METALLOGENIC EPISODES OF THE CENTRAL ANDES

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Summary

It has been recently demonstrated that evolution of magmatic activity, under certain pressure conditions, produced the right circumstances to form large ore deposits. Most of the large world-class deposits of Chile and Argentina may be explained by the right combination of a differentiated magma and proper crustal thickening.

If it is accepted that timing of thickening varies from north to south along the Andean Cordillera, it can be explained why the different large ore forming processes become younger to the south. The main mineralization in the Maricunga belt is between 13 and 11 Ma; in El Indio, 12 to 10 Ma; the mineralization in the Pelambres District about 10 Ma; in Pachón, about 9 Ma; Los Bronces-Río Blanco from 7 to 4.9 Ma and in the El Teniente approximately 4,9 Ma.

A similar trend is observed in a west to east transect along the flat-slab segment. The shallowing of the Benioff zone, since the early Miocene produced a migration of the magmatism toward the foreland, at the same time that the orogenic front and the subsequent thickening of the crust, migrated in the same direction. In this scenario, the timing of mineralization is decreasing to the east: epithermal deposits at El Indio are between 12 and 10 Ma; gold skarn at Gualilán about 9 Ma; and the Famatina Mo-Au porphyries, between 4 and 3 Ma.

Based on the previous concept, several distinct metallogenic processes have been identified, as responsible of the world-large deposits found in this sector of the Central Andes.

Introduction

The present tectonic setting of the Central Andes is a combination of crustal shortening and thickening and lithospheric thinning above two shallow dipping (20°-30°) and one flat-slab (approx. 0 to 5°) segments of the Nazca subducted plate (Isacks, 1988). The shortening accommodated by the interaction of the Nazca plate and the continental South America plate has different geometries according to structural provinces involved. But, as a general trend, it may be established that the orogenic shortening decreases as the age of oceanic Nazca plate diminishes towards the south (Fig. 1).

It is important to remark, that timing of deformation is approximately coeval, and has periods of high orthogonal convergence rates, as for example the interval between 20 and 10 Ma. These periods of maximum convergence rates alternated with periods of low orthogonal convergence. These low orthogonal rates are associated with important oblique convergence, as the one developed between Late Eocene – Oligocene times, responsible of prominent strike-slip displacements in the forearc. Transtensional areas along the strike of these faults controlled the emplacement of important porphyry copper ore bodies such as Chuquicamata and La Escondida among others.

Recent studies have demonstrated that evolution of magmatic activity, under certain pressure conditions, produced the right circumstances to form large ore deposits (Kay *et al.*, 1999). Most of the large world-class deposits of Chile and Argentina may be explained by the right combination of a differentiated magma and proper crustal thickening. Figure 2 shows the relationship between crustal thickening, amphibol break-down, and mineralization.

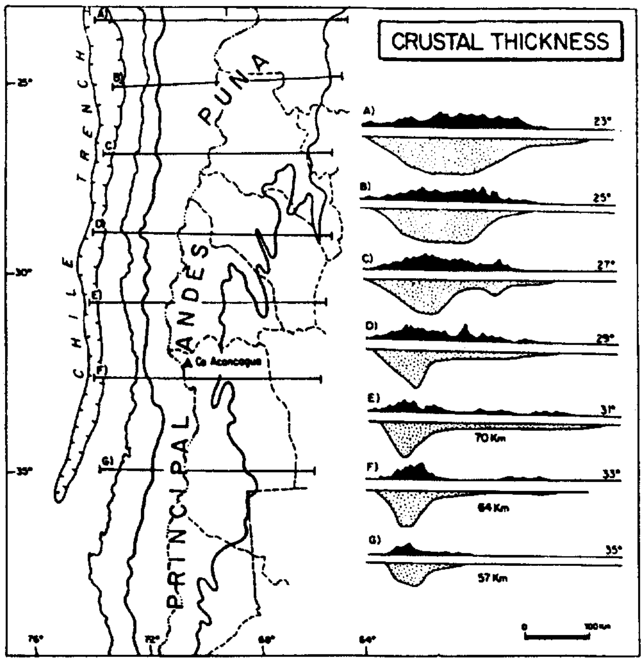

Fig. 1. Cross-section of the crustal roots of the Andes (after Introcaso *et al.*, 1992)

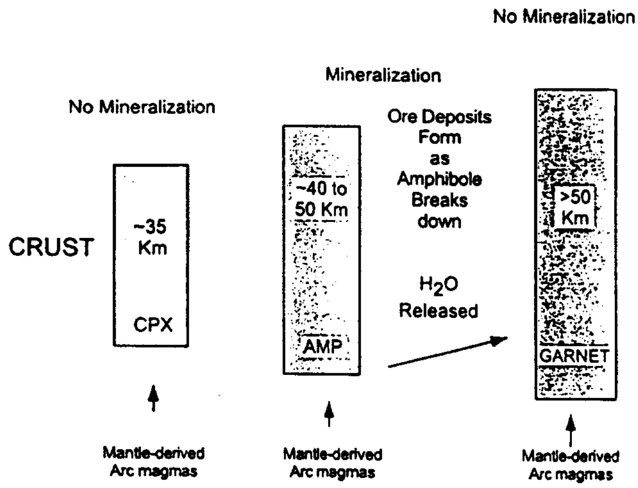

Fig. 2. Summary diagram showing correlation between crustal thickening, principal mafic residual mineral assemblage and formation of Andean world-class deposits (after Kay *et al.*, 1999)

Modern Plate Tectonic Setting

The Central Andes present a series of first order tectonic features that controls the magmatic activity, the timing and location of deformation, and the present main ore districts. In spite of the great variability of structural styles and magmatic activity along strike, there are many things in common along the region. These common tectonic and magmatic features constitute a series of major crustal discontinuities, which outstands from the tectonic framework of the Andes due to their regional importance. These major crustal features are the wrench faults developed during oblique convergence in the Cenozoic forearc, the northwestern trending lineaments, and terrane crustal boundaries.

Domeyko Paleogene Fault System

This is a wrench fault system active during Late Eocene – Early Oligocene times from north of 22° S to at least 28°S latitude. This fault system has been locally reactivated during Neogene times. The importance of this system is that it controlled the formation of local areas of trasnpressive and transtensional regimes during stages of oblique convergence. Associated with the transtensional regime, a series of openings favored the location of important porphyry copper systems, such as Chuquicamata, Chuqui Norte, La Escondida, Zaldívar, and El Salvador. These porphyries have been emplaced during late Eocene and Oligocene times.

South of 28°, the system is not so linearly developed, and several splays take account of the lateral displacement. The Paleogene system intersects El Tránsito Triassic rift, and a complex tectonic inversion is developed. Further south, the Pocuro fault located at 32°S, could be the southernmost continuation of the Paleogene system, but the kinematics of this fault are unknown. It has been interpreted either as a normal or as a reverse fault.

Northwest Trending Lineaments

There are several northwest trending lineaments, some of them well known in the literature, as the El Toro – Olacapato lineament. These features, which are interpreted as major crustal boundaries, were inherited from previous deformation. They are interpreted as deep structures that exerted a strong influence in the paleogeography of the different sequences, and even in the migration of the magmatism to the foreland. The El Toro – Olacapato trend is really outstanding. This trend displaced the Early Paleozoic platform edge several kilometers with a right lateral slip. It controls the emplacement of one of the few granitoids of Oligocene age except for the Domeyko system, the Acay Granite. The large Miocene stratovolcanoes are emplaced along this line, and even some calderas like Aguas Calientes have collapsed in the proximity. Epithermal mineralization of gold and silver is well known in Quevar and Organullo.

El Tatio – Pairique lineament is another important feature. It is related to a series of calderas, being Pairique the easternmost caldera. It may also be interpreted as continuing in the Coranzulí caldera. There are many geological features associated with this lineament besides the evident control in the Late Cenozoic volcanism. Several gold occurrences such as the Rosario de Coyaguaima Jesuitical gold mining district are aligned with this trend.

Another outstanding northwest lineament is the El Salvador – Agua Rica trend. Although this trend cannot be identified as a fault system as the previous ones, a set of volcanic bodies of Miocene to Pliocene age extends from El Salvador Paleogene porphyry copper in Chile, up to the Agua Rica Late Miocene porphyry. This trend not only includes Bajo de La Alumbrera and other epithermal systems in the Farallón Negro district, but also several others. Laguna Amarga caldera, with gold anomalies in the Puna, as well as Hoyada Honda, Cerro Azul, Laguna Colorada and Vicuña Pampa are caldera-like features associated with some hydrothermal alterations and mineral occurrences.

As the cordillera narrows to the south, the lineaments are not that long, but the tectonic control is as relevant and conspicuous as the previous ones. The Valle Ancho northwest lineament can be considered as an example, intersecting the Maricunga belt and in the Argentine side associated with three epithermal systems: Valle Ancho, Laguna Verde and Los Aparejos.

The northwest lineaments between 28° and 33°S seem to be related to the Triassic rift system, as it is seen in La Ramada fold and thrust belt. This is a thick-skinned belt developed by tectonic inversion of the Triassic rift. This link to the Northwest extension is seen again in central Mendoza south of 35°S.

Terrane Crustal Boundaries

These features constitute major structural crustal boundaries that control the limits of Paleozoic magmatic arcs, the emplacement of mafic and ultramafic rocks, and different types of justapoxed basements. These boundaries are also significant zones of weakness that affect to great depths the entire crust. When the terrane outlines are observed in relationship with the mineral occurrences, it is evident the control that exerts in their location. For example, the boundary between Chilenia (mainly exposed in Frontal Cordillera) and the Precordillera terranes, exposes in the Uspallanta, Calingasta and Iglesia valleys, an important Devonian suture. The Late Paleozoic magmatic arc is just west of this suture, and most of the mineral anomalies precisely follow that boundary.

Andean Ore Deposits, Magmatism and Crustal Thickening

If it is accepted that timing of thickening varies from north to south along the Andean Cordillera, it can be explained why the different large ore forming processes become younger to the south. The main gold porphyry mineralization in the Maricunga belt is between 13 and 11 Ma; in the epithermal gold of El Indio 12 to 10 Ma (Mpodozis *et al.*, 1995); the porphyry copper mineralization in the Pelambres district about 10 Ma; the Pachón porphyry copper about 9 Ma; Los Bronces-Río Blanco at 7 to 4.9 Ma (Warnnars *et al.*, 1985) and in the El Teniente approximately 4,9 Ma (Skewes and Stern, 1994). This trend is coherent with the decrease in thickness of the Andean roots to the south, and therefore the delay in reaching the critical thickness through the Andean deformation.

A similar trend is observed in a west to east transect along the flat-slab segment. The shallowing of the Benioff zone, since the early Miocene produced a migration of the magmatism toward the foreland, at the same time that the orogenic front and the subsequent thickening of the crust, migrated in the same direction. In this scenario, the timing of mineralization is decreasing to the east: epithermal deposits at El Indio are between 12 and 10 Ma; gold skarn at Gualilán about 9 Ma; and the Famatina Mo-Au porphyries, between 4 and 3 Ma.

A similar trend is also observed north of the previous transect, between the Maricunga belt to the west, 13 to 11 Ma, and the 8-7 Ma Bajo de la Alumbrera gold and copper porphyry (Sllitoe, 1991).

Therefore, it may be assumed that a continuous trend of decreasing ages for the mineralization is observed from north to south, and from west to east, in a parallel path to the thickening of the continental crust.

Based on the previous concept, several distinct metallogenic processes have been identified, as responsible of the world-large deposits found in this sector of the Central Andes.

Maricunga-El Indio-Pachon-Los Bronces-El Teniente Belt

Along the flat-slab segment, and its northern and southern extensions, the Late Miocene magmatic arc is preserved. This belt has not been covered by recent volcanism. In the north, the Maricunga belt was covered by ignimbrites from the large calderas and volcanic flows, as it can be observed in the southern Puna. To the south, the Pliocene to Quaternary stratovolcanoes obliterate the Latest Miocene volcanic arc. The fact that the volcanic front migrated eastwards, gave the chance of preserving the Miocene volcanic edifices, and their epithermal mineralization.

Most of the main gold and copper prospects are located in this belt, and many of them are presently under active exploration. Although this is one of the most evident areas to be explored, the length and the large amount of alteration zones do not preclude the selection of potential areas within this belt. Figure 3 shows the main prospects in the central part of the belt.

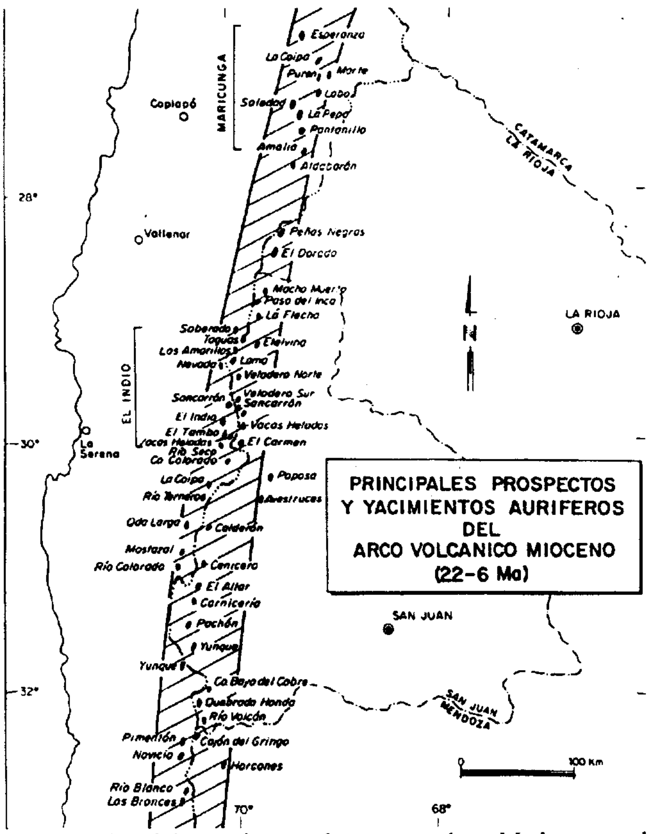

Fig. 3. Main mining projects and prospects along Maricunga and El Indio Belts.

Foreland Arc Volcanism in the Flat-Slab Segment

As thickening and volcanism shifted to the east during the shallowing of the Benioff zone, a series of fertile volcanic centers was developed. Depending on the timing to obtain the critical thickening (approx. 45 km), some areas reached that thickness associated with the right volcanic composition, as for example the Famatina area (Introcaso *et al.*, 1992). Most of the porphyries that intersect the limestones of the Precordillera geological province, have the right thickening and a proper volcanic composition (Fig. 4). The development of gold districts such as Gualilán, Guachi, and Gualcamayo among others, with different ore types, from gold skarns to disseminated gold with intense silicification in dirty calcareous shales, occurred in areas exceeding the critical 45 km thickening.

The extension and distribution of these volcanic centers indicate an obvious alignment of the main centers. One of the most outstanding corridors is the El Salvador-Agua Rica northwestern-trending zone. It seems that east migration associated with the shallowing of the subduction zone, was favored by pre-existing weakness zones in the crust, that produced a noticeable east-shifting of the volcanic centers and associated mineralization.

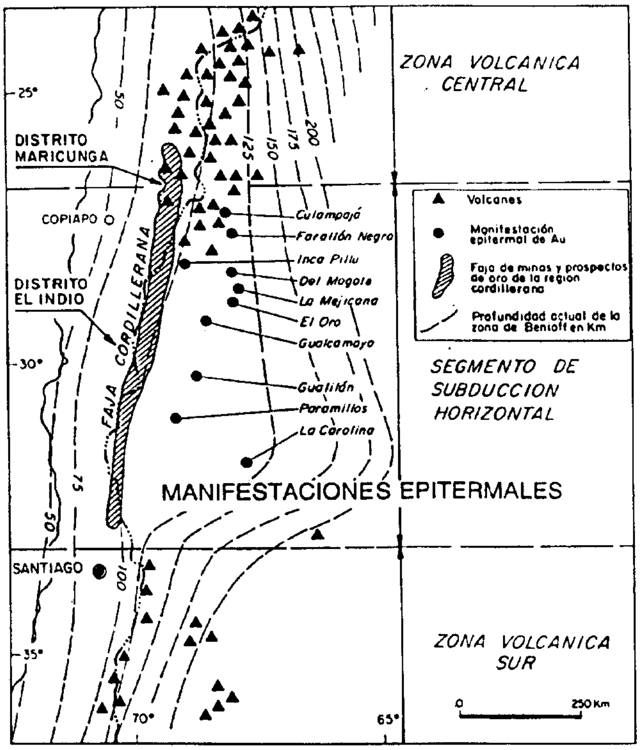

Fig. 4. Main Gold prospects related to Miocene- Pliocene volcanism in the flat-slab segment.

Extensive Latest Miocene-Pliocene Volcanism in Southern Puna

There are numerous areas of alteration, some of them coinciding with magnetic anomalies, associated with the Late Cenozoic volcanism. This volcanism covered the Maricunga Belt, but east of this belt, proper conditions could have also been obtained at younger times. Several stratovolcanoes such as El Quevar, Aguas Calientes, Pairique, Chipas, among others, have conspicuous hydrothermal systems, and are also aligned along northwestern trending fractures. Analysis of the composition of the widespread volcanism are required to evaluate the potential of this area.

The development of giant rhyolitic calderas, that remobilized large amounts of crust is associated in some cases with gold anomalies. The precise identification of there calderas and associated resurgent domes using large scale satellite imagery could guide the exploration.

Late Cenozoic Volcanism Associated with Large Calderas South of Tupungato

There are also favorable conditions to find fertile volcanism along the Andean axis south of 33°30'. As the Cordillera narrows to the south the critical thickness was only obtained along the central part of the belt, where large calderas are showing the development of important crustal melts. Along the Maipo and Atuel calderas there are many potential areas of interest. However, it is worth mentioning that the Late Cenozoic volcanism was not emplaced at an appropriate thickness south of 36°S as may be inferred from the crustal thickness reported by Introcaso *et al.* (1992).

The tectonic setting of El Teniente porphyry copper can also be obtained toward the east, at even younger times. The existence of younger volcanic centers should be properly evaluated in this region.

Conclusions

The evolution of magmatic activity, under certain pressure conditions produced the right circumstances to form large ore deposits. Most of the large world-class deposits of Chile and Argentina may be explained by the right combination of a differentiated magma and proper crustal thickening. Thus, several distinct metallogenic processes have been identified, as responsible of the world-large deposits found in this sector of the Central Andes.

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Acknowledgments

The author would like to thank Dr. Víctor A. Ramos, Laboratorio de Tectónica Andina, Universidad de Buenos Aires, Argentina, for his continuous support and input in our exploration efforts of the Central Andes.

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