PORPHYRY COPPER-TYPE MINERALIZATION AND GEOSYNCLINAL TECTONIC EVOLUTION IN THE CHILEAN ANDES (*)

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(3 fig. dans le texte et 2 hors-texte)

ABSTRACT

A tectonic palaeogeographic scheme is summarized indicating some important relationships between the geological evolution of the Chilean Andean region, especially during the Middle Triassic to Recent Andean Tectonic Cycle, and the genesis and location of porphyry type copper mineralization.

The study of the Andean Chain suggests that the location of the porphyry copper deposits is related to the transition zone which separates the eugeosynclinal and miogeosynclinal zones throughout the length of the Andean basin (mesodorsal, Frutos, 1973). The porphyry copper deposits are specifically related to the eastern fringe, located parallel to the axis of the basin, in which, due principally to the Mid-Late Cretaceous and Lower Tertiary diastrophic phases some important overthrustings occurred, with a partial riding of the mesodorsal zone on the miogeosynclinal furrow.

The spatial location of the Mid-Late Cretaceous and Tertiary magmatic processes involved in the evolution of the geosynclinal basin, the sedimentary physicochemical environment, and the tectonic structures directly associated with the porphyry copper deposits, obviously have a direct relation with the aforementioned tectonic phenomenon and with the evolution of the western margin of the continent.

It seems that the geological-geographical location of the porphyry copper deposits and also the copper-bearing tourmaline breccia pipes could be related to the following factors :

a) The miogeosynclinal Upper Jurassic to Lower Cretaceous andesitic volcanic facies, parallel marine sediments and evaporitic facies.
b) The important Cretaceous-Lower Tertiary compressive structures.
c) The Cretaceous-Pliocene transcurrent fault system, cutting diagonally the Andean Chain, with NE and NW general directions.
d) The Upper Cretaceous-Cainozoic acid hypabyssal magmatism.
e) The relatively uplifted mesodorsal zones, especially those of the Upper Tertiary, that have enhanced secondary enrichment.

Mention is also made of some plate tectonic metallogenetic models, emphasizing the volcanic characteristics observed in the youngest ore bodies.

INTRODUCTION

More than half of the world's copper production arises from porphyry copper

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orebodies. In Chile more than 60 % of the copper production comes from such deposits and the copper-bearing tourmaline breccia pipes.

Although many writers have investigated the « economic » aspects of the deposits (Flores, 1942; Ruiz and Ericksen, 1962; Ruiz et al., 1965; Thomas, 1967; Sillitoe, 1969a and b; Sillitoe and Clark, 1969; Sillitoe et al., 1970; Alfaro, 1970; Newmann, 1972, 1973; etc.), only few of them have attempted to connect genetically the geology and location of the orebodies with the palaeogeography and tectonics of their setting. In this aspect we can only mention the works by Ruiz et al., 1965; Sillitoe and Sawkins, 1971; Sillitoe, 1972; Frutos and Oyarzún, 1973; and Oyarzún and Frutos, 1973.

This paper deals in general with the geological factors displayed in common by the main Chilean porphyry copper deposits (Fig. 1), and with some ideas connecting the porphyry copper-type mineralization with the geosynclinal environment and tectonic evolution of the basin.

GENERAL CHARACTERISTICS OF THE PORPHYRY COPPER TYPE DEPOSITS

Porphyry Copper Deposits. — In Chile this specific type of deposit (e.g. Chuquicamata) agrees in general with the definition of deposits approximately equidimensional, large (i.e. 100,000,000 tons.), and low-grade (i.e. 0,9 % Cu). The primary metallic mineralization is formed by disseminations of pyrite and chalcopyrite, with lesser ammounts of molybdenite and bornite, and traces of gold and silver. In several cases supergene enrichment has significantly upgraded the primary ore.

Fairly typical porphyry copper type hydrothermal alteration generally accompanies the deposits. It has been divided by Neumann (1973) into three zones :

1. Felspar stability zone : It is the central zone, typified by potassic alteration in the form of potassic felspar and/or biotite with lesser anhydrite, sericite, some carbonates, magnetite and hematite. Primary argillization is absent and the sulphides are mainly disseminated.

2. Felspar destruction zone : It is the intermediate zone and may be further subdivided into :

a) Sericite zone, inner zone characterized by a change in the original nature of the rocks to a quartz-sericite aggregate. The pyrite chalcopyrite ratio is higher than in the felspar stability zone and the sulphides are mainly in small veinlets.

b) Argilic zone, characterized by the alteration of the felspars to kaolinite and/or montmorillonite, and

c) Siliceous zone, formed by rocks altered to cryptocrystalline quartz with minor sericite, clay minerals, and chlorite. Pyrite, usually disseminated, is the only sulphide present in both of these last zones.

3. Propilitization zone : It is the most external and it is characterized by the presence of chlorite, epidote, calcite and albite. The only sulphide is pyrite, which may or may not be present.

Breccia Pipes. — The copper-bearing tourmaline breccia pipes in Chile, (e.g. Disputada), interpreted by Sillitoe and Sawkins (1971) as post-magmatic hydrothermal collapse breccias, are generally cylindrical-shaped, subvertical bodies, circular to elliptical in plan, and ranging from 3 to 1.200 m in diameter. They are formed of angular to subrounded fragments of host-rock cemented by tourmaline, silica and polymetallic sulphides. The upper portions of these bodies are usually hydrothermally altered and are bound by sheeted contacts.

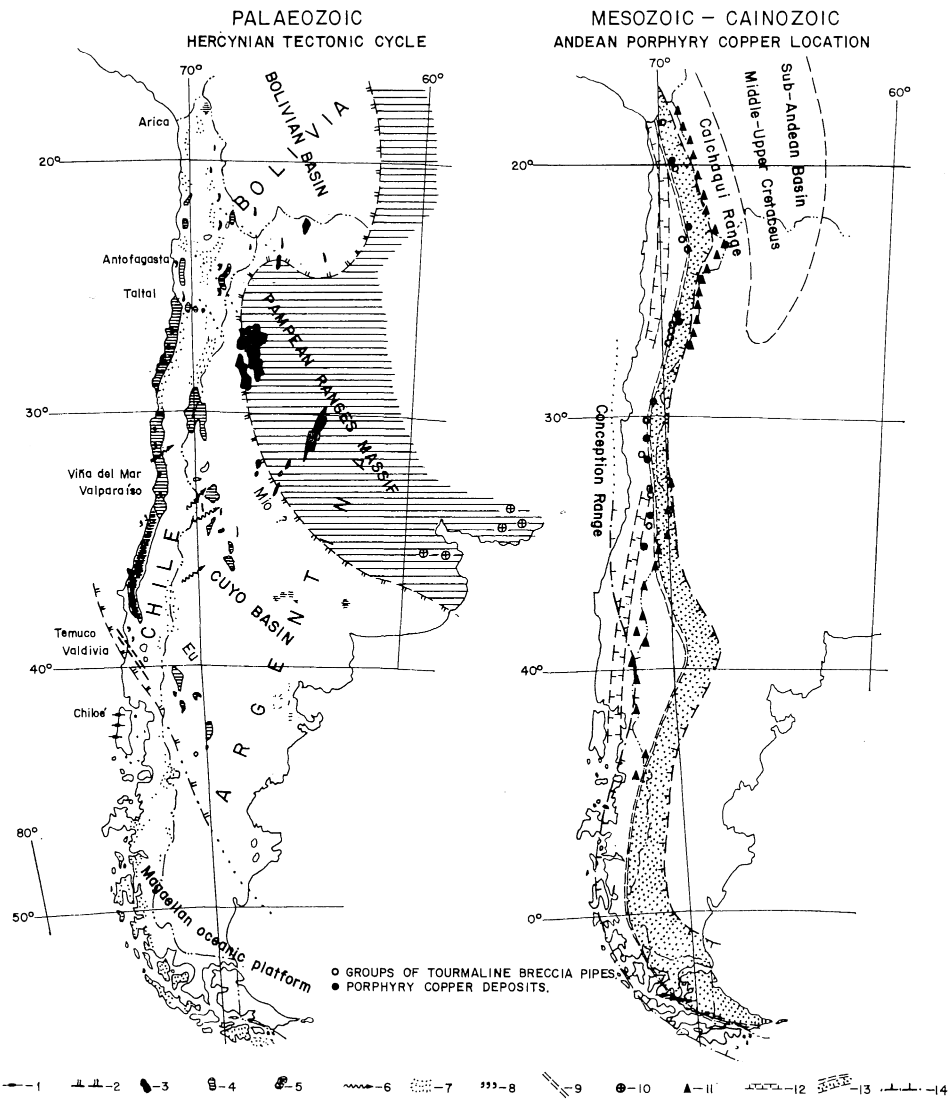


Fig. 1. — Palaeogeographic-tectonic evolution scheme
and the location of porphyry copper deposits.

1. Palaeozoic oceanic sediments (non-geosynclinal); 2. Maximum extension of palaeozoic marine basin; 3. Approximate distribution of Precambrian igneous rocks; 4. Approximate distribution of Palaeozoic igneous rocks; 5. Lower Palaeozoic granitoids; 6. Flysch facies; 7. Mesozoic-Cainozoic intrusive rocks (Andean Cycle); 8. Marine Palaeozoic; 9. Mesodorsal zone; 10. Approximate location of 2000 ± 100 m.y. rocks; 11. Recent volcanism; 12. Upper Pliocene to Recent Graben (block tectonics-Andean Uplift); 13. Mesodorsal and miogeosynclinal zone; 14. Maximum extension of Mesozoic Andean Basin.

Sillitoe and Sawkins (1971) pointed out that the hydrothermal mineralization of the pipes commenced with an early stage replacement of the host rock by introduced silica, sericite and tourmaline, resulting in the formation of quartz sericite aggregates and intense silicification and tourmalinization. This was followed by brecciation and open space filling by tourmaline, specularite, quartz, scheelite, chalcopyrite, pyrite, molybdenite, bornite, gold and galena.

Distribution, Setting and Age of the Deposits. — The porphyry copper type hydrothermal development in Chile, with or without economic mineralization, and the copper-bearing tourmaline breccia pipes are predominantly distributed in one main belt (Ruiz and Ericksen 1962, Ruiz et al., 1965). This belt, aligned approximately north-south and about 30 to 50 kilometers wide, lies on or adjacent to the Recent Andean Volcanic Chain. In northernmost Chile, as extension of the Peruvian belt, it lies on the western side of the volcanic chain, coinciding approximately with it, between latitudes 31° to 36° south, and continuing along its eastern side fading southwards into Argentina where it can be traced at least as far as 39° South. The belt is probably found again in Southern Chile associated with rocks of the Magallanes geosyncline, but the deposits so far discovered there are not very important.

The porphyry copper deposits or the barren porphyry copper type hydrothermal alteration zones may be located within several lithologic rock-types (Neumann, 1973). The most common of these are : andesite volcanics, felsic intrusives, marine and continental sedimentary rocks or a combination of these. In all cases the deposits appear to be related to an intrusive rock, generally an hypabyssal (i.e. porphyritic) rock of granitic, tonalitic or granodioritic composition. The bodies are commonly associated with Cretaceous-Tertiary faults that may be normal, reverse or transcurrent. Several of these faults have had recent activation.

According to radiometric-age determinations carried out on some of the more important bodies, (Fig. 1) the age of the mineralization ranges from Middle-Late Cretaceous to Lower Tertiary in the north (Mocha : 56.2 ± 2.6 m.y., Los Loros : 89 ± 0.6 m.y., Neumann 1973; Chuquicamata 29.2 ± 0.5 m.y.-36.9 ± 0.6 m.y., Quirt S. et al., 1971) to Pliocene, south of 31° S lat., where the location of the deposits coincide with the Recent Andean Volcanic Chain (El Teniente : 4.32 ± 0.08 m.y.-5.62 ± 0.11 m.y., Río Blanco : 4.59 ± 0.08 m.y., Quirt, S. et al., 1971).

Supergene Enrichment. — In Chile many sub-ore grade primary orebodies have been raised to economic grades by supergene enrichment, (Chuquicamata, El Salvador, Potrerillos, Andacollo) due to climatic and geomorphological factors. However, in other areas such as Mocha and Cerro Colorado (Neumann, 1973), because of the relatively rapid erosion, only the remnants of former enrichment zones remain. In other cases such as Los Pelambres, Río Blanco and El Teniente (Neumann, 1973), Pleistocene glaciation has impeded the formation of enrichment zones — only a thin disseminated chalcocite zone is present immediately below a thin oxidized capping.

THE EVOLUTION OF THE CHILEAN ANDEAN BASIN

In broad terms the Andean Geosynclinal cycle began in the Lower Mesozoic with the evolution of a pericontinental (s.s.) pericratonic basin, north of 42° S, (Andean Basin = Geoliminar Sector, Aubouin and Borello 1966; Aubouin et al., 1973), which lacks ophiolites, nappes, typical flysch sediments and regional metamorphism higher than green schists facies (Aguirre et al., 1973). This geoliminar basin gradually grades into a typical geosynclinal basin south 42° S, (Magaellan Basin = Geosynclinal Sector) which is in an intercontinental position between the Patagonian and Antarctic Cratons, (Aguirre et al., 1973) : there, flysch sediments, ophiolites, nappes, and high intermediate pressure metamorphism occur (Aubouin et al., 1973; Aguirre et al., 1973).

The tectonic evolution of the Chilean Andes shows a succession of short compressive stages (Upper Carboniferous; Mid-Late Liassic Upper Jurassic; Cenomanian; Paleocene; Oligocene; Upper Miocene) characterized by folds, reverse faulting and intrusive magmatic pulsations, followed by longer periods of no compression or relaxation phases, generally typified by normal faulting graben formation and volcanism with early predominance of acidic types (Frutos, 1970, 1973).

Thus, in strict terms, the Andean Geosynclinal Cycle (Fig. 2) commenced with a Middle to Upper Triassic distension stage (*), which produced an initial subsidence of the basin, and later eugeosynclinal and miogeosynclinal tectonic phases. The basin, oriented NNW-SSE, was emplaced over the palaeozoic basement along the south-western continental margin of South America, (Fig. 1) at an angle with the present coast line and with the structures of that basement.

During the Jurassic Lower Cretaceous span the Geoliminar Sector of the Andean Geosyncline consisted of an eugeosyncline with predominance of graywackede posits and important intercalated volcanics, well represented in the present coastal ranges of Northern Chile by the La Negra Formation and its equivalents. Towards the foreland a Miogeosyncline was built up by sediments of the sandstone, limestone, and lutite facies, but with almost no participation of volcanic materials.

Epeirogenic movements begining during the Callovian-Oxfordian synchronically with the main Jurassic batholitic intrusion, were followed by a compressive diastrophism during the Oxfordian and Kimmeridgian (Araucan tectonic phase). One or both of these processes caused, as the marine domain receded, evaporitic facies to be deposited in the basin. After these events, a narrow marine basin remained during the Titonian-Neocomian a little to the east of the Jurassic basin, which finally disappeared as a consequence of epeirogenic movements that preceeded the Middle Cretaceous (Sub-Hercynian) diastrophism. After the Neocomian and up to present, the geoliminar sector has been an emerged zone, characterized by continental facies.

Eu and miogeosynclinal domains were separated during the Jurassic along the whole length of the basin, by a subpositive ridge or transitional zone not always emerged : the liminar mesodorsal (Frutos 1973a, 1973b). (Fig. 3). This tectonic ridge evolved emerging and migrating with time towards the foreland and finally, during the orogenic phase, partially overriding the miogeosyncline area along a rupture zone (Figs. 3 and 4); especially this process took place particularly during the compressive diastrophism of the Middle to Late Cretaceous-Lower Tertiary (Sub-Hercynian-Laramic) and ended with the Oligocene and Upper Miocene compressive tectonic phases.

The latest distension period, coinciding with what has been defined as the taphrogenic phase of the Andean Cycle (Frutos and Tobar, 1973) culminated in the Upper Pliocene and is still active; the structures generated in this period have a NNE axis and appear to be intimately related to the formation of the present Andean Chain and its associated volcanism (Fig. 4), as well as to the present coastline to which they are parallel.

(*) The Middle Cambrian to Middle Triassic Caledonian-Hercynian Tectonic Cycle (Paleoidic Cycle, Borello, 1969; Frutos and Ferraris 1973); ended after the Upper Carboniferous orogeny, with the development in the Permian to Lower-Middle Triassic of the post orogenic stage in which the Hercynian orogen becomes a peneplanized platform of great extension (Corvalán, 1965; Frutos and Tobar, 1973).

In this form the taphrogenic phase of the Andean cycle (Upper Tertiary-Quaternary) has been marked since the Pliocene by acidic volcanism producing the extensive ignimbritic cover of the Altiplano. The same distension period that produced the fractures associated with the Plio-Quaternary volcanism also produced the principal structural blocks of the continental margin; these are from west to east : Trench Coast Ranges, Central Valley, Precordilleran Blocks, Precordilleran Graben — Valleys, Andes Cordillera. (Frutos and Tobar, 1973; Fig. 4).

There is clear evidence of approximately NW and NE transcurrent fault systems with right and left lateral displacement of continental dimensions (Fig. 4). These faults appear to have a causative relation to the sinuosity of the Andean Chain. Movements seem to have occurred in the Upper Cretaceous-Tertiary and have clearly been active in the Plio-Pleistocene.

During the whole development of the Andean Tectonic Cycle, active oversaturated calcalkaline volcanism and plutonism — perhaps associated with an evolving subduction zone (Frutos and Tobar, 1973) — took place in each period, in strips parallel to the axis of the structural basin (Figs. 2 and 3) and migrated steadily eastward (Farrar et al., 1970). In Jurassic times, the strip of volcanic centers was located a little to the west of the present coast line in northern Chile; from this position it migrated inland approximately 200 km to its present position at the crest of the Andes. During this migration the volcanic chain petrologically increased in K_2O (Oyarzún, 1973) and structurally changed its orientation from NNW to NNE (Frutos and Tobar, 1973).

OBSERVATIONS CONNECTING PORPHYRY COPPER DEPOSITS TO THE GEOLOGY OF THE ANDEAN BASIN

There is a close connection between the location of porphyry copper deposits and the position of the mesodorsal (Fig. 1) : they are specifically related to the eastern fringe or rupture zone of that tectonic structure, where important overthrusting and a partial riding of the mesodorsal zone on the miogeosynclinal furrow occurred during the Middle to Late Cretaceous-Lower Tertiary span.

In addition, the known deposits tend to be grouped on the mesodorsal in zones where that structure is both oroclinally folded and cut by important transcurrent fault systems trending NW and NE. The faulting and folding seem to have been produced by the tectonism mentioned before, and were clearly active until the Plio-Pleistocene (Frutos, 1973). Examples of the indicated relationship are the zones of Mocha-Cerro Colorado (20° S), Chuquicamata — El Abra (22°-23° S), and Chimborazo — Varillas (24° S).

It is suggested that the intersection of the overthrusted mesodorsal with the main transcurrent faults produced zones of crustal weakness where acid magmatism (vulcanism and related hipabyssal plutonism) was encouraged during a longer period than in adjacent areas.

The possible metallogenetic role of some host rocks is worth noting. Among these the most important are the Upper Jurassic calcareous and gypsiferous evaporitic miogeosynclinal facies found at Caracoles, Potrerillos, El Salvador, etc. In the reducing environments where these rocks were deposited high sulphur contents could be expected, probably rendering that element as the main copper-segregating agent. In connection with this environment mineralization other than the porphyry copper-type can also be found : silver, lead, zinc, copper, and gold polymetallic deposits (Fig. 3).

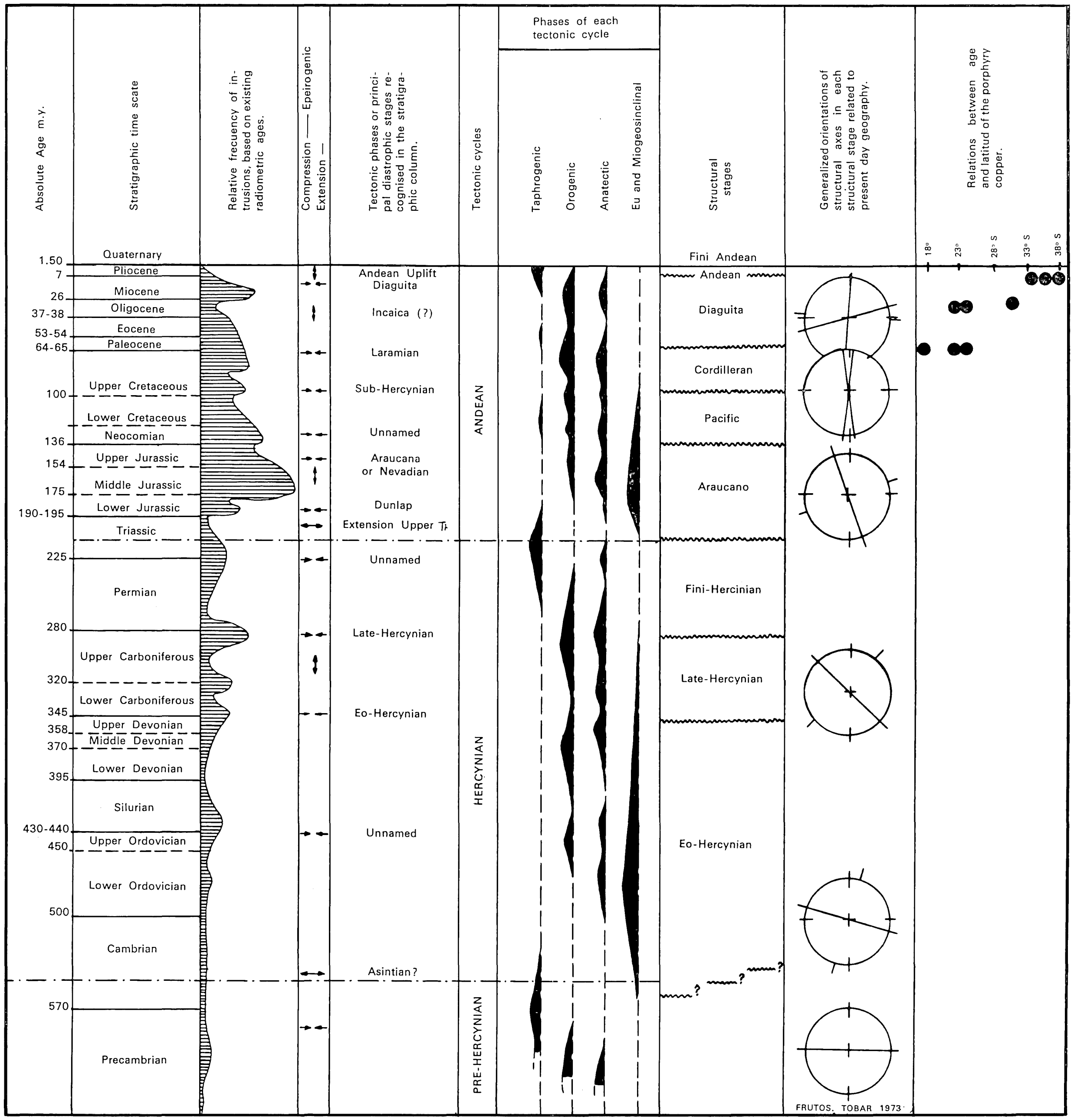


Fig. 2. — Magmatism and tectonic elements of the south-western continental margin of South America related to the time scale.

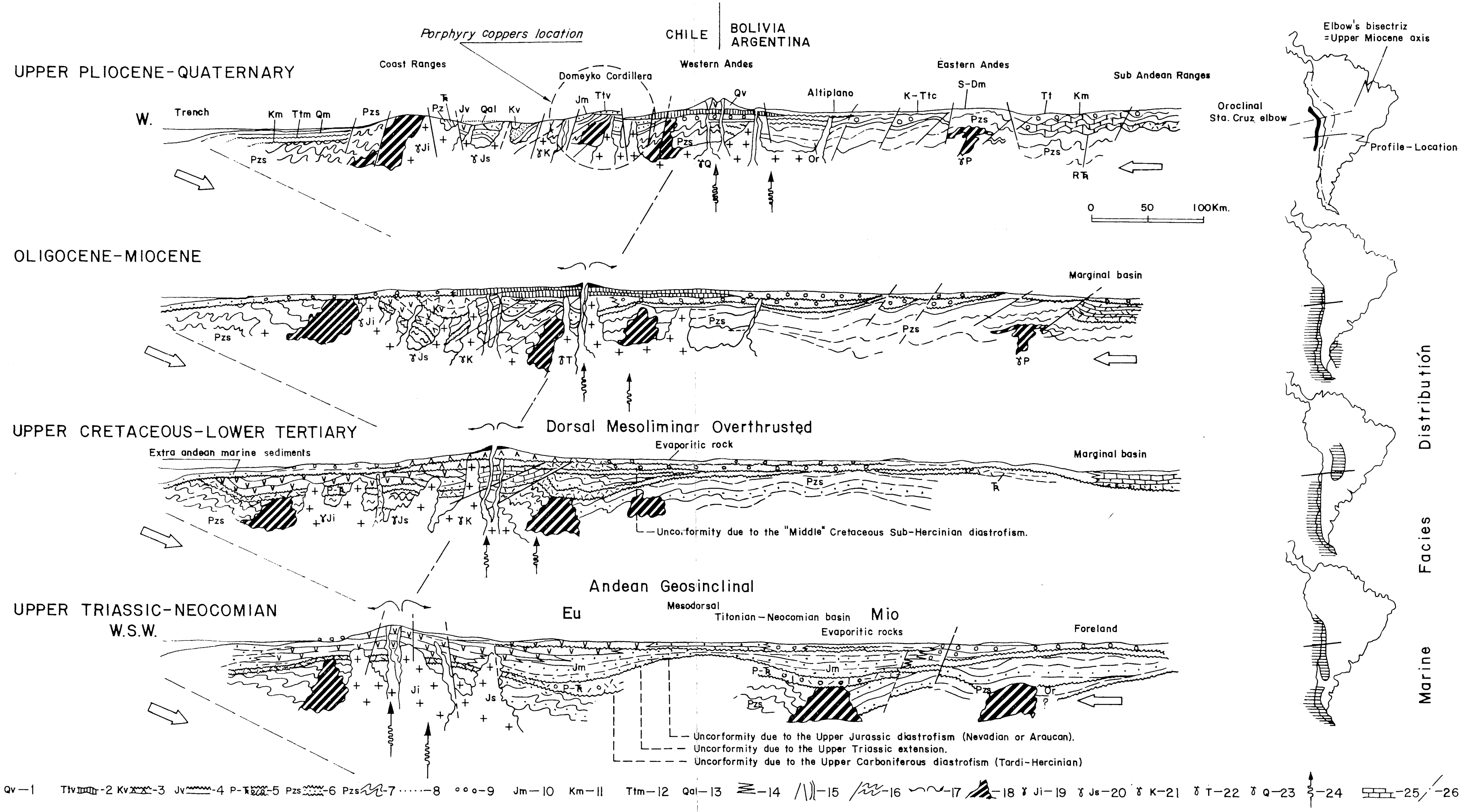
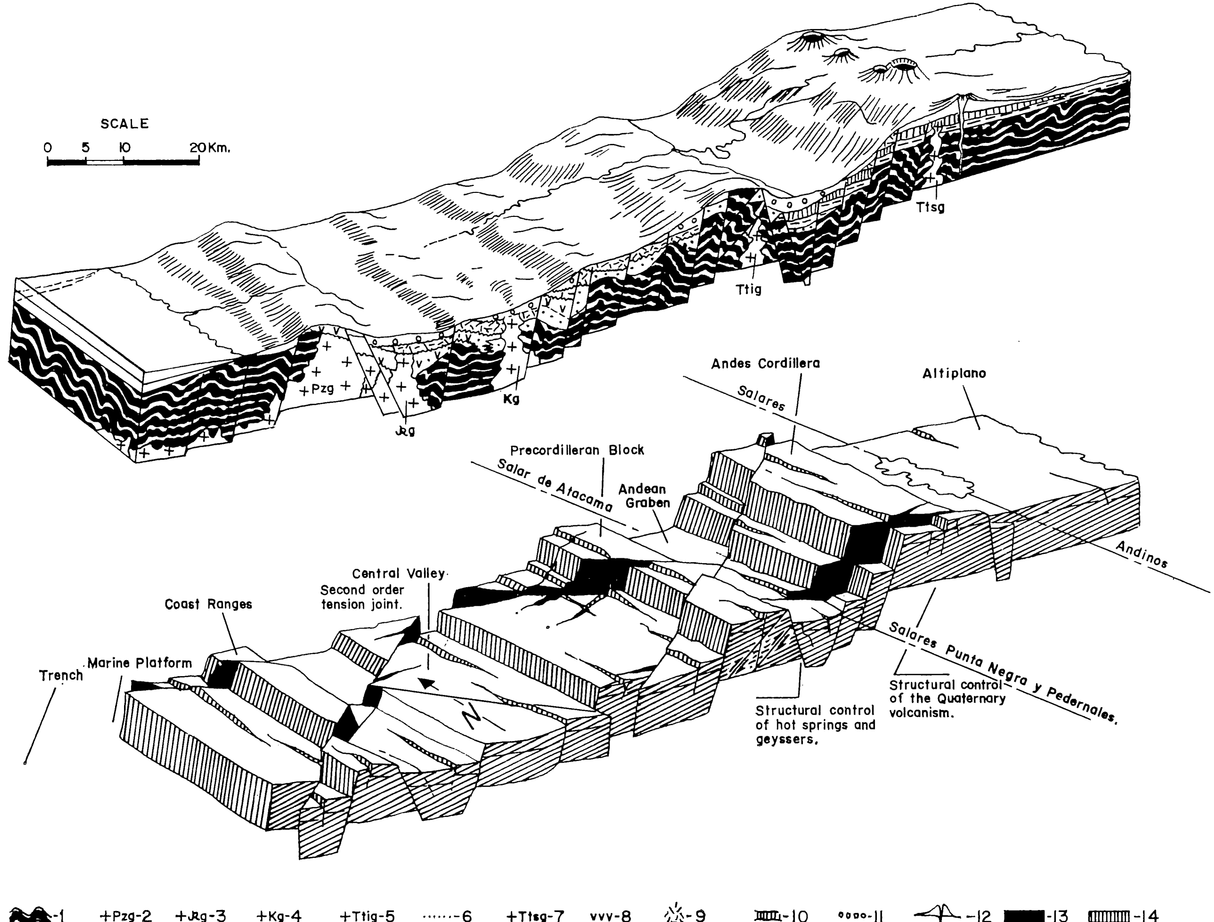


Fig. 3. — Generalized tectonic-stratigraphic evolution profile across the Andean geosynclinal system.

1. Quaternary volcanic rocks; 2. Tertiary volcanic rocks; 3. Cretaceous volcanic rocks; 4. Jurassic volcanic rocks; 5. Permian and Triassic continental rocks; 6. Palaeozoic sedimentary rocks; 7. Palaeozoic metasedimentary rocks; 8. Marine sedimentary rocks; 9. Continental sedimentary rocks; 10. Marine Jurassic rocks; 11. Marine Cretaceous rocks; 12. Marine Tertiary rocks; 13. Quaternary sediments; 14. Interfingering; 15. Extension structures; 16. Compression structures; 17. Calcalkaline volcanism; 18. Palaeozoic granitic rocks; 19. Lower Jurassic granitic rocks; 20. Upper Jurassic granitic rocks; 21. Cretaceous granitic rocks; 22. Tertiary granitic rocks; 23. Quaternary magmatism; 24. Active magmatism; 25. Limestone facies; 26. Magmatism migration toward the foreland.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Ttsg
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Andes Cordillera
Altiplano
Salares
Precordilleran Block
Salar de Atacama
Andean Graben
Andinos
Central Valley
Second order tension joint.
Coast Ranges
Marine Platform
Trench
Salares Punta Negra y Pedernales.
Structural control of the Quaternary volcanism.
Structural control of hot springs and geyssers.
-1
+Pzg-2
+Jrg-3
+Kg-4
+Ttig-5
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+Ttsg-7
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Fig. 4

The metallogenetic importance of the volcanism in Chile is under discussion. On the one hand there is a close relationship between calcalkaline volcanism, mobile belts and base metal mineralizations. On the other hand, Oyarzún (1973) has suggested that the concentration of copper in the Chilean andesites is normal for this type of rock and that their metallogenetic role would mainly depend on the mechanism that controlled their segregation.

Nevertheless, high copper values are generaly found in acid volcanic rocks. El Hinnawi and others (1969) found 3 to 1800 p.p.m. Cu in ignimbrites and rhyolites from Northern Chile, their suite of samples having more than 300 p.p.m. Cu in 20 % of it. This fact is important to consider, since it appears to be a genetic connection between some Tertiary rhyolites and porphyry copper-type and other polymetallic mineralizations (e.g. Potrerillos, El Salvador).

Finally, the extension tectonism that occurred in the Upper Tertiary uplifted the Precordilleran and Cordilleran blocks, which locally coincide with the mesodorsal zone at Sierra de Moreno, Cordillera de Domeyko, etc. That uplift caused the outcroping and/or secondary enrichment of some porphyry copper-type orebodies.

PLATE TECTONICS; METALLOGENETIC MODELS

The relation between porphyry copper deposits and global tectonics phenomena has been considered by several authors. Brousse and Oyarzún (1971), Sillitoe (1972), Mitchell and Garson (1972) pointed out the possible metallogenetic role of the oceanic crust in the subduction zones. The water dragged together with the atmophile-rich oceanic sediments would enhance the formation of calcalkaline rocks (Mc Birney, 1960; Hamilton, 1968) and/or the generation of mineralizing phases. In this manner, the coincidence in space and time of the calcalkaline rocks and copper mineralizations could be the result of the same process : introduction of marine sediments along subduction zones.

Oyarzún and Frutos (1973) proposed a new model agreeing with that of Mitchell and Garson for the genesis of the tin-bearing porphyries (i.e. the transportation of Sn as volatile halogenide by F liberated in the subduction zone), but suggested a different genetic mechanism for the copper and polymetallic porphyry-type mineralizations. In their theory the generation of copper, polymetallic and tin-bearing porphyries, would be a product of the fractional distillation of sulphur and halogen compounds at different depths in the subduction zone, and therefore at different distances from the continental margin (Fig. 5). It was also suggested that the separation at depth of hydrogen sulphide as a product of the decomposition of pyrite and water introduced with the lithospheric plate was due to their instability under the thermodinamic conditions existing in the lower portions of the subduction zone. Thus, the sulphur liberated from the conversion of FeS_2 to FeS under deep magmatic conditions would combine with the hydrogen released from the water, while the oxygen is used in the generation of calcalkaline magmas under oxidizing conditions (E. F. Osborn, 1968).

The same authors suggested that the upward migration of the H_2S to high levels in the crust would be responsible for the porphyry copper mineralization through the segregation of sulphides of Fe, Cu, Mo and other sulphophile metals contained in the calcalkaline magmas, brines, or sedimentary-volcanic formations intruded by the porphyries. Moreover, with this mechanism, it is unnecessary to postulate anomalous metal contents in the calcalkaline magmas.

Nevertheless, as magmatic differentiation continues with increasing acidity (and K content) it would concentrate the free metal content and enhance the separation of sulphides. This would explain the relation of the ore bodies with quartz-porphyries and rhyolites and also with the frequent presence of potassic alteration. The excess of H_2S would give rise to the formation of sulphur deposits, usually located in the Andean Volcanic Chain in a band parallel to but at higher levels and always more to the foreland than that of the porphyry copper deposits (Fig. 5).

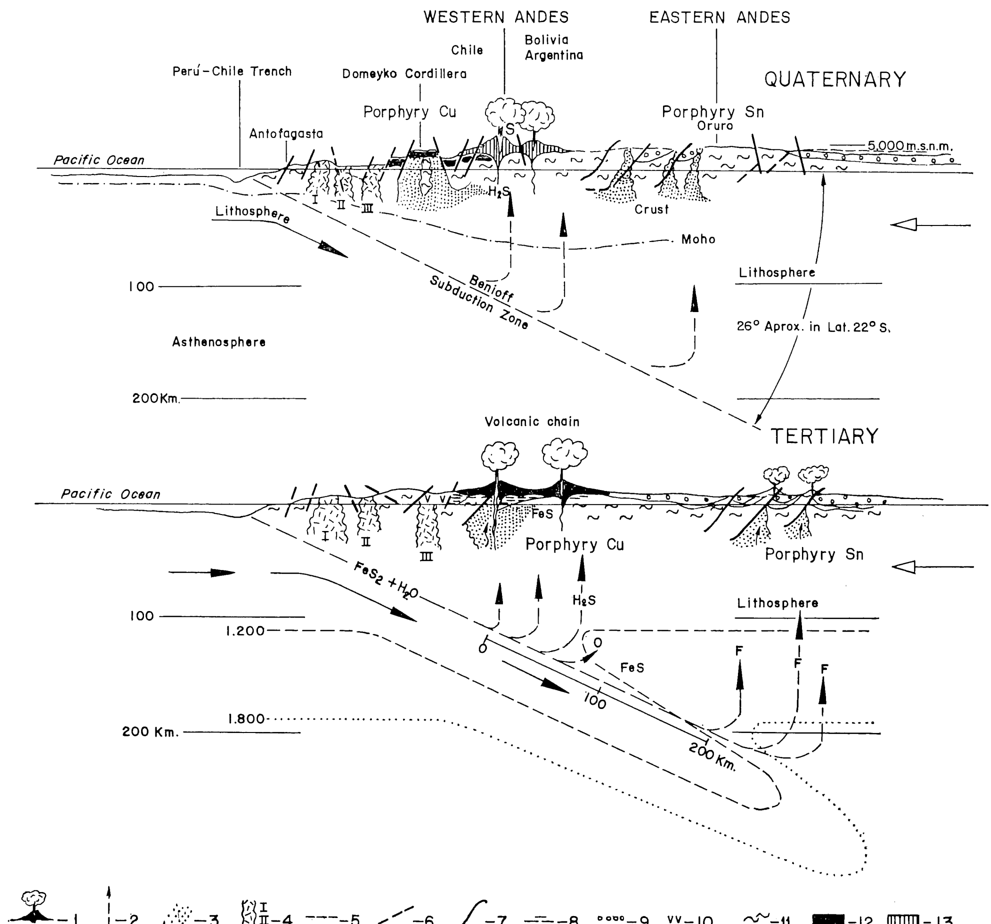

Fig. 5. — Porphyry coppers and tin-bearing porphyries.
Global tectonic genetic model (after Oyarzún and Frutos, 1973).

1. Active volcanism; 2. Active magmatism; 3. Tertiary hypabyssal igneous rocks; 4. I. Triassic-Lower Jurassic granitoids, II. Upper Jurassic granitoids, III. Cretaceous granitic rocks; 5. Quaternary continental sediments; 6. Normal faulting; 7. Reverse faulting; 8. Jurassic marine-evaporitic sediments; 9. Cainozoic continental sediments; 10. Mesozoic andesitic rocks; 11. Palaeozoic sedimentary rocks; 12. Tertiary volcanic rocks; 13. Quaternary volcanic rocks.

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