, although such a possibility is not favoured here. The increase in width of the zone of magmatism around 15 m.y. ago presumably reflected the attainment of higher temperatures over a greater down-dip extension of the subduction zone.

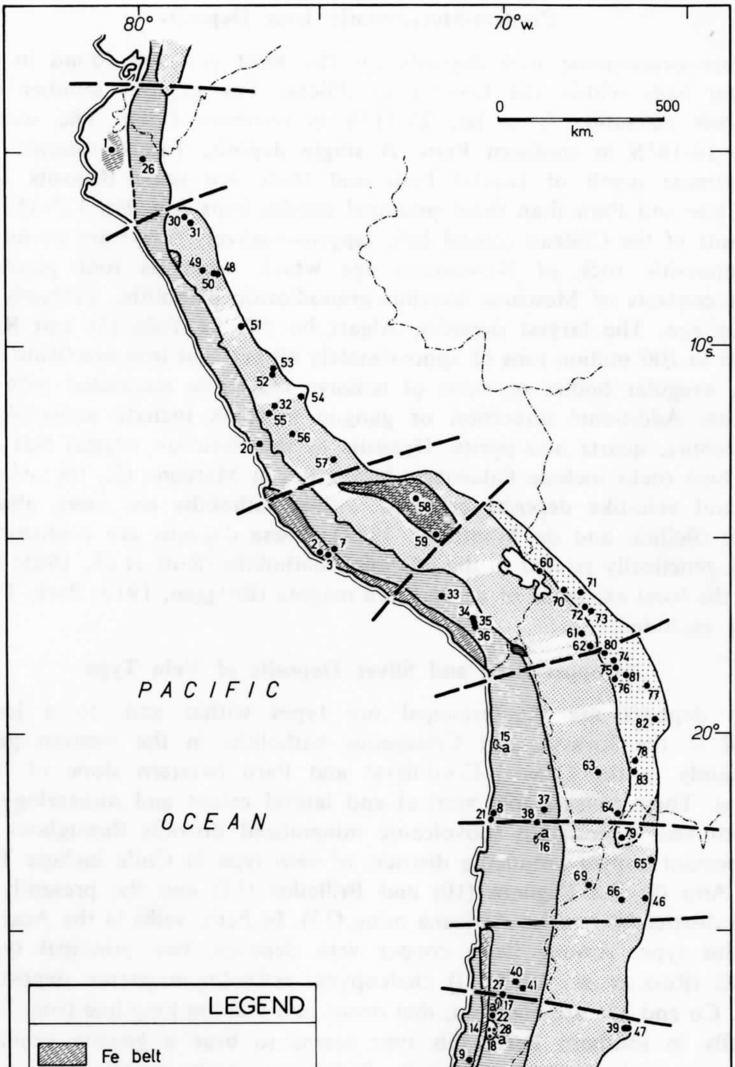
Drawing on his unpublished results, James (1973) adds support to this interpretation of the eastward migration of magmatism with time by stating that the K_2O/SiO_2 ratios of the magmatic rocks in the central Andes become progressively greater eastwards, irrespective of the age of the rocks, in conformity with the situation in modern magmatic arcs (Dickinson and Hatherton, 1967). Had the subduction zone itself advanced appreciably eastwards (Rutland, 1971) or the angle of the subduction zone varied (Mitchell, 1973), then this gradual change in K_2O/SiO_2 ratios would not be apparent. It is clear that the retrograde migration of the magmatic axis has not been constant in all segments of the central Andes and the migration has even been reversed locally.

TYPES OF POST-PALAEOZOIC ORE DEPOSITS IN THE CENTRAL ANDES

Metallic ore deposits in the central Andes are an integral and normal facet of the calc-alkaline magmatic development of the region and are genetically related to the final stages of the many intrusive and extrusive events; the red-bed deposits are an exception. Certain ore deposits are directly associated with intrusive, and others with extrusive activity. The porphyry deposits span the boundary in the subvolcanic environment between strictly intrusive and strictly extrusive phenomena (Sillitoe, 1973a). Strato-volcanoes are believed to mark the loci of important present day ore deposition.

This section summarizes the principal types of post-Palaeozoic ore deposits and their occurrence in the central Andes, preparatory to their consideration in terms of a metallogenic model in the succeeding section. It is accepted that any attempt at a classification of the ore deposits in the Andes that is partially genetic in nature involves personal bias and at times even rather arbitrary judgements, but such an approach is deemed essential for understanding the metallogeny and for planning exploration programs (see also Kirkham, 1972). Ore types recognized herein conform fairly closely to those recognized by previous workers. In the discussion which follows the numbers after the names of deposits refer to Fig. 4 and Table I and deposits are discussed from west to east across the central Andes.

Figure 4. The approximate positions of the metallogenic belts recognized in the central Andes, and the locations of ore deposits typical of the various types described.
Source: Principal transverse tectonic boundaries: Sillitoe, 1974b.
Note: Numbers refer to Table I.


80°
70° w.
10° s.
20°
30°
0
500
km.
PACIFIC
OCEAN
LEGEND
Fe belt
Chilean Ag districts
Mn districts
Cu-(Mo-Au) belt
Cu-Pb-Zn-Ag belt
Cu-Fe area
Sn-(W-Ag-Bi) belt
TECTONIC-METALLOGENIC BOUNDARY
35 ORE DEPOSIT (Identified in table I)
1
26
30
31
49
50
48
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53
52
54
32
55
56
20
57
58
59
2
7
3
60
71
70
72
73
33
34
35
36
61
62
80
74
75
81
76
77
82
15
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LC 74

Contact-Metasomatic Iron Deposits

Contact-metasomatic iron deposits for the most part are found in two linear, longitudinal belts within the Coastal Cordillera. The greatest number of deposits is in a belt extending from lat. 25-31°S in northern Chile. The second belt is from lat. 14-18°S in southern Peru. A single deposit, Tambo Grande (1), occurs in the extreme north of coastal Peru and there are some deposits farther east in both Chile and Peru than these principal coastal belts (e.g. lat. 13°-15°S) (Fig. 4). The deposits of the Chilean coastal belt, (approximatively forty) are found principally in meta-andesitic rock of Neocomian age which occur as roof pendants within or on the contacts of Mesozoic tonalitic-granodioritic batholiths, probably of Middle Cretaceous age. The largest deposits, Algarrobo (4), El Tofo (5) and Romeral (6), contain up to 100 million tons of approximately 60 per cent iron ore (Ruiz *et al.*, 1965) in lenses, irregular bodies or veins of massive magnetite associated with specularite and apatite. Additional alteration or gangue minerals include actinolite, scapolite, chlorite, biotite, quartz and pyrite. Deposits of the Peruvian coastal belt are similar, although host rocks include Palaeozoic limestones at Marcona (2), the most important deposit, and vein-like deposits enclosed within batholiths are more abundant (e.g. Acarí (3)) (Bellido and de Montreuil, 1972). These deposits are contact-metasomatic types and genetically related to the adjoining batholiths (Ruiz *et al.*, 1965; Ruiz 1967), although the local existence of an iron ore magma (Brüggen, 1913; Park, 1972) cannot be wholly excluded.

Copper-Gold and Silver Deposits of Vein Type

Vein deposits are the principal ore types within and, to a lesser extent, peripheral to the Jurassic and Cretaceous batholiths in the western part of both Chile (mainly in the Coastal Cordillera) and Peru (western slope of the Western Cordillera). Their considerable vertical and lateral extent and mineralogy distinguish them from vein deposits in subvolcanic mineralized districts throughout the Andes. Once-important copper-producing districts of vein type in Chile include Tamaya (12) Carrizal Alto (9), La Higuera (10) and Brillador (11) and the presently productive Tocopilla district (8) and La Africana mine (13). In Peru, veins in the Acarí district (7) are of this type. Among these copper vein deposits, two principal types can be recognized (Ruiz *et al.*, 1965): i) chalcopyrite-actinolite-magnetite deposits in which minor U, Co and Mo are common, that occur in a 900 km long line from lat. 22°-30°S and locally in southern Peru; this type seems to bear a genetic similarity to the contact-metasomatic iron deposits; ii) chalcopyrite-pyrite-specularite deposits, many of which have been exploited for their Au content. A little Pb, Zn, Co and Mo may also be present. In the Punta del Cobre district (14) this type is transitional to ore bodies of breccia-filling and contact-metasomatic types.

Important Ag deposits are known in this western Jurassic-Cretaceous batholithic belt at Chañarcillo (18), Arqueros (19) and Huantajaya (15), but mineralization is only rarely found in the intrusives themselves, calcareous rocks being the commonest hosts (Ruiz *et al.*, 1965). Other major Ag districts such as Caracoles (16) and Tres Puntas-Chimberos (17) are located a little further east, and along with some Cu, Au and Pb-Zn vein deposits are within the belt characterized by tourmaline breccia pipes and some porphyry Cu deposits (Fig. 4). A barite gangue accompanies the

Ag sulphosalts and very minor amounts of Co, Ni, Pb and Zn are typical (e.g. Whitehead, 1919). A noteworthy feature of these major Ag vein deposits is their rather scattered distribution within the belt of Cu deposits (Fig. 4).

Stratiform, Disseminated (Manto-Type) Copper Deposits

This ore type described by Ruiz *et al.* (1965, 1971) consists of finely disseminated chalcocite, bornite, and chalcopyrite, commonly with a significant Ag content, in volcanic rock or in sediments intercalated in volcanic sequences of Jurassic, Cretaceous and perhaps early Tertiary age. Gangue and alteration minerals are sparsely distributed and related intrusives are absent. The manto-type deposits are now second only to the porphyry Cu deposits in Chilean copper production and several deposits have reserves of several million tons.

Deposits of this type occur in the Cu-(Mo-Au) belt (Fig. 4) in volcanic sequences that are probably broadly comagmatic with the spatially related batholiths. Clusters of important deposits of this type occur in the Coastal Cordillera from lat. 22°-25°30'S and 32°30'-33°S, where amygdaloidal or brecciated upper parts of andesite flows are mineralized (e.g. Buena Esperanza (21) and El Salado (24)). Around lat. 27°S, the upper parts of ignimbrite flows are similarly mineralized (e.g. El Venado (22)). Where sedimentary rocks are mineralized, their character commonly suggests accumulation under reducing conditions. Some of the manto-type deposits have been metamorphosed by later intrusives (e.g. Panulcillo (23), Chile and Rául and Condestable (20), central Peru).

Earlier workers (Carter, 1961; Ruiz and Ericksen, 1962) classified the manto-type deposits as epigenetic-hydrothermal and related them to intrusive rocks. The current view is that these deposits are broadly syngenetic with enveloping volcanic rocks (Stoll, 1965; Ruiz *et al.*, 1965; 1971). It is known that hydrothermal fluids are dissipated from certain subaerial lava and ignimbrite flows during cooling as evidenced by the crusts of base-metal compounds sometimes observable on their upper surfaces. For instance, Cu compounds have been described from lava-flow surfaces at Cerro Negro volcano in Nicaragua (Stoiber and Rose, 1971) and a variety of base metals are present in sublimates formed during the cooling of an ignimbrite flow in the Valley of Ten Thousand Smokes, Alaska (Zeis, 1929). It is surmised that much metal is normally lost to the atmosphere, unless special conditions favouring its retention in the lava or temporally associated sediments are operative. Eruption in a shallow marine or lagoonal environment with ingress of sea or lake water to the flows and the existence of an appreciable sulphur fugacity may provide such conditions and give at least a partial explanation for the origin of the manto-type deposits. The manto-type deposits are thought to locally exhibit features transitional to those of volcanogenic massive sulphide deposits and might be considered as the extrusive equivalents of Cu deposits related to intrusive rocks.

Stratiform Manganese Deposits

Three principal horizons of Mn oxides are intercalated in a Lower Cretaceous submarine volcano-sedimentary sequence within the Cu-rich part of western Chile in a persistent narrow belt from lat. 28°-30°30'S (Fig. 4). Many of the deposits, including those in the pre-eminent Corral Quemado district (25), are interbedded with volcanogenic sandstones. The Mn deposits are believed to be syngenetic and to have been deposited from volcanic emanations under shallow marine conditions (Aguirre and Mehech, 1964; Ruiz *et al.,* 1965). Local association of ferruginous chert and copper minerals supports this view.

In the extreme northeast of Chile (Ruiz *et al.,* 1965; Cruzat Ossa, 1970) (Fig. 4) and locally in northwest Argentina (Sillitoe, 1973b), small stratiform accumulations of Mn oxides occur in superficial volcanic and clastic formations. The Mn is clearly deposited from thermal springs under both subaqueous and subaerial conditions and is related to the peripheries of Quaternary stratovolcanoes.

Manganese may also be a constituent of polymetallic vein deposits formed in a subvolcanic setting, as described below.

Copper-bearing Breccia Pipes

A class of deposits closely related to the porphyry Cu deposits is the Cu-bearing, tourmaline breccia pipes (Ruiz *et al.,* 1965; Sillitoe and Sawkins, 1971). These deposits are closely related to plutons of granodiorite composition, many of which are of early Tertiary age and located west of the large porphyry Cu deposits. The mineralization in the subcircular, near-vertical pipes consists of quartz-tourmaline-pyrite-chalcopyrite cementing altered, angular fregments of the host rocks. Gold is a by-product and scheelite-wolframite and molybdenite are important in some instances. Pipes commonly occur in groups of up to a hundred, and a hydrothermal collapse mechanism appears to be an important aspect of their genesis (Sillitoe and Sawkins, 1971). Important districts include Cabeza de Vaca (28) and San Pedro de Cachiyuyo (27) in northern Chile, Disputada (29) adjacent to the Río Blanco porphyry Cu deposit in central Chile, and Turmalina (26) in northernmost Peru.

Porphyry Copper-Molybdenum Deposits

The porphyry Cu deposits in the Andes are fairly well-known (Bellido and de Montreuil, 1972; Hollister, 1974; Howell and Molloy, 1960; Sillitoe, 1972b, 1973c; Sillitoe and Neumann, unpub.; Swayne and Trask, 1960). Most of the major deposits such as El Teniente (43), Los Pelambres (42), Potrerillos (41), El Salvador (40), Chuquicamata (38) and El Abra (37) in Chile, and Toquepala (36), Cuajone (34), Quellaveco (35) and Cerro Verde (33) in southern Peru occur in the Cu-rich, western part of the central Andes and are typical porphyry Cu deposits with recoverable Mo. These deposits all contain close to, or more than, 500 million tons of ore. They are either centred on isolated stocks (El Salvador, Los Pelambres, El Teniente) or related to the late phases of larger plutons (deposits in southern Peru). Haloes of Pb-Zn-Ag mineralization are restricted in importance or entirely absent around these deposits. Their ages vary in different parts of the orogen, from Palaeocene in southern Peru, late Eocene-Oligocene in northern Chile (Chuquicamata, El Salvador), to late Miocene-Pliocene in central Chile (Los Pelambres, El Teniente) (Laughlin *et al.,* 1968; Quirt *et al.,* 1971).

Porphyry Cu deposits are also located in isolated stocks further east as part of the belt of polymetallic Cu-Pb-Zn-Ag ore deposits to be described below (Rig. 4). These deposits are dominantly late Tertiary in age, although Michiquillay appears to be 21 m.y. old (Laughlin *et al.,* 1968). In Peru, Michiquillay (31), Hualgayoc (30) and Morococha (32) are included in this category, and in western Argentina many small prospects (e.g. Farallón Negro-Mi Vida district (39); Paramillos district (44)) are known from lat. 25°-39°S. These deposits tend to have haloes of Cu-Pb-Zn-Ag mineralization although zonation of alteration and sulphide-oxide minerals within the porphyry-type deposits themselves is similar to that in the porphyry coppers farther west.

Porphyry Mo deposits are apparently much less common in the Andes than in western North America although several prospects are known. A late Cretaceous, Mo-rich porphyry occurrence is found at Los Loros (45) in the coastal batholith of Chile at about 30°S (Sillitoe, 1973a); on the eastern margin of the polymetallic belt in northwest Argentina two small, apparently Mo-rich, prospects (46, 47) have recently been discovered (Sillitoe, unpub.); and in the polymetallic belt at lat. 8°S in northern Peru a prospect, Compaccha (48), is known.

Copper-Lead-Zinc-Silver Deposits of Vein and Contact-Metasomatic Types

This large and disparate group of deposits flanks the belt of Cu-rich, magmatic-hydrothermal deposits to the east (Fig. 4). The deposits are particularly abundant in Peru (Petersen, 1965; Bellido and de Montreuil, 1972) from lat. 6°S southward to the border with Bolivia, the belt occupying the Western Cordillera and Altiplano. The belt continues in more sporadic form from there across the Bolivian Altiplano and then southward through the Puna, Frontal Cordillera and Pampean Ranges of western Argentina. The polymetallic deposits are commonly associated with small, isolated, late Tertiary stocks of diorite (andesite), tonalite (dacite) or adamellite (quartz latite), and also with the Cordillera Blanca batholith. In Peru, they are commonly found in Jurassic-Cretaceous marine sedimentary rocks including limestones and in volcanic and clastic rocks of Lower and Middle Tertiary age farther west, whereas farther south in Bolivia and Argentina host rocks are more variable and commonly Palaeozoic in age. Copper, Pb, Zn and Ag are the principal metals recovered from the belt and within districts they are commonly arranged zonally (Petersen, 1970). Copper and Mo are of course present in porphyry deposits at several localities, as mentioned above, and the section of the belt from lat. 13°-15°S is deficient in Pb, Zn and Ag, the Cu being accompanied by Fe (Fig. 4). Some deposits (Quiruvilca (49), Casapalca (55) and Julcani (57) in Peru, Matilde (60), Laurani (61), La Joya (62) and San Antonio de Lípez (64) in Bolivia, and La Concordia (66), Famatina (67) and El Tontal (68) in Argentina) are mainly in veins. Others (Antamina (51), Yauricocha (56), Ferrobamba (58) and Tintaya (59) in Peru) consist largely of contact-metasomatic mineralization, and still others (Atacocha (53) and Morococha (32) in Peru) are a combination of both contact-metasomatic and vein types. The vein deposits are more common in the volcanics and the skarn ore bodies are restricted to calcareous rocks (Bellido and de Montreuil, 1972). The important Aguilar (65) Pb-Zn deposit in northwest Argentina could be included in the skarn category and related to an adjoining Cretaceous intrusive but doubts exist concerning its genesis, evidence from sulphur isotopes suggesting that the intrusive merely metamorphosed a Palaeozoic sedimentary metal accumulation (Linares, 1968).

The Cerro de Pasco deposit (52) in Peru consists of a pipe of hydrothermal breccia intruded by adamellite porphyry, with the principal Cu-Pb-Zn-Ag mineralization in the form of irregular bodies and veins on its contacts; it bears a certain resemblance to the porphyry class. Moreover, the San Cristóbal deposit (63) in southern Bolivia

(Jacobson *et al.*, 1969) possesses disseminated and breccia-filling Ag-Pb-Zn ore similar in many respects to that found in porphyry deposits and suggests that it could well be designated as a porphyry Ag-Pb-Zn deposit. It is worth noting that a disseminated Ag-Pb-Zn occurrence has recently been described from Hahns Peak, Colorado (Young and Segerstrom, 1973) and a probable porphyry Zn prospect is known in British Columbia (Sangster, 1974).

Many exotic metals are recovered from the polymetallic belt in Peru including Sn (at Cerro de Pasco), Cd, I, Se, Te, Hg, Bi and Ge, and when compared with the Cu belt, the polymetallic ores possess much greater amounts of As and Sb as sulphosalts. In the Peruvian part of the belt, W and Mo are locally abundant and notably so in the eastern part of the belt at lat. 8°S which includes the Mundo Nuevo-Pasto Bueno W district (50) and the Compaccha porphyry Mo deposit noted above.

It should be mentioned that after a marked gap in northern Peru and southern Ecuador, in which only Cu deposits are present (including Turmalina), the polymetallic belt resumes northward from the latitude of the Gulf of Guayaquil (3°S) (Fig. 4) and is notably rich in Ag (Goossens, 1972).

Volcanogenic Iron Deposit

In the extreme east of northern Chile at El Laco (69) (24°S) on the Puna, a large-tonnage magnetite-hematite deposit of volcanogenic origin has been described by Park (1961) and Ruiz *et al.* (1965). The deposit is distant from the Fe-rich coastal belt. Iron oxides occur as flows and feeder structures intimately related to andesitic volcanics of Pleistocene age; minor apatite and actinolite are also present.

Red-bed Copper and Uranium Deposits

Red-bed deposits in the central Andes are restricted to continental clastic sequences of molasse type and are therefore largely restricted to the Altiplano-Puna region and to the eastern side of the Andean orogen (Fig. 5). Small deposits in Peru are, however, in Lower Tertiary and Permian red beds farther west at Negra Huanusha and Doña Basilia (Petersen, 1965).

The main deposits in Tertiary formations on the northern Altiplano of southern Peru and Bolivia (Ljunggren and Meyer, 1964; Ahlfeld and Schneider-Scherbina, 1964), such as Corocoro, Chacarilla and Azurita-Cuprita, new indications further south in Sud Lípez (Kuronuma, 1971) and in the Puna of northwest Argentina (Sillitoe, unpub.), along with the San Bartolo deposit in northern Chile (Ruiz *et al.*, 1965), in addition to the deposits in central Peru, have Cu as the principal metal with only small amounts of V and U (Fig. 5). Deposits throughout western Argentina in rocks ranging from Permo-Carboniferous to Lower Tertiary in age and including the La Poma-San Carlos, Guandacol and Jáchal districts in the northwest (Fig. 5) have economic U contents (Stipanicic *et al.*, 1960); deposits in some districts also have significant V.

The deposits are stratiform, lens-shaped bodies in sandstone or conglomerate horizons which are locally bleached. Chalcocite or native Cu (accompanied by minor Pb and Ag) and pitchblende and other U oxides are the main minerals. Intrusive rocks are not related to the ore bodies and clearly do not provide a direct metal source, contrary to the conclusions of early workers (e.g. Ahlfeld, 1953). The source is believed to be

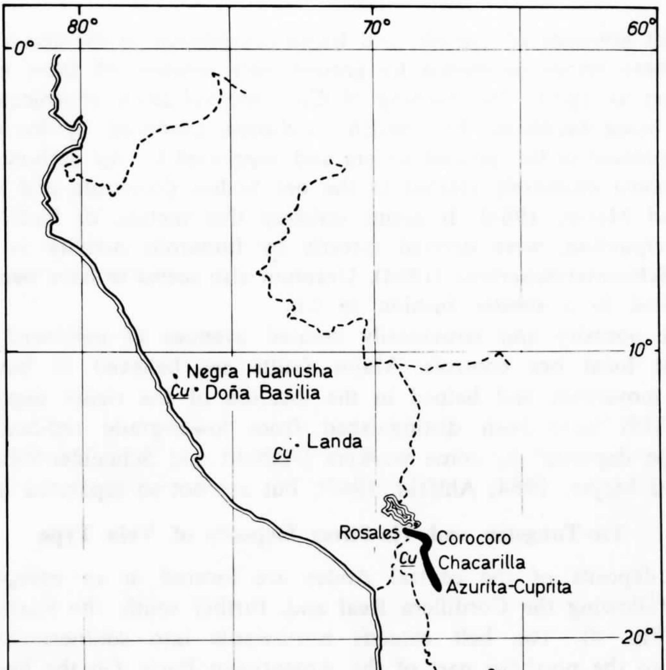


Figure 5. The distribution of red bed copper and uranium mineralization in the central Andes.

horizons of tu)s and lavas interbedded in the red-bed sequences or the red beds themselves, some of which are rich in volcanic components. Intrusive rocks may supply some of the U during weathering. The porphyry Cu deposits in northern Chile appear too distant to have acted as suppliers of Cu to the deposits on the Bolivian Altiplano (Ahlfeld, 1967; Ljunggren and Meyer, 1964).

Significant amounts of gypsum and halite are present in the red-bed sequences. Chloride-sulphate brines developed by groundwater solution of these evaporites are believed to act as agents for leaching of Cu from volcanics or volcanic debris, its precipitation being facilitated by low-Eh conditions produced by bacteria reducing the sulphate present in the ground waters and supported by the carbonaceous matter (or hydrocarbons) intimately related to the ore bodies (Entwistle and Gouin, 1955; Ljunggren and Meyer, 1964). It seems unlikely that metals, or hydrogen sulphide for their precipitation, were derived directly by fumarolic activity as proposed by Ahlfeld and Schneider-Scherbina (1964). Uranium also seems to have been transported and precipitated in a similar fashion to Cu.

Sediment porosity and structurally created avenues of enhanced permeability are important local ore controls. Major faults are believed to have controlled groundwater movement and helped in the location of the richer deposits, such as Corocoro, which have been distinguished from lower-grade red-bed deposits as "Corocoro-type deposits" by some workers (Ahlfeld and Schneider-Scherbina, 1964; Ljunggren and Meyer, 1964; Ahlfeld, 1967), but are not so separated here.

Tin-Tungsten and Tin-Silver Deposits of Vein Type

The Sn deposits of the central Andes are located in an exceptionally well-defined belt following the Cordillera Real and, further south, the Eastern Cordillera of Bolivia (Fig. 4). The belt extends northwards into southernmost Peru and southwards into the northern part of the Argentinian Puna. On the basis of current information, the Sn-W deposits are dominantly Mesozoic in age, except for those related to the Quimsa Cruz batholith of Lower Miocene age, and occur in a 30-50 km wide belt in the Cordillera Real. The Sn-W (cassiterite-wolframite-scheelite-quartz) vein deposits are found on the contacts of the several Cordillera Real batholiths and to a limited extent within them. They include Milluni (70), Chojlla (71), Caracoles (73) and Araca (72) (Turneaure and Welker, 1947; Ahlfeld and Schneider-Scherbina, 1964). Marginal to the Sn-W deposits there are small Pb-Zn and Sb veins.

The Sn-Ag deposits are found mainly in a wider belt, up to 150 km, in southern Bolivia and northernmost Argentina and many of the deposits are late Tertiary in age. Tin and Sn-As deposits include those spatially related with subvolcanic dacitic to quartz latitic stocks (Avicaya (76), Colquechaca (77)) and the Karikari batholith and others such as Huanuni (75) and Morococala (74) in Bolivia and Pirquitas (79) in Argentina cutting Palaeozoic sediments and possibly underlain at depth by source stocks (Turneaure, 1960; Ahlfeld and Schneider-Scherbina, 1964). Veins of this type are also superimposed on certain of the porphyry Sn deposits, described in the following section. Tin-W and Sn-Zn ores are also found in the southern part of the belt, where Sb and particularly Bi (Tasna (78)) are locally economic metals.

Porphyry Tin Deposits

This class of ore deposit has only recently been recognized (Sillitoe *et al.*, 1975) and is represented in the southern part of the Sn belt by several major mineralized centres including Llallagua (81), Oruro (80), Potosí (82) and Chocaya (83). Ore is low-grade and occurs in stockwork and disseminated form as an integral part of sericitic alteration centred on subvolcanic stocks of late Tertiary age. The deposits are closely comparable to porphyry Cu-Mo deposits and a similar genesis is proposed (Sillitoe *et al.*, 1975).

POST-PALAEOZOIC METALLOGENY OF THE ANDES

Synthesis of Metallogenic Zoning in the Central Andes

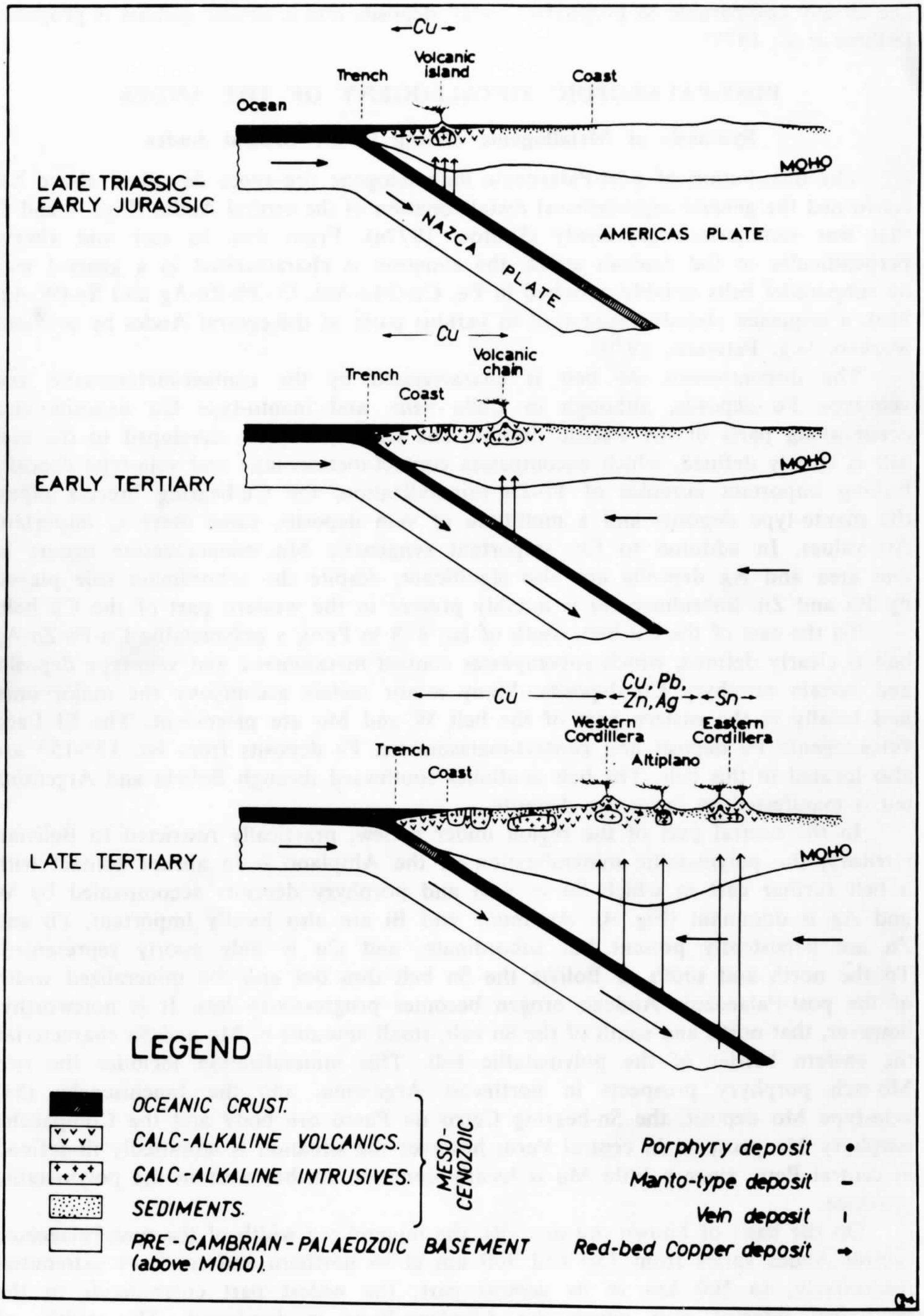
The distribution of post-Palaeozoic magmatogene ore types described above has confirmed the general asymmetrical metal zonation of the central Andes (Figs. 4 and 6) that was summarized previously (Sillitoe, 1972a). From west to east and always perpendicular to the Andean strike, the zonation is characterized in a general way by subparallel belts notably enriched in Fe, Cu-(Mo-Au), Cu-Pb-Zn-Ag and Sn-(W-Ag-Mo), a sequence already recognized in various parts of the central Andes by previous workers (e.g. Petersen, 1970).

The discontinuous Fe belt is characterized by the contact-metasomatic and vein-type Fe deposits, although in Chile vein- and manto-type Cu deposits also occur along parts of the Pacific littoral. The Cu belt is best developed to the east belt is clearly defined, which encompasses contact-metasomatic and vein-type deposits lacking important aureoles of Pb-Zn mineralization, the Cu-bearing breccia pipes, the manto-type deposits and a multitude of vein deposits, some carrying important Au values. In addition to Cu, important syngenetic Mn mineralization occurs in one area and Ag deposits are also significant, despite the subordinate role played by Pb and Zn. Subsidiary Co is notably present in the western part of the Cu belt.

To the east of the Cu belt, south of lat. 6°S in Peru, a polymetallic Cu-Pb-Zn-Ag belt is clearly defined, which encompasses contact metasomatic and vein-type deposits and certain porphyry Cu deposits. Many minor metals accompany the major ones and locally in the eastern part of the belt W and Mo are prominent. The El Laco volcanogenic Fe deposit and contact-metasomatic. Fe deposits from lat. 13°-15° are also located in this belt. The belt continues southward through Bolivia and Argentina but is manifested by fewer ore deposits.

In the central part of the region under review, practically restricted to Bolivian territory, the polymetallic mineralization of the Altiplano is in abrupt contact with a belt further east in which Sn in vein and porphyry deposits accompanied by W and Ag is dominant (Fig. 4). Antimony and Bi are also locally important, Pb and Zn are persistently present but subordinate, and Cu is only poorly represented. To the north and south of Bolivia the Sn belt dies out and the mineralized width of the post-Palaeozoic Andean orogen becomes progressively less. It is noteworthy, however, that north and south of the Sn belt, small amounts of Mo and Sn characterize the eastern border of the polymetallic belt. This mineralization includes the two Mo-rich porphyry prospects in northwest Argentina, and the Janchiscocha (54) vein-type Mo deposit, the Sn-bearing Cerro de Pasco ore body and the Compaccha porphyry Mo prospect in central Peru; however the situation is admittedly ill-defined in central Peru, since a little Mo is locally common further west in the polymetallic province.

On the basis of known ore deposits, the mineralized width of the post-Palaeozoic central Andes varies from 150 and 300 km at its northern and southern extremities respectively, to 500 km in its central part; the widest part corresponds to the latitudinal interval over which the Altiplano-Puna is developed. The widths of


←Cu→
Volcanic island
Trench
Coast
Ocean
MOHO
LATE TRIASSIC – EARLY JURASSIC
NAZCA PLATE
AMERICAS PLATE
← Cu →
Volcanic chain
Trench
Coast
MOHO
EARLY TERTIARY
← Cu →← Cu, Pb, Zn, Ag →← Sn →
Western Cordillera
Eastern Cordillera
Trench
Altiplano
Coast
MOHO
LATE TERTIARY
LEGEND
OCEANIC CRUST.
CALC-ALKALINE VOLCANICS.
CALC-ALKALINE INTRUSIVES.
SEDIMENTS.
MESO-CENOZOIC
PRE-CAMBRIAN-PALAEOZOIC BASEMENT (above MOHO).
Porphyry deposit
Manto-type deposit
Vein deposit
Red-bed Copper deposit

the different metallogenic belts also vary along the length of the orogen, as depicted in Fig. 4.

Although unrelated to this over-all zoning of magmatogene ore deposits, the position of the red-bed Cu and U deposits along the eastern side of the Andes (Figs. 5 and 6) and especially in the Altiplano-Puna region, should be emphasized. Their formation depends on the presence of red-bed molasse sequences and on the physico-chemical criteria noted above, but their location on the eastern side of the orogen seems, nevertheless, to be characteristic, as similar deposits also occupy this position in the Cordillera of the western United States where they occur in Permian and later sequences in Wyoming, Utah, Colorado, New Mexico and Texas (Finch, 1933). This should not be taken to mean that red-bed deposits are always to be found in this position along convergent plate margins, however, as shown by the presence of Carboniferous to Cretaceous red-bed U deposits with some Cu in an intraplate environment in Niger, West Africa (Bigotte and Molinas, 1973) and elsewhere.

Metallogenic Zoning in Relation to Geological Time

Subduction during the Triassic, Jurassic and Cretaceous gave rise to a number of narrow belts of magmatic rocks and associated ore deposits paralleling and close to the present coast (and perhaps continuing on the present continental shelf) and a second, latitudinally more restricted, belt further east in the Cordillera Real and perhaps locally elsewhere in the Eastern Cordilleras in the central part of the central Andes. The several episodes of magmatism in the coastal belt were dominated by Cu and Fe and those in the Cordillera Real by Sn and W. This does not necessarily imply, however, that the coastal Fe belt, for example, is the same age in northern Peru, southern Peru and northern Chile, although their ages may well be similar. On the basis of presently available data, there is a definite tendency in the western Fe and Cu belts for mineralization to retreat progressively eastward with time and to be confined to narrow, longitudinal belts during any one episode (Fig. 6). Some of the most westerly of these belts are those in which Fe and subordinate Co are concentrated. In the eastern mineralized belt, however, several episodes of ore deposition seem to have been superimposed in the Cordillera Real and significant migration of the loci of mineralization in this belt did not occur.

This same general pattern of metal distribution, with Cu in the western belt and Sn in the eastern belt, seems to have been maintained until the Middle Tertiary. Early Miocene Sn deposits are known from the Karikari batholith in the southern part of the Sn belt, and from the Quimsa Cruz batholith in the Cordillera Real and many of the major porphyry Cu deposits (Potrerillos, Chuquicamata) in the Cu belt are Oligocene.

Although more information is required before we can be precise about the exact timing, it seems that about 15 m.y. ago mineralization encompassed a much broader

Figure 6. Schematic cross-sections of the Andean orogen at about 20°S for late Triassic-early Jurassic, early Tertiary and late Tertiary times. The sections depict the distribution of ore types, the latitudinal extents of metallogenic belts, the eastward migration of magmatism-mineralization with time, and the abrupt late Tertiary expansion of magmatic-metallogenic activity.

region of the central Andes, from the eastern margin of the Cu belt to the Sn belt, for the first time (Fig. 6). Copper mineralization, including porphyry coppers, was widespread from at least 15 to 4 m.y. ago, and probably to the present day, and was accompanied by Pb, Zn and Ag vein and contact-metasomatic ores to give rise to the polymetallic belt. Copper mineralization of this age that was deficient in Pb-Zn-Ag took place along the eastern side of the Cu belt (western side of the polymetallic belt) at least in its southern part at Los Pelambres, Río Blanco and El Teniente, while low-grade porphyry Cu deposits accompanied by abundant peripheral Pb and Zn were emplaced further east in the polymetallic province (Paramillos district). At this time, Sn-Ag-(W-Bi-Sb) ores were generated in the Sn belt, dominantly in its southern part (Fig. 6).

The period from 15 m.y. onward, particularly from 10-4 m.y., accounted for a large part of the metal currently exploited in the central Andes. Judging by the present disposition of active volcanic centres, there has been a westward retreat of mineralizing activity, now probably largely confined to narrow belts in southern Peru and northern Chile and further south in central Chile. Some activity is still occurring east of this line on the Puna and Altiplano.

The descriptive term "belt" has been used to describe the broad longitudinal zones defined on the basis of metal content. When more radiometric age determinations are available, however, these belts may be subdivided into smaller linear, magmatic-metallogenic units formed during restricted episodes of magmatic activity; it is appropriate to use the term "metallogenic subprovince" for these individualized units, if the whole of the Andean orogen is treated as a post-Palaeozoic metallogenic province. At the present time, however, metallogenic subprovinces can only be defined locally (e.g. Fe and Mn subprovinces of northern Chile), so the broader, more general term "belt" is retained for the purpose of this paper.

Metallogenic and Tectonic Segmentation

The Andean orogen is, and probably always has been, divided into a number of individualized tectonic segments that have been generated because of a series of long-standing discontinuities on the underlying subduction zone; these are represented in the overlying continental crust (? and subjacent mantle) by relatively abrupt changes between geological provinces. One of the facets of the differing geology between tectonic segments is their metallogeny. A rigorous analysis is not possible until the tectonic segments of the Andes are more precisely defined on the basis of earthquake studies, but several presumed boundaries are marked on Fig. 4. Evidence from metallogenic studies suggests that certain boundaries may have changed their positions with time, although a few appear to have been reactivated at several times during the Meso-Caenozoic.

One of the striking features of the metallogeny of the region under review is the finite longitudinal extent of many of the components (metallogenic subprovinces) of the metallogenic belts. It is proposed that these subprovinces terminate at both ends against boundaries between tectonic segments. In other words, the metallogeny of each tectonic segment has its own peculiarities although an over-all similarity of metallogenic zonation between segments is apparent. Particularly obvious examples include the segmented nature of the belt of Fe deposits and the restricted latitudinal extents of the Sn belt and the line of Chilean Mn deposits. The Sn belt itself is divided by a boundary into a northern part active in the Mesozoic and a southern part not active until the Miocene. The polymetallic belt exhibits uniform characteristics from lat. 6°-13°S but at 13°S it doubles its width and changes its metal content somewhat at a well-defined tectonic boundary. South of this same boundary the Cu belt contains abundant important deposits but to the north mineralization is sparse. To the south of the boundary at lat. 22°S the polymetallic belt becomes poorer in metals and Cu tends to be more important than Pb, Zn and Ag. Less evident examples include the restriction of various types of Chilean Cu deposits to certain segments of the Cu belt (Ruiz and Ericksen, 1962; and above) and the change in age of the main porphyry Cu deposits as segment boundaries are crossed. The petrographic and age similarity between the southern Peruvian porphyry Cu deposits from Cerro Verde to Toquepala, a distance of 170 km, was emphasized by Stewart *et al.* (1974) and illustrates the within-segment uniformity of ore types. These observations, not further elaborated here, suggest that the same types of ore deposits were generated in the various segments but not necessarily at exactly the same time, whilst some ore types such as the Fe and Mn deposits are restricted to certain segments and are absent from most. The concept of metallogenic segmentation therefore provides an explanation for the metallogenic variability along the length of volcano-plutonic orogens.

There is some evidence to suggest that the boundaries between metallogenic segments may control the location of certain large ore deposits, since Chuquicamata (38), Río Blanco-Disputada (29) and other deposits appear to lie on present boundaries. The fact that late Caenozoic volcanism and associated mineralization sometimes occur as patches along segment boundaries, transverse to the main volcanic belts, as in Sud Lípez, Bolivia (Ag and Sn deposits) and along the southern border of the Puna block in Argentina (Cu deposits in Farallón Negro-Mi Vida district), tends to support this idea.

In order to provide a complete description of the components of a metallogenic province, therefore, both metallogenic subprovinces and metallogenic segments have to be delimited.

Origin of Metallogenic Zoning

Two broad models, or possibly a combination of both, may be called upon to explain the source of the metals and associated elements, and the origin of the metallogenic zoning in the Andes. These are:

1. the derivation of the metals from the crust and/or mantle, now realized to be above the subduction zone; and
2. the derivation of the metals and the control of their supply by processes acting in the vicinity of the underlying subduction zone. This hypothesis was obviously suggested (Sillitoe, 1972a; Sawkins, 1972) only after plate tectonic theory had been formulated.

Subscribers to the first model assigned Cu, Fe and associated metals to a crustal (Park, 1972; Mitchell, 1973) or to a mantle source (Stoll, 1964, 1965) whereas Sn was normally considered to be crustally derived (Ahlfeld, 1967; Ljunggren, 1962; Stoll, 1965; Mitchell, 1973). Schuiling (1967) postulated that Sn was concentrated in "culminations" in the lower crust that were tapped during magmatism. A mantle source has, however, been favoured for economic concentrations of Sn by certain workers (e.g. Sainsbury and Hamilton, 1967).

If the metals have been derived from crust and/or mantle above the subduction zone, it is difficult to visualize how the metallogenic zoning has been generated as the existence of long, narrow belts, enriched in particular metals or combinations of metals, in the lower crust or upper mantle is difficult to envisage and seems most unlikely; also, specialized units of the upper crust in the central Andes do not coincide with the metallogenic belts.

The derivation of small amounts of the various metals from crustal or upper mantle sources cannot be discounted, however, but as stated in model 2, the bulk of the metals is believed to come, in common with the genetically-related magmas, and perhaps also their contained water (Rye and Sawkins, 1974), from the region of the underlying subduction zone. The sequential release of the metals down-dip on a subduction zone, thereby giving rise to the lateral metallogenic zonation, is attributed to the series of phase transformations and partial melting processes that takes place during lithosphere descent. The details of these processes are still rather poorly defined (Wyllie, 1973).

The eastward migration of the interval on the subduction zone from which metals are liberated is thought to be due to the progressive depression of the isotherms on the western section of the zone as underthrusting continues, as outlined above.

During the early stages of magmatism, in the west of the orogen with the subduction zone at relatively shallow depths (around 80 km) (Fig. 6), Fe and Cu with some Mo and Au seem to have been the principal metals extracted during partial melting of the oceanic lithosphere. Layer-1 sediments and the upper part of the basaltic layer 2 (transformed to eclogite), including cupriferous massive sulphide deposits, seem likely metal sources at these shallower depths, as detailed elsewhere (Sillitoe, 1972b), and the abundance of Fe and, in some areas, of Mn could be taken to indicate a significant contribution from the Fe- and Mn-rich basal part (Boström *et al.*, 1969) of layer 1. Grabens related to tensional faulting produced by the down-bending of the suboceanic lithosphere as it enters the trench (Hussong *et al.*, 1973) will contain layer-1 sediments that are unlikely to be scraped off during contact with the overriding continental plate; therefore not all layer-1 sediments are accreted to the inner wall of the trench and a variable percentage would appear to be subducted. Sediments supplied to the trench across the arc-trench gap by erosion of rising magmatic arcs can be discounted as a significant metal source in the case of at least the Caenozoic central Andes as the arid climate has resulted in virtually no sediment reaching the Peru-Chile trench from lat. 8°-32°S and the trench is presently nearly free of sediment (Hayes, 1966). The widespread occurrence of Co as an ancillary metal in the western part of the orogen is also noteworthy and might be attributed to a contribution from Mn nodules, basal layer-1 sediments or the ultrabasic mantle wedge above the subduction zone.

Further down-dip on the subduction zone and at a later stage in the evolution of the metallogenic province, the release of Pb, Zn and Ag became more important (Fig. 6), and on the extreme eastern part of the zone, the liberation of Sn, accompanied locally by W, Ag and Bi, was dominant and Cu deficient throughout the Meso-Caenozoic. The origin of calc-alkaline magmas at these greater depths in excess of 200 km is even less understood, so little can be stated regarding potential sources for the Pb-Zn-Ag and Sn-W-Ag-Bi combinations. Eclogites from near the base of layer 2 or even the underlying ultrabasic mantle may undergo partial melting at these depths

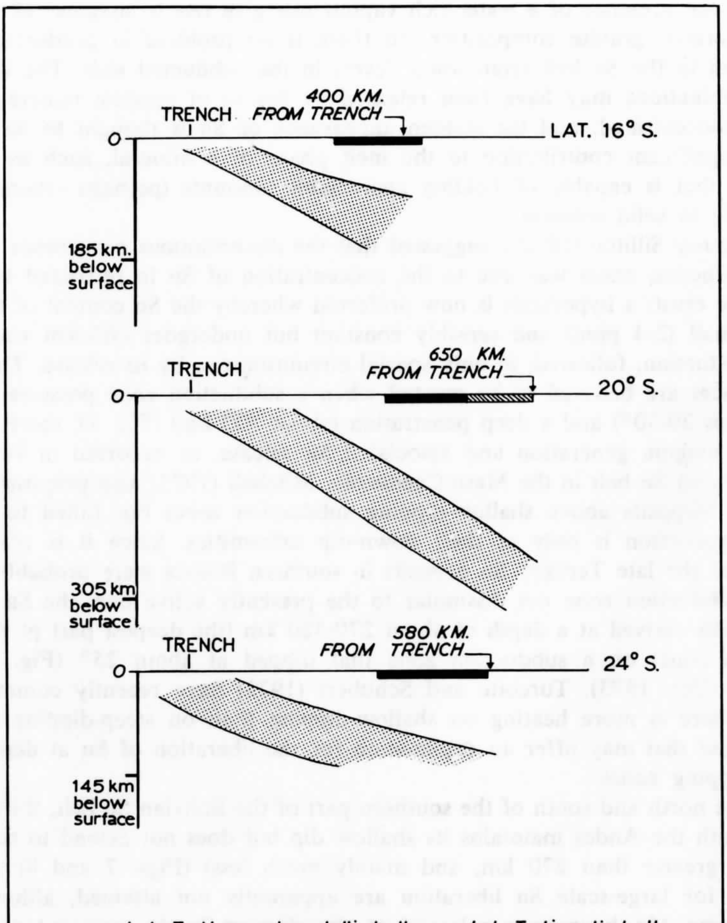


Figure 7. Cross-sections of the Andean orogen at latitudes 16°, 20° and 24°S showing the main concentrations of seismicity associated with the present subduction zone and the extents of the late Tertiary metallogenic belts. It is believed that conditions appropriate for tin liberation are only provided by the Zone at lat. 20°S.
Source: James, 1971b.

as the region of high temperature on a subduction zone is likely to broaden at depth (Toksöz *et al.*, 1971). Modreski and Boettcher (1973) have pointed out that mantle melting in the presence of a water-rich vapour can give rise to magmas of rhyodacitic or even potassic granite composition, so there is no problem in producing the rock types found in the Sn belt from lower levels in the subducted slab. The deeper-level metal combinations may have been released by fusion of specific minerals in which they are concentrated, and the sudden appearance of Sn is thought to be caused by the first significant contribution to the melt phase of a mineral, such as phlogopite or garnet, that is capable of holding appreciable amounts (perhaps several thousand ppm) of Sn in solid solution.

Previously Sillitoe (1972a) suggested that the discontinuous occurrence of Sn belts above subduction zones was due to the concentration of Sn in restricted segments of the oceanic crust; a hypothesis is now preferred whereby the Sn content of the oceanic crust is small (2-4 ppm) and sensibly constant but undergoes efficient concentration during subduction, followed, in only special circumstances, by its release. These special circumstances are believed to be created when a subduction zone possesses a shallow dip (perhaps 20-30°) and a deep penetration (about 300 km) (Fig. 7), thereby allowing deep-level magma generation and associated Sn release, as occurred in various parts of the Bolivian Sn belt in the Meso-Caenozoic. Mitchell (1973) also proposed a generation of Sn deposits above shallow-dipping subduction zones but failed to appreciate that Sn production is only at their down-dip extremities. Since it is reasonable to assume that the late Tertiary Sn deposits in southern Bolivia were probably emplaced above a subduction zone not dissimilar to the presently active one, the Sn was likely to have been derived at a depth of about 270-320 km (the deepest part pf the present, continuous zone) on a subduction zone that dipped at about 25° (Fig. 7) (James, 1971b; Stauder, 1973). Turcotte and Schubert (1973) have recently commented that at depth there is more heating on shallow-dipping than on steep-dipping subduction zones, a fact that may offer an explanation for the liberation of Sn at depth only on shallow-dipping zones.

To the north and south of the southern part of the Bolivian Sn belt, the subduction zone beneath the Andes maintains its shallow dip but does not extend to such a great depth (no greater than 270 km, and mainly much less) (Figs. 7 and 8) so that the conditions for large-scale Sn liberation are apparently not attained, although minor Sn and some Mo have been released at the deepest levels represented. Since the subduction zone attains a depth of about 270 km for 1° of latitude south of the southern termination of the Sn belt (Stauder, 1973) (Fig. 8), it would appear that the balance between Sn production or its absence is a rather delicate one; conditions on the subduction zone may well change appreciably, however, on crossing the tectonic boundary existing at the southern end of the Sn belt (Fig. 4). The concentration of Mo in the extreme east of the Cordillera of western North America suggests that Mo can perhaps substitute for Sn under certain circumstances. Further complications are undoubtedly involved as the abundant release of the Pb-Zn-Ag combination only occurred during the late Tertiary eastward expansion of magmatism, from an interval on the subduction zone over which magmas (and metals) had not previously been generated. Also the amount and type of metal released varies from one metallogenic segment to another suggesting that the processes operating on the underlying subduction zone are somewhat different, assuming an identical metal input at the trench. On

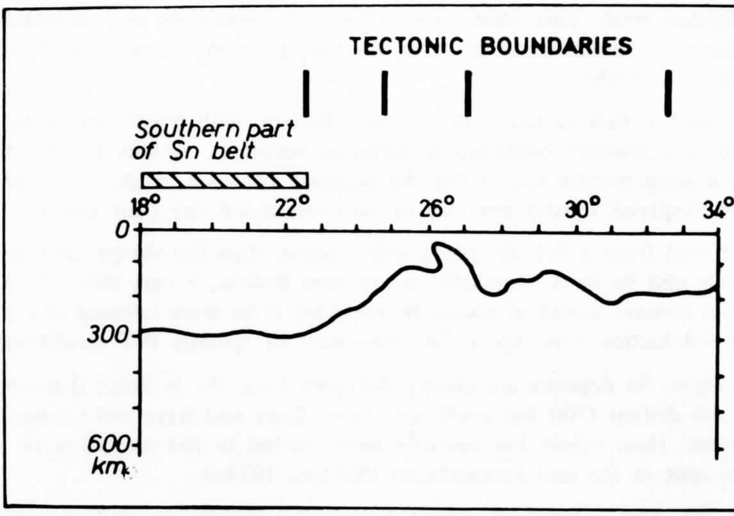


Figure 8. A longitudinal projection on a north-south vertical plane of the lower limit of intermediate-depth earthquake hypocentres from lat. 18°-34°S for the period 1969-1971, to show the relation between the depth of penetration of the subduction zone and the location of the late Tertiary tin belt. Principal tectonic boundaries are also marked.
Sources: Stauder, 1973; principle tectonic boundaries; Sillitoe, 1974 b.

subduction zones with only limited penetration or with much steeper dips, as is commonly the case in island arcs, Cu, Mo, Au and perhaps Fe are likely to be the only metals liberated in any quantity and so Pb-Zn-Ag and Sn-W belts will be unimportant.

It might be suggested that the bend in the Andes at around 18°S (the Arica elbow line) has consistently contributed to deeper underthrusting in this segment than to the north and south, as the formation of Sn deposits over an extended time interval in this segment must be more than coincidental. The increase in the rate of under-deep penetration of the lithospheric slab into the mantle, thereby entering the pressure-deep penetration of the lithospheric slab into the mantle, thereby, entering the pressure-temperature field compatible with Sn liberation, in addition to providing a stimulus to metal concentration throughout the central Andes, in particular in the polymetallic belt.

Several observations are believed to preclude the origin of the Sn in the Sn belt from crustal rocks or from a Schuiling-type culmination in the lower crust or upper mantle:

1. the Sn belt contains a high concentration of Sn deposits and follows a definite Andean trend, so is unlikely to be due to the rejuvenation of Palaeozoic (e.g., as in northwest Argentina) or Precambrian Sn in veins or pegmatites or of Sn in deposits of Rondônian type. Furthermore, late Caenozoic mineralization in the vicinity of Palaeozoic Sn deposits in northwest Argentina is Sn-free;
2. the basement beneath the Altiplano and also further west is similar to that exposed in the Eastern Cordillera, so that, if Sn were crustal in origin, Sn deposits should also

be present further west. This observation effectively precludes the derivation of Sn by crustal anatexis or assimilation or by its leaching from the upper crust by magmatic or heated meteoric fluids;

3. rocks in the Karikari batholith in southern Bolivia, with which minor Sn deposits are associated, and possibly comagmatic andesitic volcanics contain garnet which may well indicate a deep mantle source for the magmas (Brousse *et al.*, 1972) and seems to preclude widespread crustal anatexis as an explanation for their genesis;

4. if Sn is drived from a Schuiling-type culmination, then the abrupt contact between the polymetallic and Sn belts, especially in southern Bolivia, is very difficult to explain. Such an abrupt contact would of course be expected if Sn were released at a particular depth on the subduction zone upon the attainment of specific P-T conditions;

5. the Rondônian Sn deposits are clearly different from the Bolivian deposits (Ljunggren, 1964), are distant (700 km northeast) from them and were not formed above a subduction zone. Their origin has recently been related to the operation of a mantle plume or hot spot in the late Precambrian (Sillitoe, 1974a);

6. probably the most compelling evidence against a crustal or mantle source above the subduction zone for Sn and the associated metals in the Bolivian Sn belt is evidence, to be amplified elsewhere, derived from other parts of the circum-Pacific zone. Wherever Sn is found in a well-defined belt, as in Alaska (Cobb, 1960), Mexico (Ganzalez Reyna, 1956), or the small amounts accompanying W in British Columbia and the Yukon (Mulligan, 1971), it is concentrated along the landward side of the volcano-plutonic orogen and flanked trenchwards by belts containing Cu and Fe. It would obviously be too much to postulate that crustal rocks enriched in Sn, or stanniferous upper-mantle culminations, consistently occur along the landward sides of orogens. Furthermore, analysis of the metallogeny of Palaeozoic orogens in eastern Australia (Solomon *et al.*, 1972), Malaysia (Mitchell and Garson, 1972), southern Portugal (de Carvalho, 1972) and Newfoundland (Strong, 1974) all indicate a Sn belt flanking belts of the other base metals at the greatest distance from the presumed position of a trench.

In their interpretation of the Sn belts of southeast Asia, Mitchell and Garson (1972) combined models 1 and 2 above. They postulated a release of volatites, particularly F, from the subduction zone and seemed to imply the removal of Sn from crustal rocks during ascent of the volatiles, at a time of marginal ocean basin opening. Model 2, above, is preferred to that of Mitchell and Garson (1972), at least for the central Andes, as marginal ocean basins have never been present and since F was clearly not an important volatile constituent during Sn mineralization, judging by the paucity of fluorite and topaz in the Sn belt. Chlorine and B appear to have been important volatiles, as they were further west in the Cu belt, so leaving the metallogenic zoning unexplained if Mitchell and Garson's hypothesis is subscribed to.

Depth of Erosion and Metallogeny

As outlined elsewhere (Petersen, 1970; Sillitoe, 1972b, 1973a), erosion level is an important aspect when considering the distribution of ore types in the Andes or elsewhere. Even though local variations are important, meaningful regional generalizations can be made, and it is felt that the older magmatic belts have commonly been more deeply eroded than the younger ones. Thus the Triassic-Cretaceous volcanic-intrusive belts in the coastal zone and in the Cordillera Real generally represent the deepest levels of erosion in the post-Palaeozoic Andes. These belts are characterized by vein deposits within or on the contacts of the intrusive rocks, contact-metasomatic deposits, manto-type Cu deposits intercalated in the volcanic sequences and locally by the roots of porphyry deposits (Fig. 6). Deposits with pegmatitic affinity that probably represent the deepest erosion levels observable are found locally in the Cordillera Real (Turneaure and Welker, 1947) and in the coastal zone.

Further east in the Cu belt, younger and commonly smaller intrusives are believed to be less deeply eroded and host the main porphyry deposits (Fig. 6) and Cu-bearing breccia pipes, the latter perhaps representing a slightly deeper level. The polymetallic belt and the southern part of the Sn belt possess the shallowest ore deposits in the central Andes although porphyry deposits and skarn mineralization are still widespread. The Altiplano polymetallic mineralization and the late Tertiary Sn deposits have long been considered as subvolcanic, and comagmatic volcanics are locally preserved (e.g. Ahlfeld and Schneider-Scherbina, 1964). "Epithermal" mineralization is believed to occur at a shallower level than the porphyry environment and in some instances to be emplaced within strato-volcanoes directly above porphyry deposits (Sillitoe, 1973a, 1973b). This generalization tends to be complicated because lateral and vertical zoning at mineralized centres are commonly similar, and deposits from these two settings are consequently difficult to distinguish.

Although these different depths of erosion can be recognized, estimates derived from fluid-inclusion studies (Kelly and Turneaure, 1970; Sillitoe and Sawkins, 1971) suggest that most mineralized environments in the central Andes are epizonal, probably only occasionally being deeper than 7 km. Most porphyry deposits were probably emplaced at depths of 2-5 km and "epithermal" deposits may be deposited at depths as shallow as 0.5 km (Sillitoe, 1973b).

In his analysis of the metallogeny of Ecuador, Goossens (1972) suggested that the eastward change from Au, Cu and Mo deposits to Pb, Zn and Ag deposits was dominantly a matter of erosion level, with the Pb, Zn and Ag deposits occurring farther east at the highest altitudes. While there is certainly a tendency for at least Ag and Pb to concentrate in near-surface "epithermal" deposits (as for instance above porphyry deposits), Goossens' explanation for the regional zoning seems unacceptable. Evidence that the polymetallic province is related to differentiation on the underlying subduction zone and not to erosion level is provided by the presence of Pb-Zn deposits associated with the Cordillera Blanca batholith (Bodenlos and Ericksen, 1955), the southward continuation of the Pb-Zn-Ag province of Ecuador, and the presence of abundant Pb, Zn and Ag in the aureoles of porphyry Cu deposits in the polymetallic province in Peru and Argentina in contrast to the near absence of these metals around most porphyry coppers further west. The abundance of Ag relative to Pb and Zn in the polymetallic province of southern Ecuador (Goossens, 1972) may be interpreted as a special feature diagnostic of that particular metallogenic segment.

Recently, Mitchell (1973) implied that Sn deposits are formed at a deeper level than porphyry Cu deposits and postulated that Sn deposits underlie late Tertiary porphyry Cu deposits (presumably referring to Morococha) in Peru. All evidence from the Andes tends to negate this suggestion (see Sillitoe, 1973a), including that from Morococha, and the recognition in the southern Bolivian Sn belt of widespread subvolcanic Sn deposits (Ahlfeld and Schneider-Scherbina, 1964; Ahlfeld, 1967) and Sn deposits of porphyry type closely comparable with the porphyry coppers (Sillitoe *et al.*, 1975) demonstrates conclusively that Cu and Sn mineralization are formed over approximately the same depth interval and not one above the other.

CONCLUDING REMARKS

Bearing in mind the distribution of ore types in the central Andes and the consequent metallogenic hypotheses advanced above, it can be concluded that the orogen has undergone a relatively orderly metallogenic development that exhibits features typical of the metallogeny of convergent plate margins. The over-all model should, therefore, prove invaluable in deciphering older or lesser-known orogens generated at convergent plate margins. Mitchell (1973) has claimed, with little supporting evidence, that the angle of the subduction zone beneath the Andes varied with time, so rendering any attempt at metallogenic subdivisions of the region very complicated and inapplicable to comparable regions. This claim for the Andes is refuted, although minor changes in the dip of the subduction zone can of course be tolerated within the framework of the above hypothesis. The orderly distribution of ore types in the Andes in relation to the currently available pattern of radiometric ages, and the generation of Sn mineralization in the Sn belt from at least late Triassic times onwards strongly argue against Mitchell's (1973) proposal. This is not to say, however, that changes in the angle of subduction zones have not occurred in other regions, especially in the island-arc environment.

Although space does not permit detailed comparisons between the Andean metallogenic pattern and that of other orogens, a few points should be made. It is noteworthy that above many active and inactive subduction zones, especially in island arcs, a metallogenic analysis reveals the unambiguous presence of only a Cu belt and the evident absence of a Sn belt. Following from the proposals advanced above, this situation can be interpreted in terms of a steep-dipping subduction zone beneath the magmatic arc (cf. Mitchell, 1973), a situation that seems particularly common today and perhaps also in the past, so accounting for the rather scattered world distribution of Sn belts formed at convergent plate margins.

Many orogens constructed at convergent plate margins have undergone a more complex evolution than that of the central Andes; the Cordillera of British Columbia and the Yukon is one example (Monger *et al.*, 1973). As pointed out previously, however, (Sillitoe, 1972a), the post-Palaeozoic metallogenic zoning in this orogen (Brown *et al.*, 1971), from a coastal, Fe-rich belt, eastwards through Cu-Mo to W and minor Sn (Mulligan, 1971), closely parallels the Andean situation and is considered to demonstrate a gross evolutionary similarity. Even in the very wide, and in many respects atypical, Cordillera of the western United States, a zonation of metal provinces parallel to the continental margin can be discerned (Noble, 1970), that it is believed will greatly facilitate geotectonic analysis of the region. The situation is undoubtedly complex and may even entail the concurrent functioning of two shallow-dipping subduction zones during the Lower and Middle Tertiary (Lipman *et al.*, 1971). Nevertheless, the eastern margin of the orogen is characterized by a belt of porphyry Mo deposits, carrying minor Sn, in Colorado, New Mexico and western Texas and minor volcanogenic Sn deposits in New Mexico (Sainsbury et al., 1969) (cf. the eastern limit of the central Andes north and south of the Sn belt).

A greater diversity of ore types is theoretically possible in orogens generated at convergent plate margins than is apparent from the central Andes, especially if processes other than magmatic-arc construction have played a part. If island arcs are part of the developmental history, then massive sulphide deposits of calc-alkaline affinity can be expected; massive sulphide deposits might even be present within the fairly deep water parts of the early Mesozoic submarine volcanic piles in coastal Peru and Chile, in addition to the stratiform, disseminated Cu deposits. If marginal ocean basins are generated and subsequently closed or oceanic crust is accreted to the continental margin by obduction or during subduction, then massive sulphide deposits of ophiolite affiliation and other ophiolitic ore types generated at a divergent plate margin, like podiform chromite, may be present (see Sillitoe, 1972c, 1973d and Mitchell and Bell, 1973 for further details). Furthermore, as many of the ore types that presently characterize Andean metallogeny are likely to be removed by erosion during another 100 or 200 m.y. (Sawkins, 1972), the interpretation of the metallogeny of older orogens is likely to be even more complicated.

Without going into detail, it is clear that the application of a conceptual metallogenic model, such as that outlined above, to mineral exploration above active or inactive subduction zones is likely to enhance the chances of success. In particular, the realization that specific ore types are likely to be confined to a series of narrow metallogenic subprovinces paralleling the continental margin, which themselves are commonly restricted to particular metallogenic segments delimited at both ends by transverse tectonic boundaries, should aid in delimiting areas for more detailed examination. In fact the transverse boundaries way well provide promising targets in themselves. Moreover, the Andean ore types summarized above can be expected in camparable volcano-plutonic orogens so that ore search can be organized accordingly. For example, might not manto-type Cu deposits be present in the Triassic-Jurassic calc-alkaline sequences in the Canadian Cordillera? Porphyry Cu deposits have long been known from the central Andes, porphyry Mo and porphyry Sn deposits have recently been recognized, and a porphyry Ag-Pb-Zn occurrence may even be present, which clearly suggests the exciting possibility that all metals known from magmatic-hydrothermal ore deposits in the central Andes and other comparable orogens may will occur in large-tonnage, low-grade porphyry deposits.

ACKNOWLEDGEMENTS

I am most grateful to friends and colleagues from the Instituto de Investigaciones Geológicas and the Empresa Nacional de Minería of Chile, the Dirreción General de Fabricaciones Militares and the Dirección Nacional de Geología y Minería of Argentina, the Servicio Geológico and the Corporación Minera of Bolivia, Cerro de Pasco Corporation of Peru, and the United Nations (Projects Chile-28 and Plan NOA-1 Geológico-Minero, Argentina), organizations with which I have been associated in various capacities, for the provision of information and discussions over the years. Numerous companies and individual operators kindly provided access to, and information concerning, their properties. The preparation of this paper was commenced

during tenure of a Shell postdoctoral Research Fellowship at the Royal School of Mines, Imperial College, London.

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