Distribution of Trace Elements in Igneous Rocks of Peruvian Andes—Metallogenic Implications[1]

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Abstract Although numerous papers have been written on the geologic and metallogenic features of the Andes, a satisfactory hypothesis in regard to distribution of mineralization has not been presented. Previous studies of sedimentary rocks, erosion, and structure have shown only that they had local influence. Geochemical studies of igneous rocks for 11 trace elements were plotted with respect to the distance of the rocks from the Peru-Chile trench. Analyses of the geochemical contents permitted the division of the Andean orogene into two main provinces. The western province is characterized by decreasing copper content and increasing nickel, cobalt, and nickel/cobalt ratio from west to east. The eastern province is defined by high contents of lithium, rubidium, lead, and zinc.

Three structural divisions were noted. On the west, the Precambrian shield was weakly deformed during the Hercynian orogeny. The Hercynian belt on the east has a highly folded series of sandstones and shales. Between these two zones, the Altiplano is a highly mobile joint between the two mechanically different domains.

INTRODUCTION

Numerous works have been devoted to the geologic (El Hinnawi et al, 1969; Siegers et al, 1969; Pichler and Zeil, 1970; Fernandez et al, 1972; Hörmann et al, 1973) and metallogenic features (Gabelman, 1960; Ponzoni et al, 1969; Bellido and de Montreuil, 1972; Frutos and Oyarzun, 1976) of the Andes. General reviews of the concepts expressed on this topic were published initially by Petersen (1970) and more recently by Sillitoe (1976).

With reference to paragenesis of the ore deposits, the cited authors defined a zonal redistribution of mineralization in provinces or belts which can be related to the principal structures of the orogene (Fig. 1).

A direct relationship between subduction of the Nazca plate beneath the Andes and the zones of mineralization has been suggested by several authors (Sillitoe, 1972, 1976; Mitchell, 1976; Wright and McCurry, 1973; Field et al, 1976). Nevertheless, Ericksen (1976) pointed out the complexity of the chronologic events involved in the mineralization process. Clark et al (1976) advanced the idea that subduction does not explain the whole field of petrologic data and that it does not account for the distribution of the tin deposits in Bolivia.

Several authors have presented hypotheses about the distribution of mineralization (Petersen, 1970; Goossens, 1972), dealing with sedimentary rock characteristics, erosion level, and structural lineaments. In a previous paper (Amosse and Audebaud, 1978), we pointed out that those factors exert only local influence, but that the general pattern is related to the influence of subduction in the western part of the Cordillera, and to crustal fusion in the eastern part.

The present paper deals with the geochemical aspects of the problem, including additional analyses of metamorphic rocks and the metallogenic implications of the results of these analyses.

EXPERIMENTAL PROCESS

Samples were collected in southern Peru along a southwest-northeast profile similar to the geologic profile described by Audebaud et al (1976). Rocks range in age from Precambrian to Hercynian in the eastern part of the area, to Permian in the central part, and Cenozoic all along the profile.

The analysis procedure for 11 trace elements (Cu, Zn, Pb, Ni, Co, Cr, V, Mo, Sb, Li, Rb) was performed by atomic absorption spectrophotometry and grinding and solution in acid of the samples as described by Amosse and Audebaud (1978).

RESULTS AND DISCUSSION

Experimental results for each characteristic element were plotted with respect to the distance of the rocks from the Peru-Chile trench. Curves show the evolution of the trace contents of the rocks all along this southwest-northeast profile (Fig. 1). The variation curves are drawn for the following elements: copper (Fig. 2); vanadium, nickel/cobalt ratio (Fig. 3);

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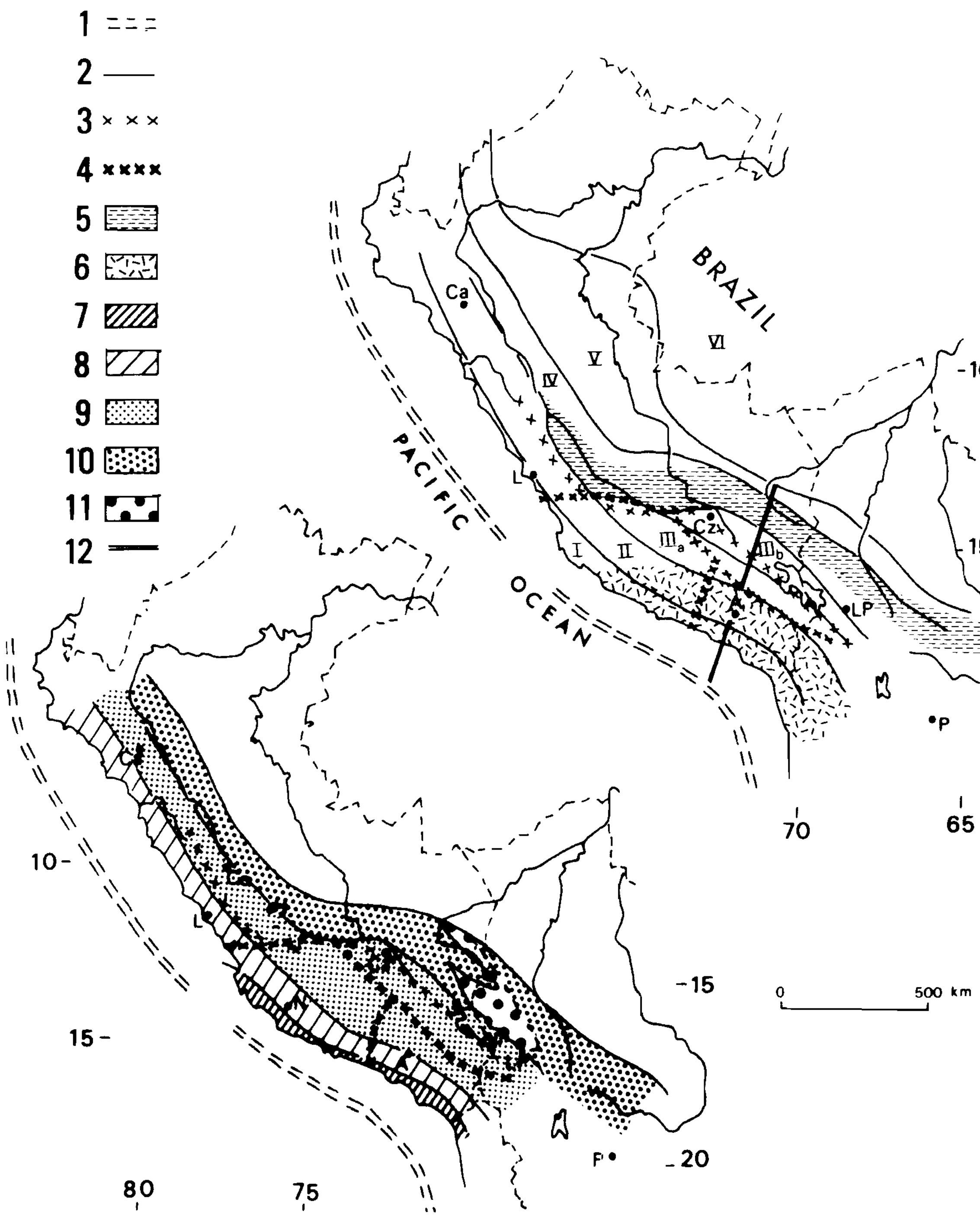

FIG. 1 —Physiographic-structural zones and metallogenic provinces in Peru. A, Arequipa; Ca, Cajamarca; Co, Cerro de Pasco; Cz, Cuzco; L, Lima; LP, La Paz; P, Potosi. 1, Peru-Chile Trench; 2, zones or provinces contacts; 3, crustal fusion zone from -30 to -46 km depth (from Aldrich et al, 1972; Schmucker et al, 1966; Ocola, 1973); 4, crustal fusion zone from -9 to -12 km depth (from same authors); 5, Hercynian belt (from Megard et al, 1971); 6, Arequipa Precambrian shield; 7, iron belt; 8, copper belt; 9, polymetallic belt; 10, Oriental Cordillera belt; 11, tin province or high-temperature mineralization; 12, profiles. Profiles are: I, coastal cordillera; II, Occidental Cordillera; III, Altiplano (a) western and (b) eastern; IV, Oriental Cordillera; V, subandean zone; VI, Brazilian shield.

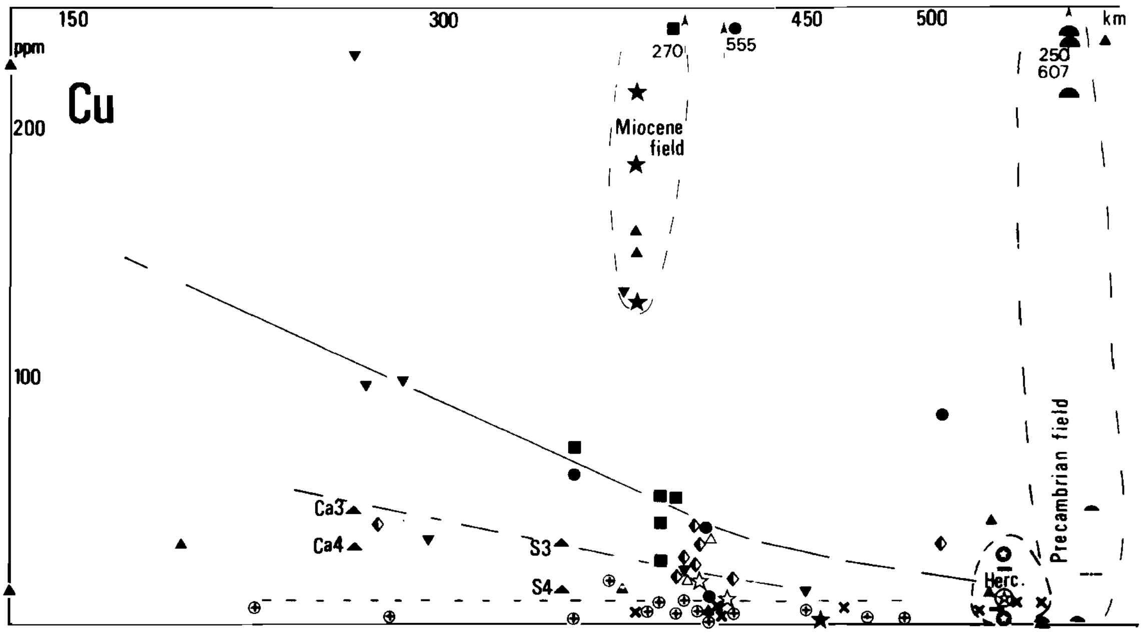

FIG. 2 —Curves of copper contents along profile Arequipa-Marcapata. Curves for Cenozoic igneous rocks: acidic rocks (- - -), basic rocks (———), intermediate rocks (- — - —). Triangles Ca and S are average contents of Pliocene volcanic rocks sampled by C. Lefevre 100 km southeast of profile (Andriambololona, 1976). Distances to trench given in abscissa in kilometers. Symbol legend same as Figure 4.

and lithium (Fig. 4), for which the variations are especially significant. Ternary diagrams Ni-Co-V, Ni-V-Cr, and Li-Ni + Co-Cu + V have also been constructed with the same experimental data (Fig. 5).

Copper, nickel, cobalt, and the nickel/cobalt ratio present a continuous variation of content in rocks along the western part of the orogene, with lesser amounts in the eastern part. However, lithium and rubidium contents show a sharp variation in the central part of the profile corresponding to the Altiplano. The localized variation observed for rubidium and lithium, and also to a lesser extent for lead and zinc, appears to be due to the passage from one geochemical zone to another. Therefore, we have divided the Andean orogene into two areas corresponding to the zones defined by the geochemical gradients of concentration. The following remarks apply only to Cenozoic igneous rocks.

WESTERN ANDES

This area includes the Occidental Cordillera and the western part of the Altiplano. The zone is characterized from west to east by high-temperature iron deposits, porphyry copper occurrences, and a polymetallic base-metals belt.

Correlatively, the curves show an eastward decrease in the copper contents of Cenozoic rocks. Copper is associated with basic igneous rocks, and is low in acidic ones. Intermediate rocks (latites, dacites) present values intermediate between the basic and acidic rocks (Fig. 2). We have noted some variability in the copper contents of basic igneous rocks near copper deposits. Thus, copper contents present a variation gradient along the profile which closely agrees with the density of copper deposits.

Nickel, cobalt, and the nickel/cobalt ratio increase eastward. Nevertheless, as deposits of nickel and cobalt are sparse, no correlation can be established with the gradient of concentration in the rocks. Only a few occurrences are reported in the Oriental Cordillera on the Pisco-Abancay deflection.

Lead and zinc values in acidic rocks increase slightly eastward, especially in the polymetallic zone where numerous deposits occur and where both average contents and overall dispersion of the values measured in the rocks are higher. In the basic rocks, the average content of zinc is always high and such rocks are never associated with zinc deposits. This fact is probably related to substitution of magnesium for zinc in the cell of chlorite.

Lithium and rubidium contents are constant in the western part of the orogene, and present a low average value except near mineralized districts (see sample in Figs. 2-4).

Finally, the ternary diagrams (Fig. 5) show a significant grouping of the data corresponding to this western part of the Andes.

It can thus be asserted that a positive or negative gradient appears for the major part of the elements (Cu, Ni, Co, Pb, Zn) along a direction perpendicular to the Peru-Chile trench (i. e., the same direction as that of the Nazca plate subduction). As a first approximation, we can assume that there is a correlation between subduction, magmatic genesis, and the presence of mineralization.

It must be emphasized that the highest temperature paragenesis is restricted to the western part of the area where the Benioff zone is shallow.

The relationship between the Nazca plate subduction and mineralization also appears to parallel the relation between metallogenic belts and the Peru-Chile trench, although only in the westernmost part of the Andes.

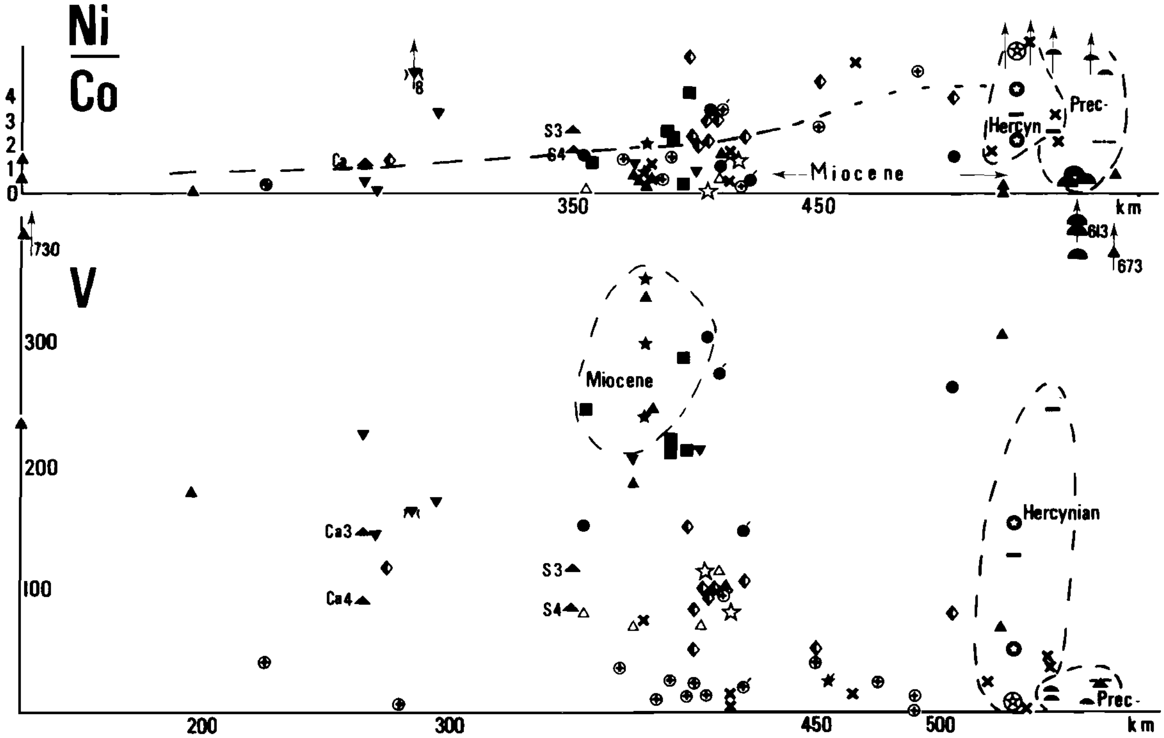

FIG. 3 —Curve of vanadium contents and Ni/Co ratio for Cenozoic igneous rocks. Symbols as in Figure 4.

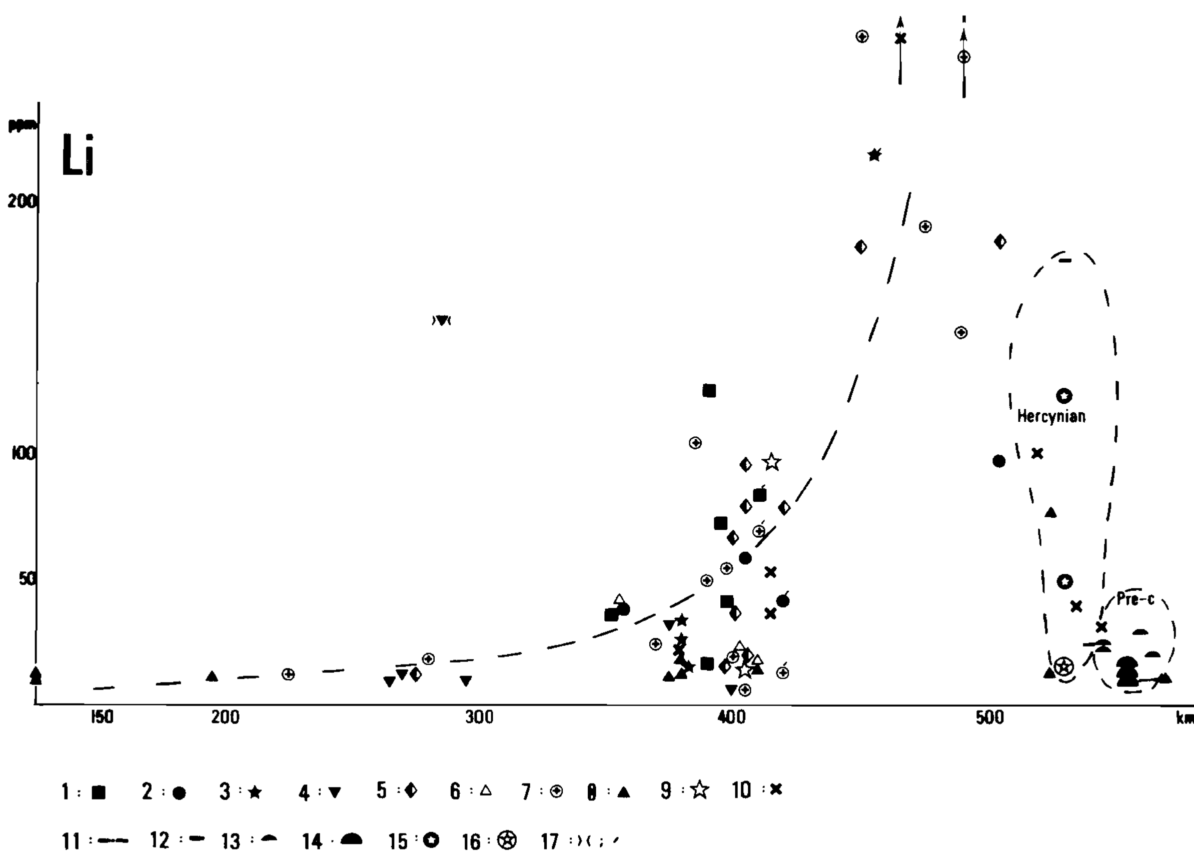

FIG. 4 —Curve for lithium contents for Cenozoic igneous rocks. Symbols: 1, basic andesite; 2, spilite; 3, phono-tephrite; 4, andesite; 5, latite or dacite; 6, trachyte; 7, rhyolite; 8, diorite or gabbro; 9, monzonite; 10, granite; 11, hornfels; 12, micaschist with andalusite; 13, orthogneiss; 14, amphibolite; 15, migmatite; 16, leucosome of migmatite; 17, sample near mineralized district.

EASTERN ANDES

The lithophile elements (Li, Rb, and to a lesser extent Pb and Zn) increase markedly in the Cenozoic igneous rocks. Ternary diagrams allow fields to be clearly distinguished between the western and eastern Andes—this distinction is related not only to lithium abundance in the east, but also to higher average contents of nickel, cobalt, and chromium, and to vanadium depletion.

The eastern Andes is characterized in the higher part of the Cordillera by epithermal mineralization (Sb, Pb, Zn) related to acidic magmatism. In places, a curious low-temperature association of antimony with tungsten appears. In the lowest parts of the Oriental Cordillera, higher temperature paragenesis (Cu, Li) crops out (Fig. 6). Another typical feature is the auriferous district in the eastern part of this zone, which is not considered here because of its pre-Cenozoic age. These features imply a high-temperature gradient in Bolivia. The acidic affinities fit with crustal influence by means of fusion zones or superficial magmatic accumulations, such as those detected by geophysical research (Schmucker et al, 1966; Aldrich et al, 1972; Ocola and Meyer, 1972). Consequently, the mineralization processes appear to be more complex in the eastern Andes than in the western Andes because of greater interference of crustal elements.

We must emphasize that mineralizations are polyphased. For the Andean cycle, the latest mineralizations are Pliocene and the earliest ones Permian. For older events, high-temperature metamorphism of probable middle Paleozoic age locally affected the thick Paleozoic sequence and the Precambrian shield (orthogneiss and amphibolites). The data and fields corresponding to these pre-Andean stages of crustal mobilization processes are shown in Figures 2 to 4, for reference only.

ANOMALIES TO ELEMENT REDISTRIBUTION MODEL

The relative constancy of geochemical characteristics of Cenozoic igneous rocks led to the previous conclusions. These features imply rather stable thermodynamic conditions in magma genesis, together with some constant interplay during the last 60 million years between subduction, the Nazca plate melting process, and crustal mobilization.

Some studies (Vivier et al, 1976) show the same trends but separate some periods of specific activities, such as those in the "anomalies" mentioned below. There are two well-established "anomalies" to the previously defined laws of distribution of elements: the Miocene anomaly and the Permian anomaly.

Miocene Anomaly

A large excess of copper and vanadium with a low nickel/cobalt ratio seems to be the characteristic "fingerprint" of the Miocene igneous rocks (Miocene-Oligocene boundary). Moreover, all districts affected by this Miocene magmatism have the same geochemical features without any reference to the distance from the trench. This magmatism is essentially basic with tephritic tendencies, and is related to the opening of a rift which existed at roughly the same position during Permian time. This structure corresponds to an east-west tensile-stress zone in the Andean orogene.

Permian Anomaly

Although we do not discuss here whether Permian magmatism is the first stage of Andean magmatism under the influence of subduction, the Permian series corresponds to a post-Hercynian stage, molasse being interbedded with rhyolitic and spilitic volcanism. Anatectic mobilization of the crust is responsible for the rhyolitic and spilitic volcanism, but the spilitic emissions reveal the ascent of deep basic magmas along the extensional faults of a rift zone (Vivier et al, 1976).

On ternary diagrams, the geochemical features of Permian magmas give fields closely related to western data fields, but the specificity of this magmatism is affected by extensive hydrothermal effects.

Northwest-Southeast Geochemical Gradient in Oriental Cordillera

Sillitoe (1976) pointed out a division in segments of the Andean orogene, from Chile to Venezuela, characterized by changes in metallogenic provinces across certain transversal lineaments, such as the Pisco-Abancay and Arica-Santa Cruz deflections. It was established by Schuiling, (1967) that such differences, for example in distribution of tin, appear in the Oriental Cordillera between Bolivia and Peru.

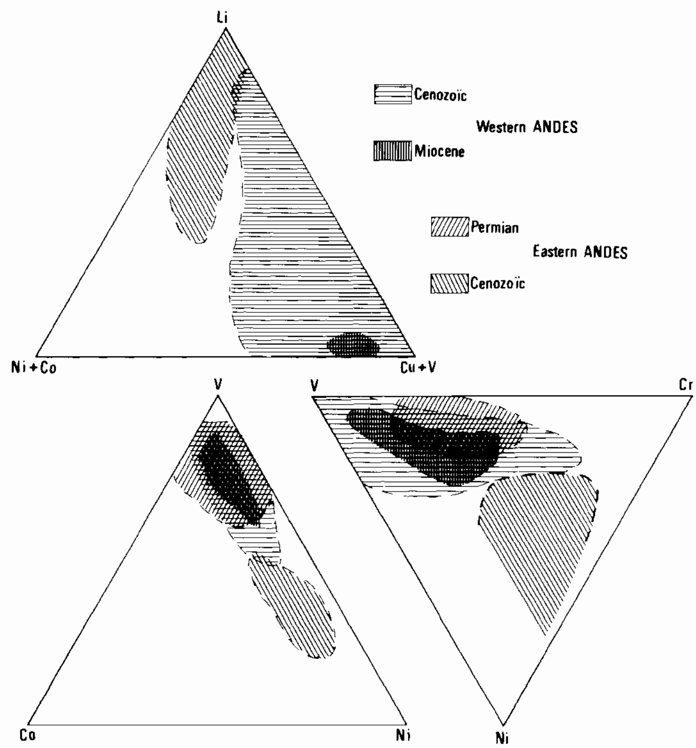

FIG. 5 —Ternary diagrams of Ni-Co-V, Ni-V-Cr, and Li-Ni+Co-Cu+V for Cenozoic and Permian rocks.

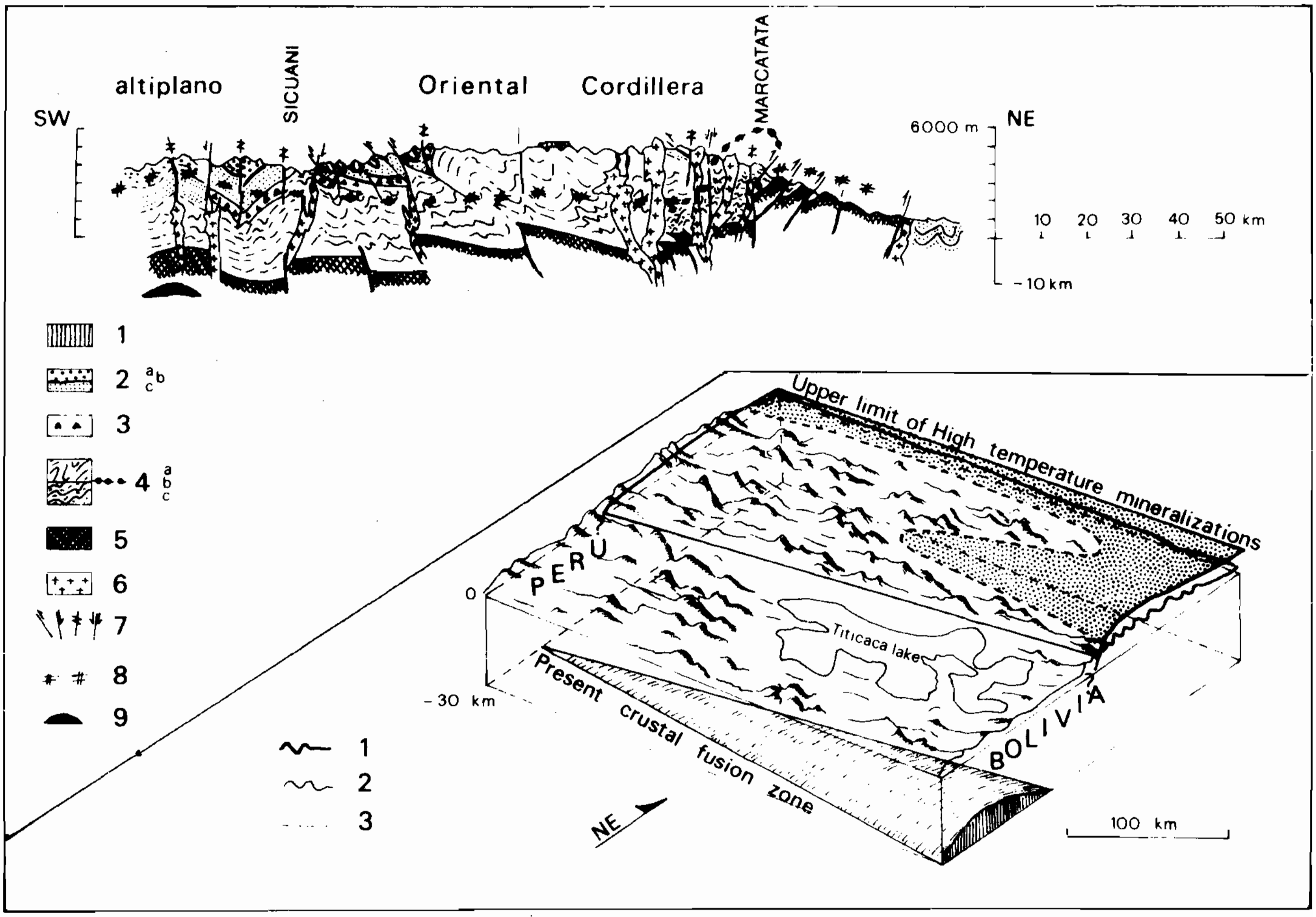

FIG. 6—Upper diagram: Structures, mineralization, and magmatic evolution in Altiplano and Oriental Cordillera. 1, Pliocene ignimbrites; 2, (a) Cenozoic conglomerates, (b) Cenozoic sedimentary copper level, (c) Mesozoic; 3, Permian; 4, Paleozoic Silurian-Devonian (a) not metamorphosed, (b) contour of Andalusite metamorphic zone, (c) migmatites in Andalusite micaschists; 5, Precambrian basement; 6, batholites; 7, faults (z for wrench faults); 8, upper limit of high-temperature mineralization; 9, shallow crustal fusion zone. Lower diagram: Tectonogram of high-temperature mineralization and present crustal fusion zone between Bolivia and Peru. 1 and 2, topographic profiles below and above high-temperature limit; 3, outcrop of tin and high-temperature mineralizations.

As stated previously, we found acidic epithermal mineralization in the upper part of the Oriental Cordillera in southern Peru and higher temperature mineralization in the lower part (Marcapata district). We relate these mineralizations to increasing intensity of hydrothermal activity from north (Peru) to south (Bolivia). Recent work by geophysicists (Ocola, 1973) describes a crustal fusion zone dipping northward between Bolivia and Peru. Accordingly, we suggest that high-temperature mineralization zones in Bolivia dip northward and crop out only in the lower part of the Peruvian Oriental Cordillera (Fig. 6). Agreement of geophysical data with metallogenic zoning is a more convincing argument than hypothetical influence of a Nazca plate more than 250 km deep at this place. Such a hypothesis can be fitted easily into Schuiling's (1967) concepts.

CONCLUSIONS

The analyses of Cu, Zn, Pb, Ni, Co, Cr, Mo, Sb, Li, Rb, and V in 80 rock samples collected along a southwest-northeast profile in southern Peru allow correlations between rock contents of some elements (Cu, Ni, Co, Pb, Zn) and known ore deposits.

The geochemical contents of igneous Cenozoic rocks sampled far from mines and prospects permit us to divide the Andean orogene into two main provinces:

1. A western province characterized by decreasing copper content from west to east and increasing nickel, cobalt, and nickel/cobalt ratio in the same direction. This effect can be attributed to direct or indirect influence of Nazca plate subduction.

2. An eastern province characterized by high contents of lithophile elements (lithium, rubidium), as well as lead and zinc. The acidic feature of the paragenesis in the major part of the ore deposits corresponds to activity along crustal fusion zones, as suggested by the geophysical data.

This division is founded on structural analysis as stated by Audebaud (1973).

The main structural divisions south of 13°S lat. are:

1. Precambrian shield (Arequipa "microplate") on the west, which was weakly deformed during the Hercynian orogeny, and where Andean structures show uplifting and

block-faulting rather than strong compressive stresses.

2. Hercynian belt on the east, with highly folded thick series of shales and sandstones. Compressive stresses of the Andean orogeny are obviously represented by extensive evidence of strike-slip faulting.

3. A transitional zone (Altiplano) which is the highly mobile belt between the Precambrian shield and the Hercynian belt. Two periods of rift activity (Permian and Miocene) and the importance of wrench faults can be attributed to the role of the Altiplano as a mobile joint between two mechanically different domains.

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