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LONGITUDINAL VARIATIONS IN THE METALLOGENETIC EVOLUTION OF THE CENTRAL ANDES: A PROGRESS REPORT

A.H. Clark[1], Edward Farrar[1], J.C. Caelles[1], S.J. Haynes[2], R.B. Lortie[1], S.L. McBride[1], G.S. Quirt[3], R.C.R. Robertson[1], and Marcos Zentilli[4].

[1]Department of Geological Sciences, Queen's University, Kingston, Ontario
[2]Department of Geology, Brock University, St. Catherine's, Ontario, Canada
[3]Chemical Projects Limited, Rexdale (Toronto), Ontario, Canada
[4]Department of Geology, Dalhousie University, Halifax, Nova Scotia, Canada

ABSTRACT

The well-exposed and intensely-mineralized central sector of the post-Paleozoic Andean orogen has emerged as a model for the generation of ore deposits at a convergent plate margin. Between Lat. 26° and 29° S, our detailed geological and geochronological studies have rigorously defined the secular and spatial incidence of congruent magmatic and post-magmatic events since the initiation of the Andean orogeny in the Late Triassic. A monotonic continent-ward migration (0.6-1.1 mm/yr) of the major centres of epizonal plutonism, volcanic eruption, and mineralization persisted from the Lower Jurassic to the Oligocene, to be followed by a wide extension of activity in the Mio-Pliocene, and, most recently, a retraction in the Plio-Pleistocene. Broadly similar time-space geometries, strongly suggestive of the derivation of the components of the magmatic-hydrothermal systems through the partial melting of subducted oceanic lithosphere at progressively greater depths along an essentially stable Benioff zone, are revealed by less detailed studies between Lat. 17° and 20° S, and to the south of Lat. 30° S.

Despite recognition of these ordered relationships, several factors critical to mineral exploration, and to a full understanding of ore genesis in the region, remain unexplained. These include the controls on: the precise timing of the metallogenetic sub-epochs; the longitudinal continuity of individual magmatic-metallogenetic sub-provinces; the longitudinal variations in mineralization intensity at different stages in the development of the orogen (i.e., the delimitation of metallogenetic domains); and the transverse and longitudinal variations in the relative abundances of the ore metals, emphasizing the Bolivian tin belt, the genesis of which cannot readily be ascribed to processes of plate consumption.

RÉSUMÉ

Le secteur central bien exposé et intensement minéralisé de l'orogène post-paléozoïque des Andes, s'est révélé un modèle de la génèse des dépôts minéralisés à la limite de plaques convergentes. Entre 26° et 29° de latitude Sud nos études géologiques et géochronologiques détaillées ont déterminé avec rigueur l'incidence séculaire et spatiale d'événements magmatiques et post-magmatiques congruents depuis le commencement de l'orogène des Andes (Trias Supérieur). Une migration monotone en direction du continent (0,6-1,1 mm./a.) des principaux cntres de plutonisme épizonal, d'éruption volcanique, et de minéralisation a prévalu du Jurassique Inférieur à l'Oligocène; elle fut suivie d'une activité plus généralisée au Mio-Pliocène, ainsi que plus récemment, d'une rétraction au Plio-Pléistocène. Des études moins détaillées entre le 17ième et le 20ième degré de latitude Sud et au Sud du 30ième degré de latitude Sud révèlent des géométries espace-temps qui se ressemblent et qui suggèrent fortement que c'est la fusion partielle à des profondeurs de plus en plus profondes le long d'une zone de Benioff essentiellement stable de la lithosphère océanique en subduction, qui a déterminé la dérivation des composants des systèmes magmatiques hydrothermaux.

Malgré l'existence de ces relations bien régulières, plusieurs facteurs décisifs à l'exploration des gîtes minéraux et à une compréhension totale de la métallogénèse dans la région, restent sans explication. Ces facteurs comprennent les contrôles sur: (i) la localisation exacte dans le temps des sous-époques métallogéniques; (ii) la continuité longitudinale de sous-provinces magmatiques-métallogéniques individuelles; (iii) les variations longitudinales de l'intensité de la minéralisation à différents stades du développement de l'orogène (c'est-à-dire la délimitation de domaines métallogéniques); (iv) les variations transversales et longitudinales de l'abondance relative des minerais, un accent particulier devant être mis sur la ceinture d'étain de la Bolivie, dont la génèse ne peut pas être attribuée aux processus de destruction des plaques dans le manteau supérieur.

INTRODUCTION

Despite the rapid emergence of a broad consensus on the spatial relationships between mineral deposits and plate tectonic environments (Guild, 1971, 1972a, and b; Sawkins, 1972; Sillitoe, 1972a, b and c; Mitchell and Garson, 1972; Mitchell and Bell, 1973; Kirkham, 1973), most of the accepted correlations remain essentially empirical. Paradoxically, convergent plate margins are the most clearcut, yet least understood, loci for major magmatic and post-magmatic mineralization. This situation reflects the paucity of reliable information in most such settings, a result of the rarity of integrated geological, petrological, and metallogenetic studies. This uncertainty is compounded by the continuing lack of agreement as to the source and mode of formation of magmas emplaced in the shallow crustal region at convergent plate margin boundaries, particularly in Cordilleran, or Andean-type continental margins, where the sialic crust represents an additional complicating factor.

The "geostill" concept, which would derive the metals now concentrated in ore deposits within the continental margin from subducted oceanic crust, is, therefore, unsupported by other than circumstantial evidence, even in active orogenic belts such as the Andes. We contend that clarification of the fundamental and secondary controls on the development of economic mineralization in such regions will require comprehensive and comparative studies of relatively restricted areas of individual lithotectonic provinces, in order to define the consistencies and variations in metallogenetic development which they exhibit.

Although there is wide agreement that the Central Andes between Lat. 10° and 35° is an ideal locale for metallogenetic research, the broad syntheses presented for this region to date are, we consider, oversimplified, and thus misleading to both ore genetic studies and mineral exploration. The present paper summarizes the results of a metallogenetic research program in the Central Andes within a *ca.* 200 km wide transect between Lat. 26° and 29°S, extending from Atacama Province of northern Chile to Catamarca and La Rioja Provinces, northwestern Argentina (Fig. 1), an arid area displaying almost unparalleled relief and bedrock exposures, and a wide range of ore deposits. Preliminary data are also presented from a more recent comparative study in the vicinity of the "Arica elbow", along a dog's-leg (Fig. 1) traverse from Tarapacá Province, Chile (Lat. 17°30′ – 20°30′S), to the eastern cordillera of northern Bolivia (Lat. 14°30′ – 17°30′S). These are here termed the "southern" and "northern" transects, respectively.

The Central Andean Metallogenetic Project (CAMP), has been built around a series of interdependent graduate research programmes described in theses by Quirt (1972), McBride (1972), and M. Zentilli (1974) and others in preparation by J.C. Caelles, S.J. Haynes, R.B. Lortie, and R.C.R. Robertson. Our metallogenetic studies in the southern transect are based upon a reconstruction of the Paleozoic and subsequent history of the central part of the South American Pacific margin through critical reappraisal of published accounts of stratigraphic and structural relationships, leading to detailed mapping of key stratigraphic sections and field studies of plutonic and volcanic igneous bodies. Correlation and extension of the stratigraphic and magmatic chronology has been aided by the K-Ar mineral and whole-rock dating of over 250 carefully selected rock specimens from the area. The compositions and, hence, possible source regions of the igneous rocks in the transect have been clarified through petrographic and major and minor element analysis of some 400 specimens of known age and geological setting. This investigation is supported by the determination of the initial strontium isotope ratios of 33 specimens of intrusive and volcanic rocks covering the entire age span of Andean magmatic activity (McNutt *et al.*, 1973; and in press), and by continuing studies on rare earth distributions (Dostal *et al.*, in prep.).

Specifically metallogenetic aspects have been approached through field and laboratory studies of a large number of representative ore deposits, with emphasis on their spatial relationships to igneous bodies, their dimensions (grade and tonnage), hypogene and supergene mineral parageneses, and radiometric ages.

Across the northern transect, field and laboratory studies, including K-Ar age determinations, are underway on the widely-spaced exposures of granitoid rocks in Tarapacá Province, to provide a framework for a more detailed investigation of the evolution of the plutons and associated Sn, W, and base and precious metal mineralization in the Cordilleras Apolobamba, Muñecas, Real, and Quimsa Cruz, constituting the Eastern Cordillera of northern Bolivia, and the northerly portion of the important Central Andean Sn belt.

In the present paper, the conclusions of the more comprehensively studied southern transect will be first summarized, before examining the less-known, and undoubtedly more complex, relationships in the Arica elbow region. Preliminary accounts of the conclusions of the studies have been given elsewhere (Clark and Zentilli, 1972; Clark *et al.*, 1973a, b). Research is continuing, particularly in the northern transect, and more detailed documentation and discussion will be presented at a later date.

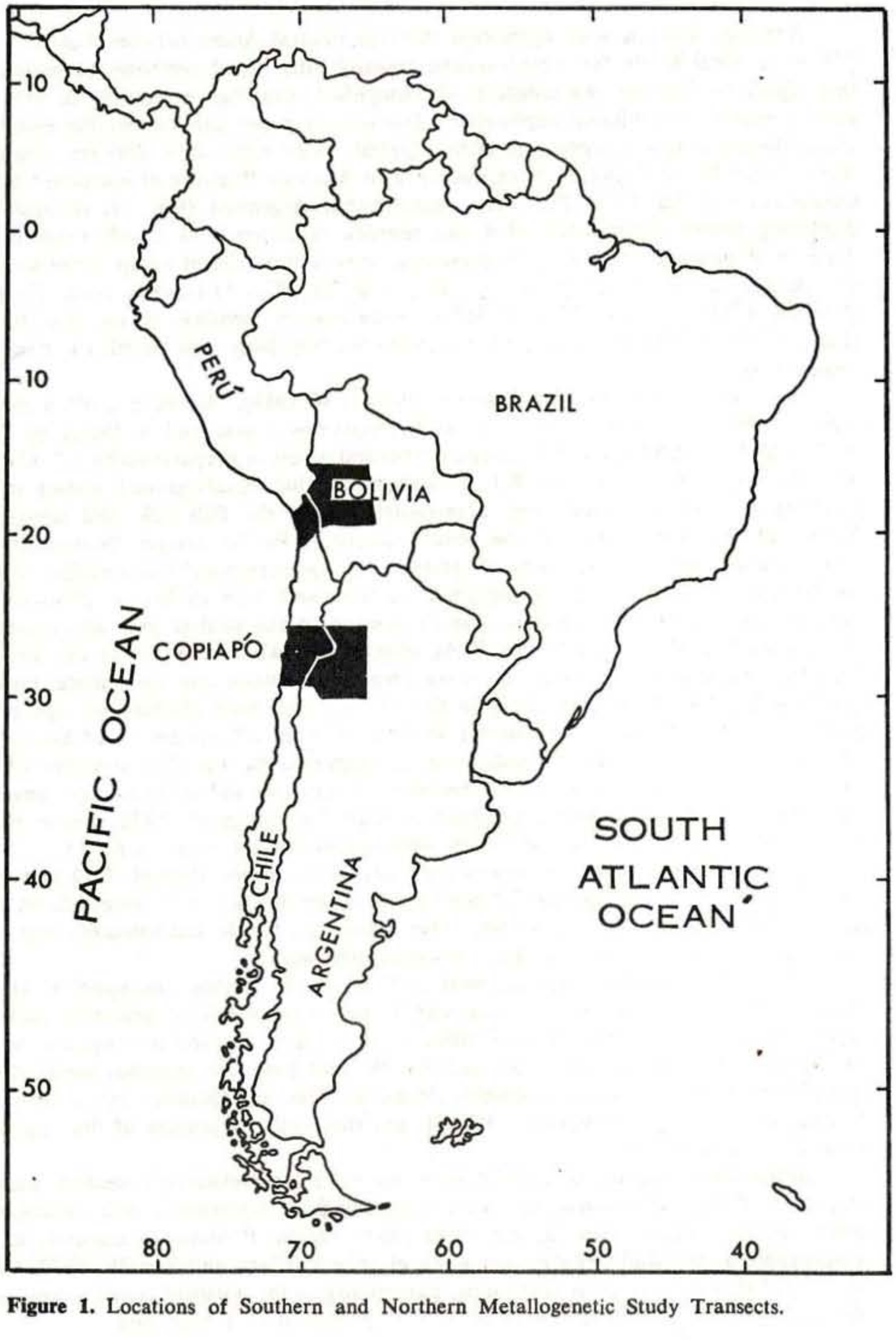


Figure 1. Locations of Southern and Northern Metallogenetic Study Transects.

SOUTHERN TRANSECT (LAT. 26° – 29°S)

Basement

All preserved segments of the Andean orogen at these latitudes evolved as an overprint upon a dominantly-crystalline sialic basement of Paleozoic and, locally, Hadrynian age. Although the late Precambrian and Paleozoic record reveals several major orogenic episodes, the youngest of which culminated in the Permian in the vicinity of the present continental margin, there was a radical change in tectonic style in the mid-Triassic. The still-active *Andean orogeny*, therefore, is considered to have commenced at that time (*ca.* 200-210 m.y.) between Lat. 10° and 35°S.

(a) The Paleozoic stratigraphic record south of Lat. 24° – 26°S defines a succession of broadly northwest-trending continental margin environments, which migrated irregularly, but grossly, to the west, away from an original nucleus, the Brazilian Shield. North of Lat. 24°S, there is evidence of a branching of the sedimentary basins and fold belts around the Hadrynian Arequipa Massif of southern Perú (Mégard *et al.*, 1971; Cobbing and Pitcher, 1972a), the main Paleozoic continental margin being truncated by the present Pacific coastline.

(b) Although Precambrian rocks may be exposed in the area, the bedrocks of the Sierras Pampeanas physiographic and lithotectonic province, long considered to be of pre-Paleozoic age (Harrington, 1956; Turner, 1970), clearly comprise predominantly Cambrian and younger Paleozoic rocks at these latitudes.

(c) The Paleozoic continental margin experienced orogeny at several periods, which are reflected as inter-regional unconformities separating well-defined stratigraphic sequences, in the sense of Wheeler (1958). Of these, at least those in the pre-Middle Cambrian, Upper Ordovician-Lower Devonian, and mid-Carboniferous, coincided in time with the emplacement of northwest-trending granitoid batholiths and plutons, and with regional metamorphism (Halpern *et al.*, 1970; Halpern, 1972; McBride, 1972). Plutons exposed within the largely autochtonous crystalline basement underlying the main Andean orogen on the Chilean flank of the Andes at these latitudes range in apparent age from *ca.* 320 m.y. to 230 m.y. (mid-Carboniferous to Upper Permian). Only the pre-Middle Cambrian orogenic and magmatic episode affected areas remote from the western margin of the present continent, reflecting a focussing of orogeny along the western boundary of the Brazilian Shield after the late Precambrian.

(d) There was a general westward migration of Paleozoic plutonic, volcanic, and metamorphic activity, coinciding approximately with the displacement of the main basins of sedimentation, although considerable overlap of plutonic centres of different ages occurred. Each pulse of batholith emplacement affected areas with wide east-west extension (up to 400 km), in marked contrast to the much narrower, longitudinal, plutonic complexes intruded during the Andean orogeny (see below).

(e) The Paleozoic granitoid rocks are characterized by the extensive development of K-feldspar megacrysts, but exhibit systematic areal trends in potash index (Bateman and Dodge, 1970). The Upper Ordovician-Lower Devonian plutonics show an increase in potash from west to east, whereas the Carboniferous bodies become more potassic in the opposite sense. These data are tentatively interpreted by J.C. Caelles as reflecting magma generation at an eastward-dipping subduction zone between 400 and 450 m.y., and at a westward-dipping zone between 310 and 335 m.y. (and probably continuing through the Permian during the westward migration of the locus of magma formation).

(f) The stratigraphic and petrochemical relationships in the Andean basement at these latitudes may be interpreted as the result of a long history of plate interaction, probably at the western margin of the proto-South American continent, and including both collision with an island-arc (Upper Ordovician-Lower Devonian) and underthrusting at the continental margin proper (mid-Carboniferous-Upper Permian).

(g) As is the case with most other segments of the extensively exposed Paleozoic orogenic belts of South America, the Andean basement in this region is only sparsely mineralized, in strong contrast to the overprinted Andean orogen. The Sierras Pampeanas of northwestern Argentina are characterized by an assemblage of post-magmatic ore deposits of the Sn, W, and rare metal (Be, Li, W, Ta, U, etc.) clan (Angelelli *et al.*, 1970). The great majority of the cassiterite- and wolframite-bearing quartz veins are probably of modest dimensions, but the complex pegmatites are of considerable economic significance as sources of beryllium and lithium. Base and precious metal veins (Pb, Zn, Cu, Au and Ag) are widespread, but less important than the above deposits. Stratabound deposits of Pb and Zn, and probably W, have yielded modest tonnages of ore, but no individual deposits of the size of the early Paleozoic Aguilar group (Lat. 23°15′S) are known.

(h) K-Ar dating (McBride) of muscovites from thirteen pegmatite and hydrothermal deposits in the Sierras Pampeanas has yielded apparent ages sensibly concident with those of the associated granitic plutons, and suggests that essentially similar post-magmatic Sn-W-rare metal mineralization occurred during both the Upper Ordovician-Lower Devonian and mid-Carboniferous plutonic episodes, an example of metallogenetic recurrence.

(i) The epigenetic ore deposits of Paleozoic age in this transect are almost entirely restricted to a relatively narrow longitudinal (i.e., northwest-trending) belt, *ca.* 200 km in width, lying approximately between Long. 65° and 68° W. To the west of this mineralized belt, no significant mineral deposits have been recognized in the crystalline basement of the main Andean orogen at these latitudes, an area some 300 km wide. If the majority of the granitoid plutons in this area are of mid-Carboniferous to Upper Permian age, as suggested by the available K-Ar and Pb-alpha dates, it may be concluded that the intensity of mineralization associated with the late Paleozoic orogenic activity decreased drastically with time as the locus of plutonism shifted to the west.

Andean Orogen

The Andean orogen between Lat. 26° and 29°S, and for a considerable distance to the north and south, is characterized by several features which are closely paralleled in few other young orogenic belts. These attributes greatly assist in the unravelling of the lithotectonic evolution of the orogen, and in the delimitation of the controls on its metallogenetic development.

(a) Eastward marine transgression over the eroded surface of the Paleozoic continental margin in the Upper Triassic and Lower Jurassic set in train a history of sedimentation in a succession of short-lived, and areally restricted, basins, entirely terrigenous after the mid-Cretaceous. Each basin, typically bounded by normal faults, received only up to 3-4 km of sediments and volcanics, which were then largely eroded before the development of the succeeding basin, generally initiated some distance inland.

Despite a total Mesozoic-Holocene stratigraphic thickness of *ca.* 16 km, therefore, there was no great accumulation at any point, and only minor "loading" of the crust occurred. No "Andean geosyncline" can be recognized at these latitudes.

(b) The Andean supracrustal rocks lie upon plutonic, volcanic, and metamorphic basement, but exhibit only incipient burial metamorphism, and no penetrative deformation. Folding and thrusting of the Andean strata are restricted to the immediate vicinity of the apical zones of Mesozoic and Caenozoic plutons, and coincided closely with their emplacement; only incompetent units suffered strong, local, folding.

There is no evidence of significant shortening or compression of the shallow crust in this region (*cf.* Rutland, 1971). Indeed, it is considered that the eroded upper portion of the previously coherent, unfragmented, Paleozoic sialic basement has so far undergone approximately 100 km of east-west *extension* during the Andean orogeny.

(c) Plutonic and volcanic activity, dominantly of calc-alkaline nature, has affected the shallow crust in the transect at narrowly spaced intervals since the initiation of Andean orogeny in the late Triassic. The magmatic emplacement style characteristic of the region comprises relatively small, often dyke-like, epizonal plutons, overlain and bordered by piles of submarine or, since the mid-Cretaceous, subaerial volcanics and volcaniclastic sediments, all components showing a longitudinal (i.e. north-south) extension. Detailed dating of several of the volcano-plutonic complexes suggests that up to 5 m.y. of volcanic activity preceded a more curtailed period of simultaneous intrusion and volcanism, followed by further minor volcanism. These magmatic episodes were separated by periods of relative magmatic quiescence, which, however, saw the eruption, in the Caenozoic, of regionally-extensive rhyodacitic ash-flow sheets. The latter did not attain the extreme development shown by the Neogene ignimbrites of northermost Chile and adjacent Bolivia and Argentina (Zeil and Pichler, 1967). Plutonic emplacement was accompanied by, and probably caused, local updoming of the shallow crust, and simultaneous subsidence of the adjacent regions, to form elongated basins which rapidly infilled with minor volcanic flows and thicker successions of largely volcaniclastic detritus eroded from the uplifted blocks.

(d) The earlier, Jurassic and Lower Cretaceous, episodes of volcanism and subjacent plutonism led to the construction of island-arcs upon the outer edge of the sialic crustal margin, while the younger volcanics, emplaced during the episodic tectonic uplift of the Andes—which here commenced in the early Caenozoic (Mortimer, 1973)—generated considerable subaerial strato-volcanic relief, culminating in the Neogene-Holocene Alta Cordillera which reach altitudes of well over 6000 m at these latitudes.

This model, proposed by Zentilli (1974), for the surficial development of the Andean orogen is in strong contrast to those presented by most previous authors (e.g., Rutland, 1971, 1973). The lack of detailed gravity or seismic studies in this transect prevents confident assessment of the three-dimensional nature of the exposed granitoid plutons, but these probably conform to the shallow-rooted form advocated by Hamilton and Myers (1967). Thus, erosion of the cordillera to modest depths, perhaps as little as 3-5 km, could destroy almost all evidence of the Andean orogeny; the Andes at these latitudes constitute an essentially epicrustal phenomenon.

(e) Extensive analysis of the Andean volcanic (by M. Zentilli and J.C. Caelles) and plutonic (by S.J. Haynes) rocks in the transect has defined, for the first time, the compositional evolution of magmas since the initial stages of the orogeny; previous studies have been largely restricted to the youngest volcanic rocks. The intrusive and extrusive rocks emplaced along the main axis of the orogen are predominantly of calc-alkaline nature, and display only minor differences with respect to the calc-alkaline suites of the western Pacific island arcs (e.g. Taylor, 1969). A wide range of composition, from quartz diorite and diorite (or even gabbro), or high-alumina basalt and low silica andesite, to quartz monzonite, or dacite, rhyodacite, and rhyolite, is represented in the majority of the volcano-plutonic episodes (see below). Basaltic rocks are rare or absent in the youngest strato-volcanic complexes, which are largely made up of dacites, rhyodacites, and andesites, and there is a probably significant increase in the proportion of the more silicic members with time; rhyolitic rocks appear to be of only minor occurrence in the early-Mesozoic centres. Intermediate compositions, quartz diorite-granodiorite and andesite-dacite, are the most voluminous.

Comparison of the minor and trace element contents of the volcanic rocks, subdivided on the basis of their silica contents, with those documented by Taylor (1969), reveals very close similarities for all elements, with the exception of Mo and Sn; these are enriched, by an order of magnitude and two-three times, respectively, in some of the Andean rocks but cannot *a priori* be considered to reflect a sialic crustal inheritance.

All plutonic and volcanic rocks from this transect display well-defined, coherent, trends on total alkalis *vs.* silica and potash *vs.* silica plots. Alkaline rocks are not known to occur in any quantity in this region, but Pliocene volcanics in the Pocho area, near Córdoba (31°30′S), located to the south and east of the innermost known Andean volcanic centres in the immediate transect, are markedly alkalic (J.C. Caelles).

(f) Volcanic and plutonic rocks from individual age subprovinces (see below) exhibit gross chemical similarities, suggestive of a comagmatic origin.

(g) Rocks of a particular silica-content range show few significant compositional trends from west to east across the orogen at these latitudes. Calculation of the potash-indices of volcanic, subvolcanic, and plutonic rocks, however, reveals a marked eastward increase. Thus, the ratio $\frac{K_2O \times 1000}{SiO_2 - 45}$ increases from a mean value of *ca.* 100 for volcanics and plutonics exposed in the Cordillera de la Costa (100 to 175 km from the present Perú-Chile trench) to *ca.* 300 for rocks in the Farallón Negro strato-volcanic complex, which lies 500 km from the trench. This essentially linear increase across the traverse may be extrapolated to the alkalic (potassic) Pocho volcanic field to the southeast, strongly implying the existence of a unifying, fundamental, control across a *ca.* 400 km stretch of the continental margin, and extending as far as 700 km from the trench.

Application of the empirical "K/h" relationship refined by Dickinson and Hatherton (1967) and Dickinson (1970) for young andesitic and associated volcanic rocks of the circum-Pacific orogenic belts, delimits inferred sites of magma generation for these rocks which overlap, in all cases, with the *present* Benioff seismic zone (Kausel and Lomnitz, 1968; Swift and Carr, 1973), at depths from *ca.* 50 to over 300 km.

This relationship is sufficiently systematic to permit the recognition of a second-order disturbance in the correlation of potash index with distance from the trench. Following the Eocene-Lower Oligocene magmatic activity (see below), there was a distinct, though minor decrease in the potash index (from *ca.* 170 to 90), which is tentatively interpreted as the result of a slight, but significant, shallowing of the site of magma generation in the early Neogene (Zentilli, 1974).

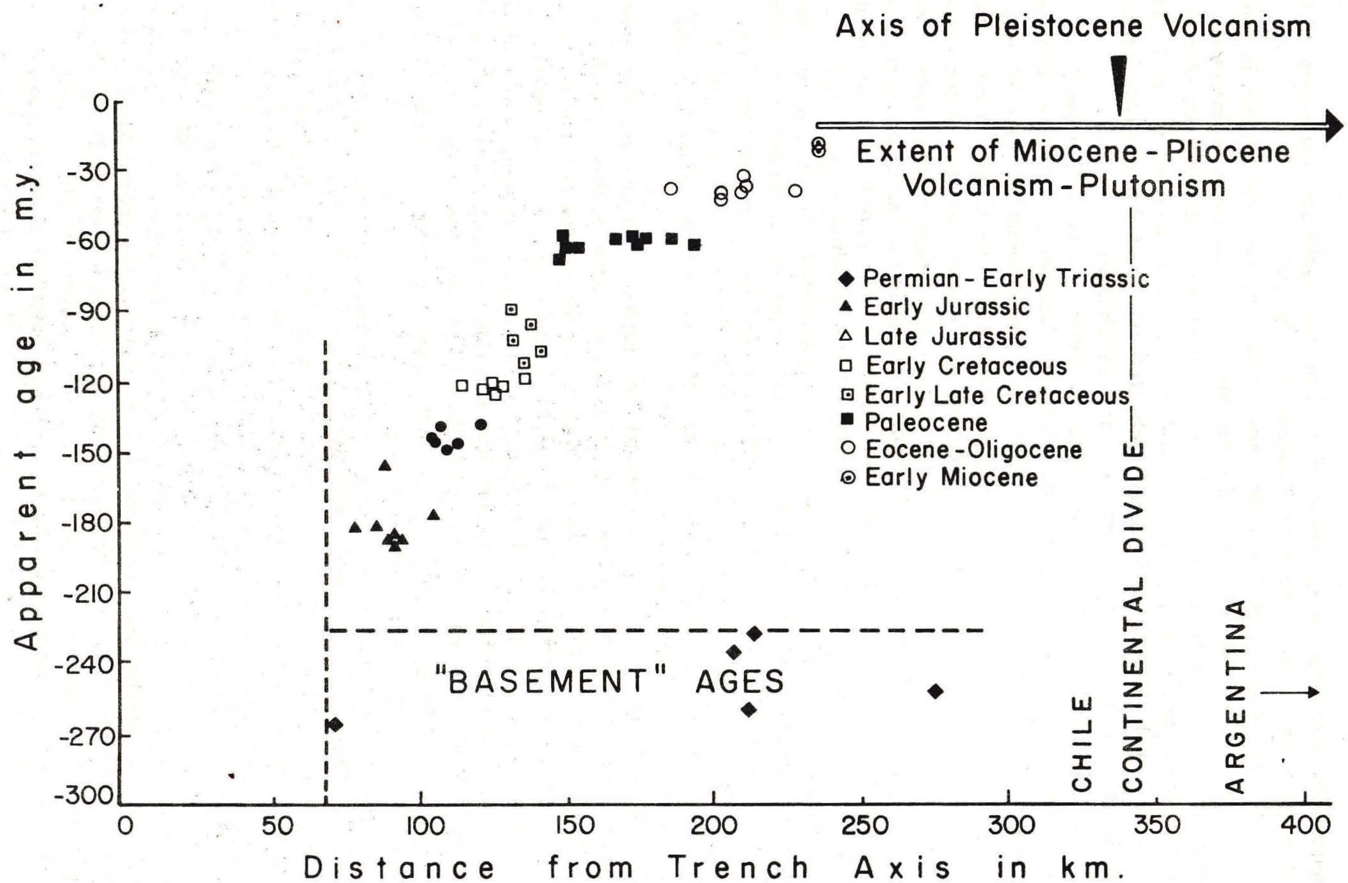
(h) The majority of the minor elements show no systematic trends in concentration from west to east. Thus, Cu, Zn, Pb, Mo, Ti, and Sn occur in essentially similar amounts in volcanic rocks of similar silica content across the transect (Zentilli, 1974 and J.C. Caelles, in prep.) There is also no transverse decrease in the K/Rb ratio coincident with the increase in potash index (*cf.* Jakeš and White, 1970). Yttrium and U, however, exhibit marked, continent-ward, enrichments.

(i) Systematic K-Ar mineral dating of plutonic rocks, and mineral and whole-rock dating of volcanics (Quirt and McBride), has permitted the elaboration of a rigorous chronology of magmatic activity across the transect. Of the 250 ages so far completed, only those for the Mesozoic volcanic rocks are clearly in error, owing to the effects of burial and contact metamorphism. The great majority of the radiometric dates are in strict conformity with the known stratigraphic relation-ships (Zentilli), while the effects of episodic tectonic uplift can largely be discounted, particularly for the Caenozoic record, where the uplift history of the cordillera is well-established (Mortimer, 1973). Detailed documentation of this geochronological study, the most comprehensive yet made in the Andes, is in preparation, but it may be noted here that the doubts as to the validity of the K-Ar data (as presented in a preliminary form by Farrar *et al.* (1970)) recently expressed by several authors (e.g. James, 1971; Stewart *et al.*, 1974) are unfounded. A detailed local study of this nature provides numerous internal checks on the significance of individual dates unavailable to broader regional investigations.

The radiometric data define a remarkably regular continent-ward displacement of plutonic foci during the evolution of the Andean orogen at these latitudes, initiated by the emplacement of Lower Jurassic plutons in the present immediate coastal area. Projection of the ages found for the plutonic rocks onto an east-southeast traverse perpendicular to the present Perú-Chile trench yields a smooth curve indicating a uniform, monotonic migration of intrusion at a rate increasing from *ca.* 0.6 mm/yr in the early Mesozoic to *ca.* 1.10 mm/yr in the mid-Tertiary. Volcanism closely shadowed the plutonic activity, although the earliest submarine eruptions were of somewhat wider areal extent than the coeval plutons.

Episodes of magmatic activity of early to middle Jurassic (191-176 m.y.), late Jurassic (156-137 m.y.), early Cretaceous (128-117 m.y.), mid- to late Cretaceous (107-87 m.y.), Paleocene (67-59 m.y.), late Eocene to early Oligocene (44-34 m.y.), and Oligocene-Miocene (23-22 m.y.) ages may be defined on this basis. The products of each volcano-plutonic episode were largely restricted to narrow (maximum 40 km wide), areally discrete, longitudinal belts. This long-persistent, ordered pattern of magmatic activity is, as far as is known, unparalleled elsewhere; the general inward migration of plutonism in Peru, lucidly described by Stewart *et al.* (1974) is, for instance, considerably less systematic. It is evident that the coastal Mesozoic batholith at these latitudes—part of the great Andean batholith—was built up through the accretion of a succession of laminar, dyke-like, clusters of plutons, and that major central intrusive complexes of the type so well described from the coastal batholith of central Perú by Cobbing and Pitcher (1972b) are subordinate or absent.

(j) Integration of the geochronological data with the tectonic and stratigraphic relationships, summarized above, provides a model for the evolution of the Andean


Axis of Pleistocene Volcanism
Extent of Miocene - Pliocene
Volcanism - Plutonism
Permian - Early Triassic
Early Jurassic
Late Jurassic
Early Cretaceous
Early Late Cretaceous
Paleocene
Eocene - Oligocene
Early Miocene
"BASEMENT" AGES
CHILE
CONTINENTAL DIVIDE
ARGENTINA
Apparent age in m.y.
0
-30
-60
-90
-120
-150
-180
-210
-240
-270
-300
0
50
100
150
200
250
300
350
400
Distance from Trench Axis in km.

supracrustal zone, in which successively younger volcano-plutonic complexes were emplaced from west to east, with concomitant updoming and deformation of their immediate envelopes, and the development of marginal, short-lived sedimentary basins.

(k) This ordered migration of magmatism was, as far as is known, interrupted only once in the 200 m.y. history of the orogen. In the Miocene (*ca.* 11 m.y.), following a mid-Tertiary period in which a marked slowing down of the eastward displacement resulted in a local overlapping of volcano-plutonic centres of different ages, there occurred an abrupt extension of magmatic activity deep into the continent. At these latitudes, isolated strato-volcanoes erupted through the Paleozoic basement at distances of up to 250 km to the east of the former inner boundary of the orogen, giving rise to a belt of dispersed igneous activity many times broader than those formed earlier. The inward "breakout" is also considered to have generated the alkalic volcanism in the Córdoba region, noted above, and, further north, led to the formation of the wide constructional Puna plateau.

In the Sierras Pampeanas, the Farallón Negro and Sierra de Famatina volcanic centres formed at this time. Ten K-Ar ages from the former (Caelles *et al.*, 1971; McBride, 1972) delimit a history of strato-volcanic growth spanning the interval from 11 to 6.8 m.y. B.P. The smaller Famatina complex erupted between 6 and 5 m.y. B.P., simultaneous with the later stages in the development of the large-scale basin and range topography which dominates the Sierras Pampeanas, where horst mountains rise to over 6000 m. This episode of normal faulting represents the easternmost expression of Andean tectonic activity at these latitudes.

By the Upper Pliocene (*ca.* 3 m.y.), an equally rapid contraction of volcanism was underway, leading to the construction of the great dacitic-andesitic strato-volcanic complexes which constitute the present Alta Cordillera along the international frontier. These were initiated in the Pliocene (Mortimer, 1973), and culminated in the early Pleistocene; only fumarolic activity persists in this transect. The main axis of this most recent phase of Andean magmatism lies at a distance from the Perú-Chile trench which conforms to the plot of age *vs.* distance from the trench for the older igneous centres.

The Mio-Pliocene "breakout", therefore, is seen as an ephemeral episode in an otherwise rigorously ordered migration of magmatic activity. We would predict that the next phase of volcanism will affect areas *ca.* 25-50 km to the east of the present cordilleran divide.

The systematic eastward increase in potash index noted earlier is maintained throughout this episode; thus, the late Pliocene-Quaternary volcanoes of the Alta Cordillera are markedly less potassic than those in the Farallón Negro and Famatina centres.

(l) Determination of the initial strontium isotope ratios for thirty Andean volcanic and plutonic rocks, embracing the entire age range of magmatic events in this orogeny, provides additional data for the characterization of these rocks (McNutt *et al.*, 1973), although interpretation remains ambiguous. Only three values for basement rocks in

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Figure 2. Age relationships of plutonic, granitoid, rocks in western part of Southern Transect, from K/Ar mineral ages by G.S. Quirt (1972). Apparent ages are projected onto a traverse perpendicular to the present Perú-Chile trench (modified from Quirt (1972) and Zentilli (1974)).

this immediate transect are available, and extrapolation from other areas of the Paleozoic terrain is probably unwarranted. The Andean igneous rocks display a relatively restricted over-all range of initial ratio, from 0.7022 to 0.7077 ($\pm$0.0003). The earliest, Jurassic, plutons exhibit irregularly variable ratios (0.742 – 0.7059), but, from the mid-Cretaceous onwards, there has been a systematic, age-dependent, increase in initial ratio, from *ca.* 0.7022 to 0.7077 (Quaternary volcanics). This trend, with a correlation coefficient of 0.87, is followed by volcanic, hypabyssal, and plutonic rocks, with compositions ranging from high-alumina basalt, or quartz diorite, to rhyolite. There is no correlation between initial strontium isotope ratios and the Rb or Sr contents, or Rb/Sr ratios.

These data, and especially the extremely low ratios of several of the Cretaceous plutonic rocks, strongly imply that, although all the Andean magmas must have passed through considerable thicknesses of sialic crust, they have a subcrustal origin and experienced little crustal contamination. The time-dependent increase in initial ratio since the Cretaceous is tentatively inferred to reflect a progressive change in the source materials, degree, and phase equilibrium relationships, of partial melting, and, particularly, a gradual increase in the contribution of a material rich in Sr^{87}.

(m) The long history of intensive mineral exploration and production on the arid Chilean flank of the Andes at these latitudes, centred on the old town of Copiapó, provides an excellent basis for the assessment of the ditribution and magnitude of metallic ore deposits. Only in the higher mountains (above 4000 m) has exploration been on a modest scale, owing to the remoteness and severe climate. In contrast, the mining tradition has been less strong in adjacent Argentina, but several large camps, including the Capillitas Cu-Pb-Zn-Au-Ag-Mn mine, and the Famatina Au-Cu district, have been successfully developed in the past. As noted, previously, there has been a moderate recovery of Be, Li, Sn, and W from pre-Andean ores.

The distribution of mineral deposits in this transect, therefore is probably known as well as in any other region of the Central Andes (Ruiz *et al.*, 1965; Angelelli, 1950), although there is scope for discovery of important mineralization centres, as witnessed by the confirmation of several porphyry Cu-Mo deposits in the Farallón Negro volcanic complex (Angelelli, 1970).

The great majority of endogenous Andean deposits in the area are vein, breccia pipe, stockwork and contact metasomatic ores of the class grouped as "cordilleran" by Sawkins (1972), and exhibit numerous common features. The most productive deposits at the present time are the El Salvador porphyry Cu-Mo (92,420 tons Cu; *ca.* 900 tons Mo, 1973), and several magnetite bodies which yield approx. 5.3 m.t. of 63 per cent Fe ore annually (production to be considerably expanded). In addition, a large number of small- and medium-sized mines produce between 20,000 and 30,000 tons of Cu. No deposits are now worked specifically for Au or Ag, once the major products of the region, but the precious metals are recovered in considerable amounts as by-products of Cu mining. The great 19th century Ag camps lie abandoned, although plans are underway to redevelop Chañarcillo, the richest of these.

In addition to the above metals, modest amounts of Co, Hg, W, Pb, Zn, and Mn have been produced in the past from generally small vein deposits, while several Neogene volcanoes in the high Cordillera have been worked for native sulphur.

There is little present mining activity from Andean deposits (see below) in Catamarca and La Rioja Provinces of Argentina. The once important Cu camp of

Capillitas is reduced to a source of gem-quality rhodochrosite. Intensive exploration is underway, however, on the Mn-Au-Ag and porphyry Cu-Mo deposits within and peripheral to the Farallón Negro centre.

(n) The magmatic-hydrothermal deposits of this transect exhibit a restricted distribution close to the volcano-plutonic interface. The subvolcanic setting of the El Salvador (Swayne and Trask, 1960; Gustafson and Hunt, 1971) and Potrerillos (March, 1935) porphyry Cu deposits is well-established, as is that of the smaller porphyry centres in the Farallón Negro (Caelles *et al.*, 1971; Llambias, 1972; Sillitoe, 1973) and Famatina (Plan La Rioja, 1973) volcanic complexes. Similarly, the great majority of the bonanza Ag deposits occur within volcanic centres or in the upper zones of epizonal plutons, although the Chañarcillo veins have an ambiguous setting (Segerstrom, 1962). Whereas the high Andes have been generally discounted as an exploration target for metallic mineralization (*e.g.* by Ruiz and Ericksen, 1962), we are in agreement with Sillitoe (1974) that the Neogene and Quaternary strato-volcanic complexes of the region may overlie or enclose porphyry-type mineralization, a conclusion supported by the numerous mineralized alteration zones known in the vicinity of the Chile-Argentina frontier at these latitudes (Plan N.O.A. 1, 1972). The lack of important mineral deposits in the immediate coastal area (up to *ca.* 30 km inland) appears, however, to reflect a significant diminution in the intensity of late-magmatic acitivity in the oldest Andean plutons, of Lower Jurassic age.

In addition to this epigenetic mineralization, associated strictly with volcano-plutonic centres, several important Cu and Cu-Ag deposits in the Copiapó area have apparently been emplaced in volcanic flows at variable distances from their sites of eruption. These disseminated, stratabound, deposits include several in submarine andesitic lavas of Mesozoic age (*cf.* Ruiz *et al.*, 1971), and at least three in Paleocene continental rhyolites, both lavas and ash-flow tuffs. Detailed studies by R.B. Lortie of the latter group demonstrate that sulphide deposition took place through the agency of fumarolic activity, probably representing recirculated meteoric waters, during the cooling histories of the host flows (Lortie and Clark, 1974).

Mineralization throughout this transect appears to have been a very shallow phenomenon, and it is clear that some of the more superficial deposits may have been eroded from the older volcano-plutonic complexes, particularly in the Cordillera de la Costa. This inhibits reliable assessment of the relative intensities of the hydrothermal processes in the different sectors of the orogen, but does not wholly disguise the over-all pattern of metal distribution. A model such as that recently advanced for the Ecuadorian Andes by Goossens (1972), in which metal zonation is held to reflect varying depths of erosion of a layer-cake stratigraphic succession, is unacceptable in this region.

(o) K-Ar dating of hydrothermal alteration minerals associated with numerous ore deposits in this transect (Quirt and McBride) confirms that ore deposition was sensibly coincident in time (i.e., within *ca.* 1-2 m.y.) with local igneous activity throughout the development of the orogen. Thus, ore-forming processes migrated coherently with the volcanism and plutonism across the transect, thereby delimiting a series of "metallogenetic sub-provinces", each of which evolved within a definite "metallogenetic sub-epoch", and overlaps geographically with the parent magmatic sub-province. There is no evidence of the occurrence of mineralization at distances of greater than a few km from igneous bodies of similar age.

This unified time-space geometry of igneous and post-magmatic hydrothermal activity, extending over some 200 m.y., strongly implies a genetic relationship between the two, but does not in itself demonstrate their consanguineous origin.

(p) Estimation by M. Zentilli of past production and of known and probable reserves of several key metals in this transect reveals several points of interest (Fig. 3). Lack of information on the 19th century production of Ag, Au, and the base metals, introduces considerable uncertainty, as does the very preliminary development of the porphyry centres in Catamarca and La Rioja Provinces. Further, the influence of erosion and supergene enrichment processes on the metal contents of the deposits is difficult to assess. It has been assumed that the amounts of base and precious metals concentrated in enrichment zones are a broad reflection of their previous occurrence in the overlying, now eroded, portions of the deposits. Further, since the great majority of the important Mesozoic-Caenozoic deposits, with the exception of the magnetite bodies, have suffered generally similar degrees of enrichment (Sillitoe, 1969), it is tentatively assumed that this factor has not caused great distortions in the metal production picture.

In any event, it is clear that Cu is a major constituent of the great majority of Andean ore deposits of all ages, from the mid-Jurassic to late Tertiary. Considerable Cu has been recovered from the Paleocene and earlier sub-provinces, but, even if allowance is made for differences in erosive uncovering, it appears that the Upper Eocene-Lower Oligocene sub-province, which includes the El Salvador and Potrerillos porphyry coppers, as well as several undeveloped deposits of the same type, was markedly enriched in this metal. Similarly, despite the relatively minor production so far, the large number of porphyry Cu deposits in the Neogene Farallón Negro and Famatina volcanic centres suggests that the *average intensity* of Cu mineralization may there exceed that in the 44-34 m.y. sub-province. On this basis, it is tentatively concluded that Cu was the predominant metal concentrated in all episodes of the Andean orogeny at these latitudes, and that the intensity of Cu mineralization may have increased with time—generally, that is, from west to east.

The dominance of Cu was broken at only two periods in the development of the orogen: (i) in the early to mid-Cretaceous, when the major contact metasomatic Fe deposits formed adjacent to the Cretaceous plutons (Ruiz *et al.*, 1965); and (ii) in the latest Cretaceous and Paleocene-Eocene, when the rich Ag deposits were emplaced. The period of major Fe mineralization appears to represent a well-defined, and short-lived (*ca.* 130-100 m.y.) episode, which occurred towards the close of the intrusion

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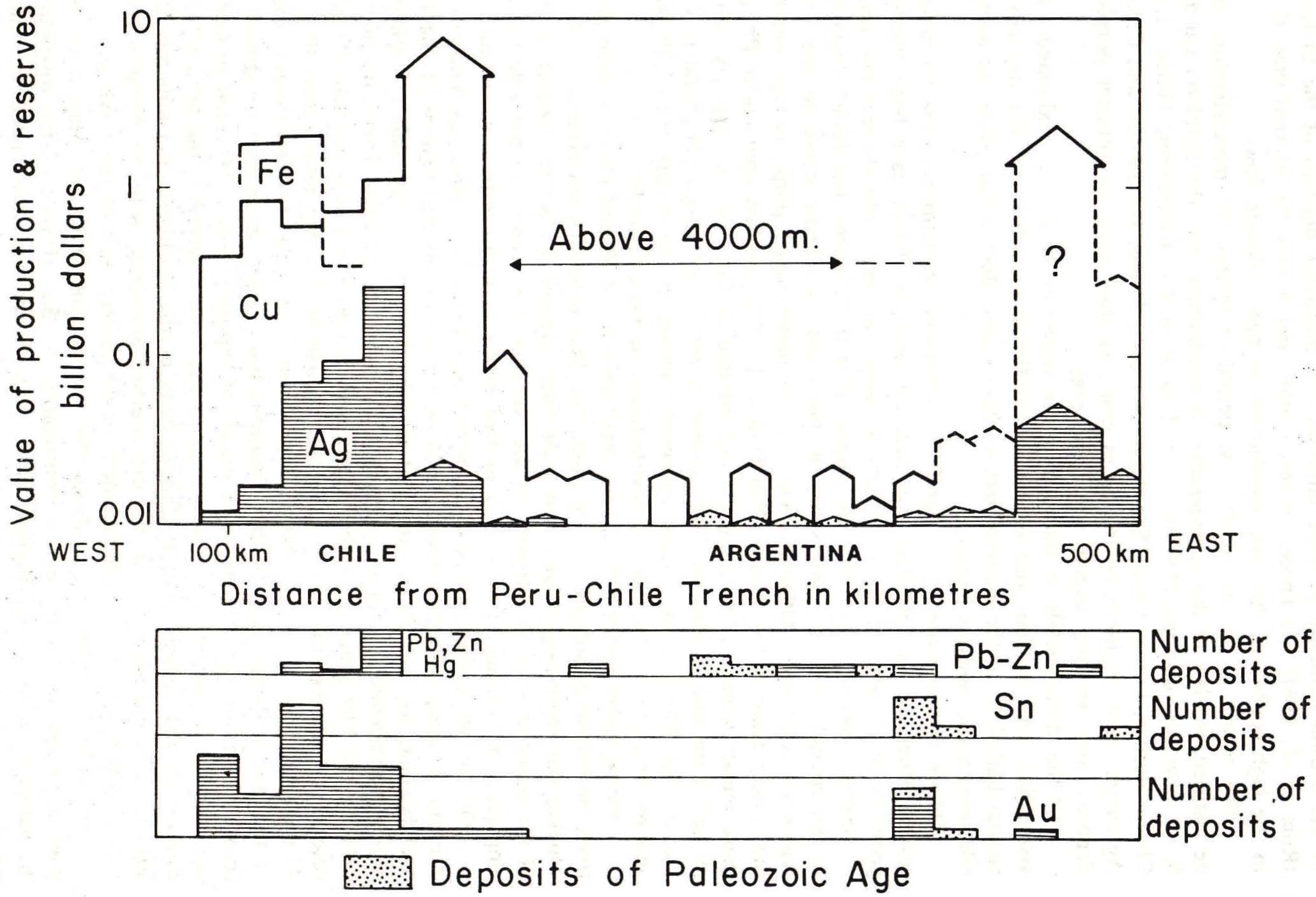
Figure 3. Synoptic chart showing the variation of estimated value of mineral production plus reserves, or number of deposits, for several metals in the Southern Transect, with increasing distance from the Perú-Chile Trench. For the upper part of the diagram, total recorded production, plus estimated reserves, have been recalculated into dollar value of metal (1972 prices). Arbitrarily, the smallest deposits considered have been ascribed minimum tonnages of 10^4 tonnes for Cu metal, 2×10^6 tonnes of 60% Fe ore, and 500 tonnes of Ag. The lower part of the diagram shows the number of deposits within 20 km-wide longitudinal belts, parallel to the Perú-Chile Trench. This diagram suggests that the greatest proportion of Fe, Cu, Ag, Au and Hg deposits lie in the western third of the Andean metallogenetic province. All of the Sn, and many of the Pb-Zn deposits in the east are of pre-Mesozoic age (dotted) and therefore not genetically related to Mesozoic-Cenozoic (Andean) tectogenesis (modified from Zentilli, 1974).


10
1
0.1
0.01
Value of production & reserves
billion dollars
Fe
Cu
Ag
Above 4000m.
?
WEST
100km
CHILE
ARGENTINA
500km
EAST
Distance from Peru-Chile Trench in kilometres
Pb,Zn
Hg
Pb-Zn
Number of deposits
Sn
Number of deposits
Au
Number of deposits
Deposits of Paleozoic Age

of the coastal batholith at these latitudes. No magnetite deposits of the El Laco type (Ruiz *et al.*, 1965) are known in this region, and it may be inferred that, if present in the high cordillera, they are mantled by younger volcanic flows.

The reality of the *ca.* 80-55 m.y. period of intense Ag mineralization needs to be justified, in view of the considerable Ag production from the porphyry Cu deposits. It is, however, demonstrable that the Tres Puntas – Chimberos, Garín, Ladrillos, Checo, Bordos, Lomas Bayas, San Antonio, Pampa Larga, Bandurrias, and Chañarcillo Ag camps have produced several times more Ag than have the younger porphyry Cu deposits, also working largely supergene ores.

Of the minor metals produced from this region in the past, Co exhibited a marked association with Ag, but also occurs in significant quantities in older deposits in the coastal batholith, in the western part of the orogen. Both metals show an affinity for relatively mafic igneous bodies.

There is less evidence of significant transverse variations in the abundances of several other metals, including Au, Mn, Pb, and Zn. These have been produced in generally minor amounts from primary deposits scattered across the transect. Important Au mines, however, have been developed from the Ojancos and Jesús María districts in the coastal batholith, only some 40 km from the Pacific coast, to the Famatina region of Argentina. Although many of the undeveloped porphyry-type deposits on the eastern flank of the Andes (Plan D.O.A. 1, 1972) contain appreciable Pb and Zn, these metals appear to be generally subordinate to Cu, and, in porphyry centres of all ages here and in adjacent Chile, display a zonal distribution peripheral to Cu and, locally, Au. Thus, no significant eastward increase in the occurrence of Pb and Zn, and no decrease in Au, can be demonstrated at these latitudes.

Among other minor metals, very small amounts of W and Hg have been produced from the Paleocene sub-province in Chile, but there is insufficient evidence to determine whether this represents a significant local concentration. There are however, no records of the occurrence of W minerals in the Neogene ore deposits in the volcanic centres emplaced in basement terrain rich in that metal in northwestern Argentina.

Of the two metals, Mo and Sn, which are present in anomalous amounts in the Andean volcanic roks (see above), little is known of the distribution of the former. Molybdenum has only been produced as a by-product of large-scale Cu mining, but minor molybdenite is evident in many Cu deposits of all ages. There are no reliable data on the Mo contents of the Argentinian porphyry deposits, so that it cannot be determined whether there is a significant change in Cu: Mo ratio across the orogen. At these latitudes, Sn mineralization at *any* scale is restricted to the Paleozoic basement of the Sierras Pampeanas. Neither cassiterite nor stannite have been recognized in the course of very extensive microscopic studies of hypogene ores of Mesozoic or Caenozoic age, and the former mineral has not apparently been detected in the once extensively-worked alluvial deposits on the Chilean flank of the cordillera. Tin minerals are also absent, or exceedingly rare, in the ore deposits associated with the Neogene volcanic centres which cut the Sn-rich basement in the eastern part of the traverse.

(q) The overwhelming evidence that ore-forming fluids are saline aqueous solutions prompted a reconnaissance investigation by S.J. Haynes of the distribution of the halogens, chlorine and fluorine, in the plutonic rocks and associated post-magmatic ore deposits of the transect, employing electron microprobe and ion-specific electrode (Haynes and Clark, 1972a) analytical techniques. It was hoped that this study, the first investigation of the evolution of halogen abundances in igneous rocks emplaced at different stages in the development of an orogenic belt, would yield evidence relating mineralization intensity variations to host-rock compositions. It was, however, found that there was no systematic change in the Cl and F contents of plutonic rocks from the Lower Jurassic to the Lower Miocene, unless any such original trends have been obliterated through post-magmatic events (Haynes and Clark, 1972b). Further, it is evident that these generally strongly-mineralized plutons do not exhibit unusually high or low halogen contents; they are only marginally enriched relative to average granitoid rocks. No relationship exists between halogen contents and the intensity of base metal mineralization, although the Cretaceous plutons associated with the contact metasomatic magnetite deposits are enriched in Cl, apparently reflecting an isolated episode of halogen-rich magmatism.

Hydrothermal biotites from the Fe deposits are markedly enriched in both Cl and F, while those from porphyry Cu centres in this transect, and elsewhere in northern Chile are strongly enriched in F but not in Cl, suggesting that the former was present in considerable abundance in the early, post-magmatic fluids.

(r) Few determinations of stable isotope distributions have been presented for ore deposits in this transect. Hypogene pyrite, chalcopyrite, and anhydrite from the El Salvador deposit, however, exhibit sulphur isotope ratios suggestive of high temperature fractionation of an initial composition close to that of meteoritic sulphur (Jensen, 1971), perhaps lending support to the ultimate derivation of that element from a deep-seated source unaffected by interaction with sea water sulphate or with meteoric water (*cf.* Field, 1973; Rye and Sawkins, 1974).

Interpretation of the Geological and Metallogenetic Evolution of the Southern Transect

The strikingly systematic time-space geometry of magmatic and hydrothermal activity across this Andean transect, and the equally uncomplicated tectonic history of the region, provide unusually firm restraints on the metallogenetic relationships, without, however, unambiguously determining the source regions and materials of the ore-forming components or the controls on their shallow crustal distribution. The persistant temporal and spatial association of igneous bodies and ore deposits throughout the 200 m.y. evolution of the orogen at these latitudes is strong *prima facie* evidence for a genetic relationship, and encourages the development of a regional model for metallogeny.

The age relationships of the epizonal intrusions and volcanic piles, and their chemical and isotopic characteristics, are interpreted as indicating an origin in a sub-crustal environment, and the minimal roles of crustal anatexis or contamination. Our conclusions are strongly at variance with those of several other workers in northern Chile, particularly Pichler and Zeil (1969, 1972), who have repeatedly argued that the andesitic and rhyolitic rocks of the northern Chilean Andes were derived through fusion of, respectively, the deep and shallow crust. We will elaborate elsewhere our objections to the hypotheses put forward by these authors, and will here merely state that our data may be most parsimoniously interpreted as indicating that the great bulk of the coeval volcanic and plutonic rocks in this transect had a common origin and source region.

Our model for magma generation is similar to that proposed, e.g., by Jakeš and White (1970), for the origin of the tholeiitic, calc-alkaline, and shoshonitic suites of the Pacific island-arcs. Partial melting is considered to have occurred within the upper, crustal, layers of a subducted slab of oceanic slab of oceanic lithosphere, or, possibly, in the mantle immediately overlying the downgoing plate. The orderly migration of magmatic activity, and the systematic eastward enrichment in potash, suggest that the partial melts were generated at progressively greater depths along, or close to, the upper surface of a slab of eastern Pacific oceanic lithosphere which has been subducted beneath the western margin of the continent in an essentially consistent orientation since the Upper Triassic. Magma generation attendant on the underthrusting of the cool plate had been initiated by the lowermost Jurassic, at depths perhaps as shallow at 50 km, beneath the present coastal zone. Successive pulses of calc-alkaline magmatism, the narrow, longitudinal, shallow crustal expression of which is taken to reflect the vertical projection of two planes—the surface of the downgoing slab and the isothermal interval over which appreciable partial melting occurred—were subsequently generated down to depths as great as 200-300 km in this transect, and penetrated the crust to at least 600 km inland. The magmas rose diapirically without significant interaction with the Paleozoic sialic crust. Despite the large total volume of magma which has so far been emplaced in the shallow crustal zone, its production as areally restricted, comparatively small, aliquots caused only local heating of the crust at any depth, and probably no considerable melting of the latter took place. Certainly, the chemical and isotopic similarity of the plutonic and volcanic rocks discourages acceptance of a model for batholith development such as that persuasively argued by Presnall and Bateman (1973) for the Sierra Nevada batholith. The intrusive and volcanic components of the different magmatic pulses in this transect are regarded as basically consanguineous.

The eastward increase in potash index and initial strontium isotope ratio of the Andean magmas cannot be explained until more is known of the mechanism of magma generation at convergent plate margins, still a highly controversial topic (e.g., Wyllie, 1973). The potassicity increase is, however, accepted as reflecting a depth- (and pressure-) dependant partitioning of this alkali during partial melting, as proposed by Dickinson and Hatherton (1967). The remarkable correspondance of our data, for rocks ranging in age from *ca.* 160 to <1 m.y., with those presented for "Quaternary" andesitic suites from many sectors of the circum-Pacific mobile belts, is strong evidence for the validity of the empirical correlation between K_2O-index and depth of magma formation (*cf.* Neilson and Stoiber, 1973). In this transect, the potash index is clearly independent of the thickness or composition of the sialic crust.

The more complex trends exhibited by the initial strontium isotope ratios are also difficult to interpret at present. We regard the gradual increase in the ratio with decreasing age for Cretaceous and younger rocks, as probably the result of a progressive mixing of two distinct source materials; one with a low ratio (*ca.* 0.7020-0.7030), the second enriched in radiogenic strontium (possibly, *ca.* 0.7100). The former may have been unaltered oceanic basalt, but the nature of the latter is unclear—the attainment of ratios in the younger volcanic sub-provinces similar to that of pelagic sediments (0.709) renders these an improbable source. Further, the sedimentary veneer on the downgoing plate would be expected to be melted before the underlying basalts. It may, therefore, have been a factor in the development of the relatively high initial ratios shown by some of the coastal Jurassic plutons, inferred to have been derived from shallow depths. Another possible candidate for the Sr^{87}-enriched material is the altered periodotite underlying the basaltic layer, which would perhaps be tapped in progressively greater proportions as the volume of rock affected by the partial melting increased with increasing pressure. Sialic crust is, however, considered to have played at the most a very minor role, in view of the very low ratios shown by the Cretaceous plutonic rocks, and the absence of any correlation between initial Sr^{87}/Sr^{86} ratio and the Rb/Sr ratio of the Andean magmas.

The slow depression of the zone of magma generation, at a probable down-dip rate of less than 0.8-1.3 mm/yr., suggests that only a proportion of the uppermost layers of the subducted lithosphere was affected by the partial melting, since a minimum mean rate of plate consumption of *ca.* 1.0 cm/yr can safely be assumed for the Mesozoic and Caenozoic. As a corollary, it may be inferred that the subducted crust underwent only periodic single-stage melting.

Two, possibly inter-related, mechanisms may be proposed to account for the ordered depression of the zone of melting over this extended period: (a) a gradual increase in the rate of plate convergence, from the Upper Triassic to the present; and (b) the progressive cooling of the mantle overlying the downgoing plate merely as a result of the consistently lower temperature of the latter. There is considerable evidence that the rate of convergence did indeed increase, from *ca.* 1 cm/yr in the Jurassic to as much as 11 cm/yr in the Mio-Pliocene. The latter hypothesis would imply that even fairly large changes in the rate of subduction had no drastic effect on the temperature distribution in the vicinity of the upper surface of the slab, if they occurred gradually.

The short-lived Neogene break-out episode, although constituting a disturbance of the ordered pattern of melting, perhaps provides evidence of the validity of the above models. This eastward extension of the zone of epizonal magmatism is inferred to reflect a comparable downward penetration of the zone of partial melting along the upper surface of the slab. The systematic variations in potash-index imply that the site of magma generation was retained along essentially the same plane that had thus far controlled melting, although the mid-Tertiary decrease in K_2O/SiO_2 ratio probably reflects a second-order decrease in the angle of dip of the slab at the outset of this episode of rapid downward expansion of the zone of melting (N.B. This change in dip is presumably much less than those postulated by, e.g., Mitchell (1973)).

The most probable cause for such an effect, which may be considered as "catastrophic" within the previously regular evolution of the thermal regime beneath the continental margin, would be an abrupt and perhaps considerable increase in the rate of plate consumption. Herron (1972) has demonstrated that, at *ca.* 15-9 m.y.ago, accretion of the east Pacific oceanic plates was occurring at both the East Pacific Rise and the Galapagos Rise, perhaps resulting in unusually high rates of convergence at the continental margin. Subsequently, since *ca.* 9 m.y.ago, spreading has been restricted to the East Pacific Rise, and thus there was perhaps a significant decrease in convergence rate in the Upper Miocene and Pliocene. These two postulated marked changes in convergences rate coincided approximately with the initiation and termination of the Neogene break-out episode, if allowance is made for a *ca.* 4 m.y. delay between the onset of increased consumption rate and the arrival of the resulting magmas at the surface.

In summary, we conclude that the observed geological and geochemical regularities in the evolution of this transect of the Andean orogen are strong evidence for a still-continuing and generally uniform history of plate consumption since the late Triassic. The extremely systematic time-space geometry of magmatic activity in this region is, we suggest, evidence for an *essentially* consistent position and configuration of the subducted oceanic plate over a 200 m.y. period. A similar conclusion has been reached by James (1971a), without, however, presenting supporting geological and petrochemical evidence. Markedly less regular spatial and chemical relationships would, intuitively, be expected if: (i) the subducted plate (and trench) were displaced bodily towards the continent; (ii) the dip of the plate changed significantly; (iii) reversal(s) of dip occurred; or (iv) the site of magma generation was displaced a considerable distance from the hanging-wall and upper zone of the subducted plate.

In view of the continuing controversy concerning the inter-relationships of igneous rocks and post-magmatic ore deposits (Holland, 1972; Sheppard *et al.,* 1969), it is not surprising that integration of the geological and metallogenetic histories of this (or any) region remains difficult, despite the spatial and temporal congruence of magmatic and hydrothermal activities. Ore deposits in the southern transect have not received the detailed attention afforded several in Perú, and the absence of data on the distributions of oxygen and hydrogen isotopes prevents serious discussion of the roles played by juvenile-magmatic, and meteoric waters in the formation of the ores. In addition, within the main axial portion of the province, the country rocks of the majority of the volcano-plutonic centres are volcanic and sedimentary rocks of similar age and chemistry; there is thus inadequate contrast with the environment to resolve the problem of the source of the metals concentrated in the deposits. The striking similarities between these deposits and those of Neogene age emplaced into the Paleozoic plutonic and metamorphic basement in the Sierras Pampeanas, a geochemically and metallogenetically contrasted environment, however, strongly argue for a magmatic origin for the bulk of the base and precious metals in the Andean ores. It is interesting to note that similar conclusions have been reached in the few published studies of Andean ore deposits involving stable isotope determinations (Rye and Sawkins, 1974; Landis, 1972). This does not imply that meteoric water systems of the type advocated by Taylor (e.g. 1973) were not generated in the vicinity of the apical zones of the areally restricted epizonal plutons and volcanic edifices in this region, but that they were primarily engaged in leaching metals from the cooling igneous bodies rather than from their host-rocks, or developed *after circulation* of juvenile, ore-forming, waters.

Further correlation of the constituents of the ore deposits with the magmatic systems is presently impracticable. Whereas some metals, particularly Ag and Co, display a statistical association with igneous rocks of restricted composition, the majority of the metals, including Cu, exhibit no such preference. It may be argued that, with the exception of the Lower Jurassic plutons and the youngest volcanoes, essentially all exposed Andean igneous bodies at these latitudes are seen to be associated with significant Cu mineralization. This metal is, therefore, typomorphic of the entire span of Andean magmatic events, over a transverse distance of at least 400 km. The host-rocks are not, however, significantly enriched, or depleted, in Cu (see above), and it is clear that the total quantity of that metal introduced during the Andean orogeny into the shallow crust of the continental margin was not unusually great, either considered over-all or per unit volume of shallow crust. Further, the amount of Cu concentrated in the many ore deposits of this great "copper province" represents only a small fraction of that present in the igneous bodies.

The comparative scarcity of deposits of Pb and Zn, emplaced in similar abundances as was Cu into the orogen, cannot be readily explained, as Oyarzún (1973) has stressed. The local association of Pb minerals with Mesozoic carbonate rocks on the Chilean flank of the Andes constitutes only a minor effect in the general distribution of Pb deposits, which occur largely in association with Cu mineralization in granitoid plutons and volcanic centres. It may be concluded, therefore, that, despite a "normal" availability of these metals, post-magmatic conditions were only locally favourable for their concentration, whereas Cu, and perhaps Mo, were deposited "at the drop of a hat" throughout the province. At the extreme, it may be observed that fluids capable of transporting and depositing Sn in any significant quantity were apparently not evolved, despite the presence of appreciable fluorine in the granitoid rocks and the above-average abundance of this metal in the Andean igneous rocks.

Even in a region in which the over-all lithotectonic development is well-understood and strikingly ordered, therefore, consideration of the source of the ore-forming components devolves upon second-order processes and conditions in the immediate vicinity of the deposits. It might be suggested that the characteristic style of emplacement of the succession of small volcano-plutonic centres in this area led to the repeated development of a surficial environment favourable for the formation of intense hydrothermal mineralization, particularly of Cu. Perhaps the local updoming and basin development associated with the periodic igneous activity generated meteoric water "plumbing systems" of unusual efficacy in leaching metals from the igneous bodies. Of the metals which might be expected to have been leached from the igneous rocks (Holland, 1972), however, only copper, molybdenum, silver, and gold were deposited in abundance in the immediate vicinity of the cooling bodies. Lead, zinc, and tin, if present in significant concentrations in the solutions, were either deposited in superficial environments which were subject to rapid erosion, or, more probably, were dispersed into groundwater systems or escaped through fumarolic activity.

In this context, the halogen distribution data are difficult to interpret. Holland (1972) has elegantly demonstrated that the time of evolution of a post-magmatic fluid, and its $Cl:H_2O$ ratio, together exert a major control on the extraction of the base metals from a crystallizing granitoid melt, and that the volume of fluid generated is less important. It might be inferred that, across the southern transect, conditions were unusually favourable for the formation of highly saline, and strongly leaching, post-magmatic fluids. Some correlation with the residual chlorine contents of the host granitic bodies might, therefore, be expected. There is no such relationship, except in the case of the Cretaceous plutons which are, however, associated with magnetite deposits. The latter intrusions may represent a pulse of magma ununsually enriched in halogens, which caused extensive late- and post-magmatic leaching of Fe from the plutons and their andesitic host rocks.

In the light of these "surficial" problems, speculation as to the ultimate sources of the Cu and other metals now residing in the Andean orogen must be regarded as hazardous. *If* the ore-forming elements rose through the crust in the Andean magmas, the absence of any significant transverse changes in their abundances in the igneous rocks implies that they were partitioned ("distilled") into the melts to generally similar degrees at all stages in the evolution of the orogen. If crustal anatexis or contamination are discounted as quantitatively significant sources for the magmas and the metals, as suggested by the chemical and isotopic data referred to above, and if the model we propose for the generation of the magmas during plate subduction is valid, it may be concluded that the different base and precious metals were fractionated into the calc-alkaline magmas to similar degrees at depths ranging from *ca.* 50 km to more than 200 km. Thus, confining pressure is tentatively inferred not to have a major effect on the transfer of metals to partial melts in a subduction environment, in contradistinction to Sillitoe's (1972b) hypothesis. Further, in view of the absence of any clear relationship between the metal contents of the igneous rocks and the incidence of major ore deposits, it would seem premature to argue, as does Sillitoe (1972c), that the unusual development of, say, Cu deposits in the northern Chilean sector of the continental margin is the result of the subduction of oceanic lithosphere markedly enriched in that metal. Despite the recognition of the wide distribution of Cu-bearing metalliferous sediments on the Nazca Plate (Dymond *et al.*, 1973), it is considered that such enrichments *may* be irrevelant to the formation of endogenous ore deposits within the continental margin. All components of the subducted lithosphere probably normally have adequate metal contents, and these are probably sufficiently partitioned into the partial melts generated during subduction—these stages in the metal cycle are perhaps subordinate in importance to the surficial environments in which the magmas released their metals to the hydrothermal systems.

From a more practical standpoint, it must be re-emphasized here that the transverse, continent-ward, zonation of metals—from Fe, through Cu + Au and Pb + Zn + Ag, to Sn + Mo—which has been highlighted by Sillitoe (1972b) and several earlier workers in the Central Andes, does not occur in the intensely-mineralized Lat. 26° – 29°S transect. Thus, although the major Fe deposits do occur in the westerly part of the orogen, they are separated from the Pacific littoral by an area with few known Fe deposits, but numerous Cu, Au, and Co ore bodies. The most important Ag centres again lie in the western part of the province, immediately east of the Fe belt, and to the west of the greatest development of Cu deposits. Further, Pb, Zn, and Au deposits appear to have formed at essentially the same level of intensity throughout the cordillera. There is no clear evidence of an eastern Mo-rich sub-province, while Sn deposits of post-Paleozoic age are entirely absent. The critical importance of the distinction between Andean deposits, and those formed during the development of the Paleozoic basement, is therefore evident.

NORTHERN TRANSECT (14°30′ – 20°30′S)

Our studies in northermost Chile and Bolivia, along a traverse skirting the Peruvian frontier and approximately bisecting the Arica elbow, are at an early stage, and comprehensive data are lacking on the time-space incidence of igneous and hydrothermal activity, and, particularly, on the compositional trends of the igneous rocks. Geophysical studies in this region, however, (James, 1971b; Ocola *et al.*, 1971) have clarified the deep crustal structure of the continental margin, while the general geological relationships are well enough known to permit the recognition of several significant similarities and differences in the evolution of this Andean transect relative to that between Lat. 26° and 29°S.

Tarapacá Province of northern Chile has experienced only minor exploitation of endogenous ore deposits in comparison with the Copiapó area. In part, this reflects the enormous extent of Neogene ignimbrites on the western flank of the Andes, which may be presumed to have mantled numerous older volcano-plutonic complexes and the associated mineral deposits. Copper and other mineralization is, however, widespread in the outcropping Mesozoic and early Caenozoic terrain, and there is no evidence of markedly lower over-all mineralization intensity in this area.

The Arica elbow transect differs in one cardinal metallogenetic aspect from the southern transect—the presence along the entire length of the eastern cordillera of the Central Andean Sn-Ag belt (Turneaure, 1971), the greatest known concentration of primary Sn deposits. This belt borders the eastern margin of the *altiplano*, an extensive plateau underlain by considerable thicknesses (15 km) of Caenozoic continental sediments and volcanics, which again has no direct counterpart between Lat. 26° and 29°S.

The salient features of the geology and metallogeny of this complex region are summarized in the following paragraphs, largely from the work of previous geologists, and particularly that of Ruiz *et al.* (1965) and Salas *et al.* (1966) in Chile, and Ahlfeld and Branîsa (1960) and Ahlfeld and Schneider-Scherbina (1964) for Bolivia.

(a) The pre-Andean stratigraphic record in this transect is generally clearly established in the eastern cordillera of Bolivia, where thick sections of only weakly metamorphosed, Ordovician and younger Paleozoic sediments have been extensively studied. These successions define a long history of marine sedimentation in the early Paleozoic, with few significant disturbances, leading to littoral conditions in the late Paleozoic. The intracratonic and ensialic setting of this longitudinal belt has been stressed by Mégard *et al.* (1971), who consider it to have been a long-persistent locus of downwarping and sedimentation between the Brazilian Shield, to the east, and the Precambrian Arequipa Massif, partially preserved along the present Pacific margin of the continent.

Mégard *et al.* (1971) and Martínez *et al.* (1972) recognized two major Paleozoic orogenic episodes in this basement: an "early-Hercynian" event, bracketed in the Upper Devonian-Lower Carboniferous interval; and a "late-Hercynian" event, of probable Middle Permian age. The local, lower greenschist facies, metamorphism of the Paleozoic sediments in northern Bolivia was ascribed to the latter episode.

To the west, in southern Perú and northern Chile, the pre-Mesozoic evolution of the proto-Andean cordillera is poorly-known, but it is clear that the Mesozoic and younger Andean strata were deposited upon a basement largely made up of Paleozoic or older metamorphic and igneous rocks. Evidence of a "Baikailan" orogenic episode (Martínez *et al.*, 1972) is afforded by the late Precambrian (~660 m.y.) K-Ar mineral ages documented by Stewart *et al.* (1974). In the Arica area of Chile, small inliers of metamorphic rocks, the Belén Schists (Salas *et al.*, 1966), protrude through the Andean cover. These were assumed to be of Precambrian age by Mégard *et al.* (1971), but they could be Paleozoic. The continuity of Precambrian rocks beneath the Paleozoic basement is unknown in this area.

Scattered K-Ar dates (447-395 m.y. B.P.) reported by Stewart *et al.* (1974) for granitoid bodies in southern Perú may reveal a period of plutonic activity during an early Paleozoic orogeny, possibly representing the northerly continuation of the Upper Ordovician-Lower Devonian event defined by our geochronological studies in the southern transect. Correlation of the few available Upper Paleozoic radiometric ages with specific orogenic events, however, remains difficult. It would appear that the main axis of Paleozoic diatrophism lay close to the present coast of southern Perú and northern Chile, and there is an apparent eastward decrease in the general intensity of both deformation and metamorphism.

(b) No major endogenous base or precious metal mineralization is *known* to have been associated with the Precambrian and Paleozoic basement in this northern transect, a situation paralleling that in the western area of the southern transect. It should be emphasized that there have been no investigations specifically directed towards the distinction of Paleozoic or older ore deposits in much of this region.

(c) The scattered, and largely weathered, outcrops of plutonic rocks on the western flank of the Andes in Tarapacá Province do not lend themselves to the precise determination of the time-space geometry of intrusive activity. The few published K-Ar dates (Levi *et al.*, 1963), however, and continuing studies by S.L. McBride provide a framework.

On this basis, it is deduced that an eastward migration of igneous activity, similar to that defined in the southern transect, occurred in the Mesozoic and early Caenozoic. The oldest plutons known, exposed in the immediate coastal area from Quebrada Camerones (Lat. 19°05′S) to the vicinity of Iquique (20°15′), are of Upper Jurassic age (150-139 m.y.), essentially coeval with the second volcano-plutonic episode recognized in the Copiapó region. The pre-Middle Jurassic age proposed on stratigraphic grounds for the gabbroic rocks in the Mal Paso area (Lat. 18°35′ – 19°S) is perhaps correct, but unsubstantiated. Stewart, Evernden and Snelling (1974) have, however, inferred the existence of intrusions of Triassic age in the southern Peruvian coastal region (16°16′S) on the basis of a single K/Ar age determination (204 m.y.).

Further inland, several Pb-α zircon ages in the Iquique region suggest the occurrence of Cretaceous plutons, but these data should be treated with caution. The next plutonic episode confirmed by K-Ar dating is of lower Eocene age (58 m.y.), while a short distance to the east, in the Andean Precordillera, Oligocene ages (39-32 m.y.) have been found for several small stocks.

The ash-flow tuff sheets of the Oxaya Formation (Salas *et al.*, 1966) blanket the *pampa* between the Cordillera de la Costa and Precordillera of northernmost Chile. These constitute part of the Liparítica Formation of Brüggen (1950), for which radiometric ages spanning much of the Neogene have been presented by several authors in northern Chile. No dates have been presented for these rocks in the Arica region, but we have determined an age of 17.5 m.y. for a porphyritic rhyodacite plug in the Precordillera which is interpreted as part of the feeder system for these enormous ignimbrite sheets.

Further to the east, no geochronological studies have been carried out on the high strato-volcanoes of the Andean divide, but their range of erosive state suggests that their extrusion spanned the interval from the Pliocene to the Holocene, as did that of the youngest eruptions in the southern transect.

Further age determinations in this region would be desirable, but it is suggested that the rate of eastward migration of the magmatic foci was regular, as in the southern transect. A mean rate of continent-ward displacement of *ca.* 0.5 mm/yr. is tentatively inferred, approximately two-thirds of that experienced between Lat. 26° and 29°S. This slower movement may directly reflect the somewhat steeper dip of the (present) Benioff seismic zone in this region (Kausel and Lomnitz, 1968; Swift and Carr, 1973).

(d) The western part of the Andean orogen at these latitudes, therefore, exhibits a time-space geometry of igneous activity in the Mesozoic and Caenozoic similar to that demonstrated further south. To the east, the eastern cordillera of Bolivia display several similarities and differences with respect to the southern transect. From *ca.* Lat. 18° southwards, a strictly west-east traverse would, however, reveal a Neogene break-out episode very similar to that in the Sierras Pampeanas. Small plutons and volcanic centres erupted along the Bolivian eastern cordillera, and, although few radiometric ages have been presented for these bodies, a Mio-Pliocene age seems inescapable (Ahlfeld and Branisa, 1960; Evernden, 1961). The oldest K-Ar date in the area, 19 m.y., is for the relatively extensive Karikari batholith (Radelli, 1968; Evernden, 1961). There is no evidence in this sector of the eastern cordillera of the existence of pre-Neogene igneous rocks, whether Paleozoic or, as proposed by Schneider-Scherbina (1962), of Triassic-Jurassic age. Thus, between Lat. 18° and 22°S, the late Tertiary saw a radical eastward expansion of magmatism, comparable to, but perhaps commencing slightly earlier than, that in the southern transect. This short-lived episode appears to be a fundamental feature of the recent evolution of a long stretch of the Central Andes.

In northern Bolivia, however, this pattern does not persist. The granitoid batholiths of the Cordillera Real, and areas to the north, are considerably older than the subvolcanic centres of central and southern Bolivia. Preliminary dating by Evernden (1961; *vide* Clark and Farrar, 1973), and our own more extensive geochronological studies by S.L. McBride and R.C.R. Robertson confirm that the major plutonic event in this area occurred in the Upper Triassic (*ca.* 210-200 m.y.), perhaps persisting into the Lower Jurassic. The close concordance of numerous age determinations in this region strongly implies that they reflect the time of emplacement of the plutons, and not a subsequent tectonic event. Martínez *et al.* (1972) and Mégard *et al.* (1971) postulated the existence of Hercynian granites in this area, on the basis of the development of a strong foliation in some plutons which is, in a general sense, concordant with that of the enclosing greenschist facies slates and phyllites (see above). We have found, however, that such tectonized intrusions consistently exhibit K-Ar mineral ages which are characterized by great internal discordance, and which are consistently younger than those of the undeformed bodies, which yield Triassic ages. We conclude therefore that the Cordillera Real was affected by strong tectonism during the Mesozoic, but that there is no convincing evidence for the existence of Paleozoic (Hercynian) plutons in the area.

The intrusions of the areally restricted Illimani, Quimsa Cruz, and Santa Vera Cruz massifs which lie between the Cordillera Real and the subvolcanic belt of central Bolivia, appear to represent a correspondingly intermediate plutonic episode. These granitic rocks yield ages with limited spread around the Upper Oligocene-Lower Miocene boundary (28-22 m.y.), despite their marked petrographic similarities to the Triassic granites immediately to the northwest.

In summary, it is evident that the eastern cordillera of Bolivia experienced an irregular longitudinal and generally southward migration of magmatism throughout the Mesozoic and Caenozoic, but that the southerly igneous bodies conform to the break-out pattern characteristic of areas to the south. An Andean traverse bisecting the elbow between Arica and La Paz would, therefore, be marked by an initiation of plutonic activity at the eastern margin of the orogen, to be followed by an inward propagation of activity from the continental margin. The latter process may have begun in the Lower Jurassic, as between Lat. 26° and 29°S, the pre-Upper Jurassic bodies having foundered with the subsidence of the western flanks of the coastal cordillera in the late Tertiary, as Mortimer (1973) has proposed. The periodicity of volcanism and plutonism in this transect *appears* to have been similar to that further south, but the precise timing of the different volcano-plutonic events may have differed; e.g., there is little evidence of a widespread Oligocene phase of emplacement between Lat. 26° and 29°S, whereas this affected wide areas of the Precordillera of northermost Chile. Certainly, there are as yet insufficient data for the recognition of discrete volcano-plutonic episodes which simultaneously affected considerable lengths of the Andean cordillera. Many of the magmatic sub-provinces have finite longitudinal extents, but the nature of their terminations, whether gradational or abrupt, is unknown. The 200 m.y. plutonic province probably continues northwestward along the eastern Andes of Perú (Stewart *et al.*, 1974), but cannot be confirmed in areas to the south of northern Bolivia. It would thus appear to be a feature charateristic of the Arica elbow region, and to have preceded the normal history of Andean magmatism which commenced in the Lower Jurassic.

(e) Although the radiometric data are sparse, particularly in the western (Chilean) part of the orogen, hydrothermal mineralization was probably closely associated in time and space with igneous activity throughout the northern transect. Thus, the oldest-known ore deposits in the region are the important Sn-W vein systems of the Cordillera Real province, which yield K-Ar ages similar to, or slightly younger than, the associated granitoid rocks (205-195 m.y.). In this area, the Upper Triassic age of the large Chojlla (Evernden, 1961), Bolsa Negra, Chacaltaya, and Candelaria W-Sn deposits have been confirmed. The Cordillera Real area therefore represents a well-defined plutonic and metallogenetic sub-province, characterized by the formation of W, Sn, and, to a lesser extent, Bi and Au mineralization.

The focus of mineralization then moved a considerable distance, to the western boundary of the mobile belt, where numerous manto and vein Cu deposits of probable volcanic-exhalative origin (Salas *et al.*, 1966) were emplaced in andesitic rocks of the Arica Group, of probable Middle Jurassic age, in the Cordillera de la Costa. The most important endogenous mineral deposits in the coastal area, however, have probably been the Huantajaya and Santa Rosa silver veins (Lat. 20° 13-17′S), in marine sediments and andesites of Middle or Upper Jurassic age, cut by bodies of porphyritic microdiorite (Ruiz *et al.*, 1965), and situated only a few kilometres from the coast. Thereafter, the locus of mineralization migrated inland, probably closely accompanying the magmatism. In the Arica region, the ages of numerous vein and breccia pipe Cu deposits, containing minor W, Au and Mo, and of a more easterly series of subvolcanic deposits, with porphyry affinities (Sillitoe, 1974), bearing Pb, Zn, Ag, Sb, Bi, and even traces of Sn (the Capitana mine, Ticnámar district; Salas *et al.*, 1966), as well as Cu, are not precisely determined; however, Paleocene or Eocene ages for the former, and a Neogene age for the latter may be inferred. The Eocene age (56.5 m.y.) of the Mocha porphyry Cu to the south (Lat. 19°49′S) has been confirmed (Quirt *et al.*, 1972); this is similar to that of the Toquepala porphyry Cu-Mo deposit in southern Perú (58.7 m.y.; Laughlin *et al.*, 1968). In the Precordillera of Iquique Department, Oligocene ages have been found for the Queen Elizabeth, Yabricoya and Copaquire porphyry Cu-type centres (Quirt *et al.*, 1972, and S.L. McBride, unpub. data), however.

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Subsequently, hydrothermal activity on a major scale commenced in association with the Upper Oligocene plutons of the Illimani, Quimsa Cruz, and Santa Vera Cruz districts, forming a highly productive, but areally restricted, Sn-W metallogenetic sub-province. Later, in the Mio-Pliocene, the locus of mineralization shifted to the sub-volcanic Sn-Ag-W-Sb-Bi centres of central and southern Bolivia (radiometric data are available only for Llallagua — 8.6-9.4 m.y.; Evernden, 1961). There is a progressive increase in the intensity of mineralization in the Sn belt with decreasing age, but it is not clear to what extent this is a reflection of erosional level. More extensive radiometric dating will be required to assess Ahlfeld's (1967) suggestion that several distinct Neogene-Pleistocene metallogenetic epochs are represented in the "subvolcanic" sector of the Sn belt.

The most recent magmatic activity in the transect, along the Chile-Bolivia frontier, is not known to be associated with sulphide mineralization, but native S deposits are widespread.

(f) As will have become evident, the transverse pattern of metal distribution in this transect is radically different from that of the southern. Copper again appears to be widespread and, probably, dominant in a great number of the hydrothermal deposits on the Chilean flank of the Andes, ranging in age from Jurassic to Oligocene. Although this metal is present as an accessory constituent in many of the deposits of the Bolivian eastern cordillera (an approximate average grade of 0.05-0.1 per cent might be estimated), it is only very rarely dominant (as in the Laurani centre). In its place, Sn, W, and, particularly in the southern sector, Ag, Sb and Bi are abnormally enriched, yielding a polymetallic sub-province unparalleled in the southern transect. While Sn as well as W is present in very minor amounts in the western deposits of Tertiary age in northernmost Chile, the enormous concentrations of these metals in the eastern part of the orogen represents a metallogenetic anomally of first magnitude, while the abundance of Ag, Bi and, especially, Sb in the latter area is perhaps even more striking. Neither metalloid has been recovered from deposits in the southern transect. The Sb may, however, be of Paleozoic age.

As in the southern transect, Ag here displays a complex distribution. Its great enrichment in the eastern cordillera is undoubted, but the existence of economically important Ag deposits in the immediate coastal region, and in the Chilean Precordillera cannot be ignored. Thus, important Ag deposits have formed across the entire width of the orogen at these latitudes, a distribution in strong contrast to that shown by the southern transect.

At these latitudes, therefore, a west-to-east traverse would show a zonation from Cu (with some Ag), through Cu-Pb-Zn-Ag, to Sn-W-Ag-Au-Sb-Bi-Pb-Zn. This trend is closer to that regarded as typical of the Central Andes by Sillitoe (1972b) and other authors, but also displays some important differences, notably in the distribution of Au, and specific local characteristics, such as the great enrichments of Sb and Bi in the east. Further, there are no known major Andean Fe deposits in this region, while Mo is probably closely associated with Cu and shows no significant eastward increase.

(g) The few published analyses of igneous rocks from this transect are an insufficient basis for the determination of long-term trends in the evolution of the orogen. The local studies of Katsui and González (1968) on the Payachata group of Neogene-Holocene volcanoes, and those of Fernández *et al.* (1973) in southwestern Bolivia (considerably to the south of the present transect), however, show that the volcanic rocks in the broad region are significantly enriched in potash relative to rocks of similar age and distance from the Perú-Chile trench in the Lat. 26°-29°S transect. This feature, suggestive of systematic *longitudinal* trends in rock chemistry in the Central Andes, approximately correlates with the present dip of the Benioff zone, which shallows to the south, and is inferred to reflect regionally-applied controls on magma composition over a considerable stretch of the cordillera (Zentilli, 1974).

There are, however, few analytical data for Pre-Neogene plutonic or volcanic rocks in the transect, whether in northern Chile or in the Bolivian eastern Andes, so that no conclusions can be made regarding possible changes in average magma composition with time. James (1971a), in a reconnaissance study of this region, concluded that the configuration of the subducted lithospheric plate has remained essentially constant since the initiation of the Andean orogeny, but the rock analyses on which this conclusion was based were derived from such a length of the cordillera as to be of very dubious value in this context.

One aspect of the chemistry of the igneous rocks of the region deserves further mention. El-Hinnawi *et al.* (1970), in a study of the trace element contents of ignimbritic rocks on the Chilean flank of the Andes, have inferred a genesis through fusion of the sialic crust, largely on the basis of the unusually high Sn concentrations they found. We, however, have carefully analyzed several specimens collected (Clark) from the sites sampled by those authors in the Arica region, and have found no evidence of such elevated Sn contents, which may have resulted from analytical error.

Interpretation of the Geological and Metallogenetic History of the Northern Transect

On the basis of the known geological relationships in the Arica orocline region, certain conclusions as to the evolution of this transect of the Andean orogen may be reached, although these must be regarded as far less substantiated than those made further south. By the same token, our knowledge of the controls on mineral deposit distribution in this area is at a very preliminary stage.

As noted above, the Chilean flank of the Andes apparently experienced a Mesozoic and Caenozoic history similar to that of the Copiapó area, characterized by the conti--nent-ward migration of volcano-plutonic centres and, probably, of tectonism and sedimentation in associated shallow longitudinal basins. The rate of migration, somewhat slower than that in the southern transect, suggests the operation of a similar broad control, and strengthens the interpretation made in the latter region. Thus, we consider that Andean magmatism was here again the result of partial melting close to the upper surface of an "easterly"-dipping oceanic plate, and that the main locus of magma generation was progressively depressed from originally shallow depths. As in the southern transect, the Andean magmatic, sedimentary, and tectonic events were superimposed on a generally coherent crystalline basement, which here includes late Precambrian elements, and which was deformed largely through lateral extension throughout the Andean orogeny.

The southern part of the transect, at the latitude of Iquique (*ca.* Lat. 20°S), was subject to Neogene eastward extension of magmatic activity, similar to that between Lat. 26° and 29°S, which generated the subvolcanic centres of the eastern cordillera of Bolivia, and much of the volcanism which affected the intervening *altiplano*. Again, this implies the existence of late-Tertiary plate inter-relationships similar to those which prevailed further south, evidence of the over-all continuity of Andean tectonic evolution between Lat. 18° and 29°S.

In the immediate vicinity of the Arica elbow, however, these systematic relationships are replaced by a more complex pattern. The Triassic plutons of the Bolivian eastern cordillera have no apparent close correlatives in more southerly transects of the Andes. They represent the *initiation* of magmatic activity in the ensialic Paleozoic sedimentary belt, and their emplacement was not accompanied by intense diastrophism. Essentially simultaneous plutonism affected at least part of the present Pacific coastal belt, in southern Perú, but continuity of the two loci of intrusion cannot yet be demonstrated. This important plutonic event, with an intra-orogenic setting in the main deflection of the Central Andes, cannot readily be related to processes of Pacific plate subduction at the western margin of the continent.

It is tentatively concluded that the Triassic granites of the Cordillera Real and the Peruvian eastern Andes—and, perhaps, the much younger plutons of the Quimsa Cruz and adjacent massifs—were generated through partial melting at considerable depths, unrelated to subduction of eastern Pacific lithospheric plates. This implies a process of deep melting, perhaps caused by the westward displacement of a portion of the Brazilian Shield and underlying mantle at the time of opening of the southern North Atlantic. Petrochemical and isotopic studies by R.C.R. Robertson, now underway, will, it is hoped, contribute to the solution of this complex problem.

These complexities are paralleled by the unusual metallogenetic development of the eastern Andes in the oroclinal region, characterized as they are by the predominance of Sn and other rare elements, and constituting an anomaly superimposed upon the "normal" pattern of Andean metallogeny.

CONCLUSIONS

Our detailed geological and ore deposit studies in the Andean cordillera between Lat. 26° and 29°S have demonstrated the protracted development of economic mineralization in intimate association with the epizonal emplacement of largely calc-alkaline magmas, giving rise to a series of well-defined metallogenetic sub-provinces and sub-epochs. In this Andean transect, the evidence strongly encourages the conclusion that the metallogenetic development of the orogen is a direct expression of a continuous process of lithosphere plate consumption, and, in this respect, the promise of the central Andes as a "field laboratory" for the clarification of metallogenesis at convergent plate environments is fulfilled. Correlation of the ore-forming mechanisms and materials with the magmatic systems is more tenuous, but it is tentatively inferred that a classical magmatic-hydrothermal origin is acceptable for the great majority of the known ore deposits.

The controls on the intensities and metal ratios of the ore deposits, however, are considered to have operated only in the shallow crust, in the immediate vicinity of the mineralization centres. There appear to have been no significant changes in the amounts of the different ore metals which have been introduced into the orogen through the last 200 m.y., and there is no clear reason for the dominance of ore-grade mineralization of Cu over that of the comparably abundant Pb and Zn. Moreover, several metals, particularly Ag, display a capricious distribution over the entire Central

Andes, and there is no evidence of any metallogenetic inheritance from the generally sparsely-mineralized Paleozoic basement in the richly-endowed Andean overprint.

Within the context of Andean metallogeny, considered as a whole, it is concluded that the Central Andean Sn belt represents a gross anomaly which cannot readily be explained in terms of the processes of oceanic plate consumption and partial melting which appear to have generated, albeit indirectly, the equally enormous tonnages of Cu sulphides in the region. A salient feature of the Sn belt is its confinement to the easternmost part of the Andean orogen, or to the underlying Paleozoic basement. The great majority of economic Sn deposits are restricted to a narrow belt, 2000 km in length and with a *maximum* width of 300 km, within which the locus of granitoid igneous activity and associated Sn mineralization has migrated longitudinally, in strong contrast to the behaviour of all other components of the orogen. If continuity of this belt from the Neogene subvolcanic centres of northernmost Argentina (*ca.* Lat. 23°30′S) to the Paleozoic deposits of the Sierras Pampeanas can be assumed, at least five main episodes of Sn-rich mineralization may be recognized: Ordovician-Silurian; Lower Carboniferous; Upper Triassic; Upper Oligocene; and Mio-Pliocene. Thus, Sn deposits formed in the course of two Paleozoic orogenies, in a period of (?) intra-orogenic plutonism, and at least twice during the Andean orogeny. Each segment of the Sn belt exhibits features distinguishing it from the others, and formed under specific conditions in association with granitoid magmatism in the upper crust.

The hypotheses advanced by several authors to account for the distribution of Sn deposits in the Andean cordillera are, we consider, difficult to accept. Thus, Petersen (1972) has argued that one or more of political traditions, vegetative cover, and host-rock lithology may have delimited the Sn belt. The two former factors, however, cannot convincingly be applied to the apparent decrease in mineralization intensity in the eastern Andes of southeastern Perú relative to northern Bolivia, while the occurrence of important Sn deposits in a wide range of sedimentary and meta-morphic host-rock lithologies probably rules out the latter. Mitchell and Garson (1972) and Oyarzún and Frutos (1973) have proposed that unusual concentrations of F have caused the generation of major Sn mineralization in the eastern part of the orogen. There is no evidence, however, that the Bolivian Sn deposits or associated granitoid rocks are markedly enriched in F, and fluorite and topaz are not abundant. Further, our finding that the fluids responsible for the porphyry Cu-Mo deposits in Chile were rich in F suggests that, even if the Sn were transported in solution as a fluorine complex, the presence of high concentrations of this halogen would not have been responsible for the segregation of Cu and Sn on a regional scale. It should also be emphasized that the majority of the Bolivian Sn belts are S-rich, so that the differential "fractional distillation" of S and F in a subduction environment, as proposed by Oyarzún and Frutos (1973), is untenable. Mitchell's recent (1973) discussion of the influence of major variations in the angle of dip of Benioff zones on the relative distributions of Sn and Cu deposits finds no support in the inferred tectonic evolution of the Central Andean continental margin, and appears to be based upon a mis-conception as to the nature, distribution, and environment of formation of these deposits.

Finally, Sillitoe's (1974) hypothesis that Sn is fractionated most strongly into those partial melts generated at greatest depths (*ca.* 300 km) during the subduction of an oceanic lithosphere plate, although fitting some aspects of the regional distribution of Sn deposits, is difficult to reconcile with the known occurrence of such deposits in the central Andes and their basement. Thus, the complete absence of Sn minerals in the Neogene porphyry Cu centres of the Sierras Pampeanas, a region rich in Paleozoic Sn deposits, and the sudden abrupt transition in northern Argentina from these deposits to the Sn-polymetallic centres of the main Sn belt, do not correspond to any known changes in the downward penetration of the subducted plates, which apparently attain depths of approximately 600 km throughout this region of the Central Andes. Further there is no evidence of a correlation with inferred transverse discontinuities in the downgoing plate. The formation of major Sn deposits of Upper Triassic age in northern Bolivia argues against a direct relationship to the Andean subduction episode, even if, as seems probable, these host-plutons are of deep-seated origin.

We tentatively conclude, therefore, that the great concentration of Sn deposits in the Andes of central South America reflects a contribution from a persistent anomaly, which has been drawn on periodically since the early Paleozoic. This zone, more probably located in the upper mantle than in the lower crust, corresponds to the "Sn belts" delimited by Schuiling (1967), and coincides with one of them. Thus, between Lat. 26° and 29°S, it is inferred that this zone was tapped twice during the Paleozoic orogenic episodes, but had been effectively depleted by the time the Neogene magmatism was generated in the same area.

It is fully realized that many of our conclusions as to the probable mechanisms for the development of metallogenetic provinces are negative, reflecting the still incomplete knowledge of the evolution of the Central Andes and their ore deposits. We consider, however, that the extensive documentation of the temporal and petrochemical relationships of hydrothermal activity in the intensely mineralized Lat. 26°-29°S transect provides a better basis for the clarification of the factors which have controlled the distribution of ore deposits at a convergent plate margin than has hitherto been available. The outstanding metallogenetic problems have at least been thrown into relief. In particular, the ill-defined nature of the relationship between the chemistry and size of the deposits and the development of the orogen should discourage broad-brush generalization. The wholly-inconsistent metal zonation displayed by even the Central Andes renders the application of such putative metal polarity to more complex or older convergent plate margins extremely hazardous.

Our hypothesis of a polygenic derivation of the metals concentrated in the supracrustal region of this great metallogenetic province represents a complication of an otherwise elegantly simple model, but is difficult to avoid. The fundamental controls, if any, on the longitudinal variations in mineralization intensity and composition (metallogenetic domains) remain obscure. It is undoubted that the thermal régime in the vicinity of the underthrust slab, which is clearly transversely segmented at the present time (e.g. Swift and Carr, 1973), must be complex, and correlation of the ore deposit distribution with such features will remain difficult. Consistent distinction between supracrustal and deep-seated influences on ore deposition must precede broad acceptance of the validity of the "geostill" concept.

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