SPACE-TIME RELATIONS BETWEEN MINERALIZATION AND MAGMATISM: ARGENTINIAN ANDES (27°-28°S)

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SUMMARY – New regional geological compilation and field work, including petrological and geochronological data, facilitated the reconstruction of the volcanic history of the southern end of Central Volcanic Zone in Argentina (between 27°-28°S). Cenozoic arc migration and broadening extended volcanism over several geological provinces such as Cordillera Frontal, Precordillera, Famatina and Pampean Ranges. Four major volcanic events built different volcanic arcs in this Andean segment: 1) a Paleogene magmatic arc, 2) an Oligocene-Early Miocene volcanic arc (the Maricunga Belt), 3) a Late Miocene volcanic arc which migrated and broadened to the east, and 4) a Pliocene-Quaternary volcanic arc that is today represented by fumarolic activity on Nevado's Ojos del Salado volcano. The volcanism developed above a thickened crust and was accompanied by the emplacement of important copper-bearing porphyries and development of epithermal precious metal deposits.

1. INTRODUCTION

The Andean mountain chain encompasses the record of a classic magmatic welt from subduction of oceanic crust under a continent. The Central Volcanic Zone (CVZ) of the Andes, an active volcanic arc (between 16°-28°S), developed along 1500 km of continental margin between Southern Peru and Northwestern Argentina. It is flanked to the north and south by zones of sub horizontal subduction (flat-slab zone) lacking active-volcanism (Barazangi and Isacks, 1976) and is bound by the Altiplano-Puna high plateau (average elevation of 3700 m above see level).
The Argentinean Andes mountain range between 27" and 28° *S* (Figure 1) includes the northern end of the flat-slab zone and the southern end of the CVZ. From Argentina to the Chilean border four morpho-structural units converge: Sierras Pampeanas, Famatina, Precordillera and Cordillera Frontal, (Figure 1). This is also a zone of transition between the Altiplano-Puna Plateau to the north and the basement cored Sierras Pampeanas to the south.
The subduction angle of the Nazca plate changes from 30° E, (under the Puna), to sub-horizontal south of 27° S in this area (Cahill and Isacks, 1992). Neogene andesitic volcanism also disappears to the south. In the flat-slab subduction zone there is eastwards migration of the volcanic arc and deformation in Argentina and Chile (Mpodozis *et al.,* 1996; 1997). This region also hosts the earth's highest stratovolcanoes composed of thick sequences of andesitic to dacitic lavas and pyroclastic flows intruded by dacitic to rhyolitic domes.
The Cenozoic volcanism is characterized by eruption through thick continental crust, in places over 70 km thick (Beck *et al.*, 1996). The extraordinary crustal thickening is essentially a Neogene phenomena, attributable to structural processes (Allmendinger *et al.,* 1997). On the basis of geochemistry and geophysical data, Kay and Mpodozis (2002) used magmatism as a tool in deciphering the Neogene tectonic evolution.
The Andean segment between 27°-28°S is increasingly important in terms of economic mineralization associated with Cenozoic volcanism.
The Maricunga Belt is an important gold district of the Central Andes, 20 km wide and about 200 km long in a N-S direction, starting in Chile and continuing into Argentina south of 27°30'S. It contains important epithermal deposits of gold and silver (La Coipa, Esperanza, Arqueros, Refugio, Marte and Cerro Casale), which are associated with central volcanic structures, dome complexes and hypabyssal intrusions. Ages range from 24 to 12 Ma (Sillitoe *et al.,* 1991; Mpodozis *et al.,* 1995). On the western border of the present Andean segment some exploration targets have been identified (e.g. Valle Ancho, Laguna Verde, Río Salado, Tres Quebradas) (Rubiolo, 1999) and farther east, in the Sierras Pampeanas, important Cu-Au-bearing porphyries and epithermal deposits are found.
Near the Chilean border there are mining exploration targets (e.g. Laguna Verde, Valle Ancho, Rio Salado) with similar characteristics to the epithermal Au-Ag Maricunga Belt deposits. In the eastern extremes of this segment, important Cu-bearing porphyries and hydrothermal deposits have been identified (e.g. Farallon Negro, Bajo La Aumbrera, Agua Rica, etc.). Many Cu-Ag-Au mineral deposits are associated with Cenozoic volcanic rocks, and have some specific petrochemical characteristics.

2. METHODOLOGY AND OBJECTIVES

In order to understand the space-time relationship between volcanism, tectonism and metallogeny, it

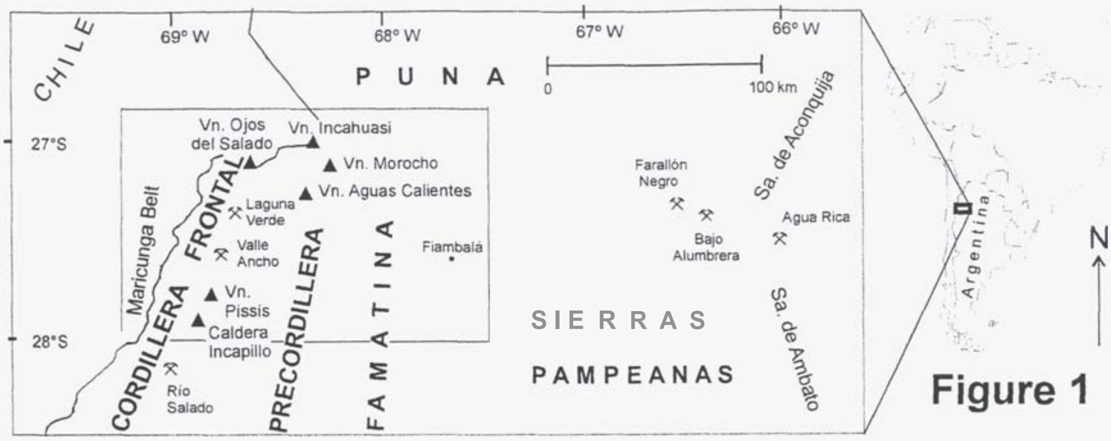

Figure 1: Location of the study area in the Andes between 27" and 28°S (Argentina).

was fundamental to prepare an updated regional geologic map on scale 1:250,000. This work compiled new and existing information on the regional distribution of eruptive centres and magmatic rocks, petrology, geochemistry of major and trace elements (Figures 3 and 4), and mineral and whole rock K/Ar and $^{40}Ar/^{39}Ar$ isotopic dates (Figure 2). These new regional studies were done (in part under the Multinational Andean Project), **from** Sierras Pampeanas to the Chilean border between 27" and 28" S.

3. CENOZOIC MAGMATIC HISTORY

The Cenozoic magmatic history began with the development of a 'Paleogene volcanic arc in Chilean territory **(40-28** Ma). Neogene volcanism started about 26 Ma, and migrated to the east from 17 to 12 Ma. At this time, the flat subduction zone developed in the northern Puna (Kay et al., 1999). The distribution of the igneous units in space and time is shown in Figure 2.

3.1 Magmatic Stage 1

During the Oligocene-Lower Miocene (27-17 Ma) a volcanic arc formed the Maricunga Belt (Mpodozis et al., 1995), about 200 km long by 20 km wide. This volcanic belt was weakly developed in Argentina between 27°-28°S and is represented by intrusive rocks and porphyries (OMip) and volcanic and volcano-sedimentary rocks (OMiv). In addition, a series of intramontane basins with continental red-bed deposits developed (EMis). The Maricunga belt contains important epithermal Au-Ag and porphyry Cu-Au deposits associated with central volcanic structures, dome complexes and hypabyssal intrusions. Ages range from 23-21 Ma (Sillitoe et al., 1991; Mpodozis et al., 1995; Zappettini et al., 2001).

3.2 Magmatic Stage 2

During the Middle Miocene (17-11 Ma) the volcanic arc continued migrating to the east, where it is dominated by intermediate volcanic rocks (Mmv) and pyroclastic felsic rocks (Mmt). A second mineralization episode in the Maricunga Belt is linked to the emplacement of 14-12 Ma fault-controlled "gold porphyries" (e.g. Mina Marte; Sillitoe et al., 1991), near the end of the second volcanic stage. This mineralization is found only in subvolcanic domes or porphyritic rocks, and erosional remnants of pyroclastic flows free of hydrothermal alteration.

3.3 Magmatic Stage 3

In the Late Miocene (11-5 Ma) the volcanic arc rapidly migrated and broadened to the east. Predominantly andesitic and dacitic rocks (Msv) were erupted accompanying by dacitic pyroclastic flows (Mst). Farther east, copper porphyries and epithermal gold mineralization (9 – 6 Ma; Sasso and Clark, **1988)** occurred in the Pampean Ranges in the Farallon Negro volcanic field (e.g. Mina La Alumbrera, Agua Rica, not on the map).
Hyaloclastite and till material interbedded with dacitic-andesitic lavas from the Cordillera Frontal (7.59 ± 0.08 Ma, dated by $^{40}Ar/^{39}Ar$, Rubiolo *et al.*, 2000) show evidence of interaction between felsic magma and glacial ice in a region today dominated by strongly arid conditions. This suggests a humid cold climate during the Late Miocene for the Central Andes at the 27° S., as opposed to the extreme dryness that dominates at the region at this moment. Also Neogene sedimentary deposits to the east (in the Pampean Ranges), contemporary with those volcanic rocks, show evidence of a climate more humid than the present one. Strong aridization has taken place since the Pliocene in association with uplift of the Pampean Ranges (sierras de Aconquija and Ambato) in the east.

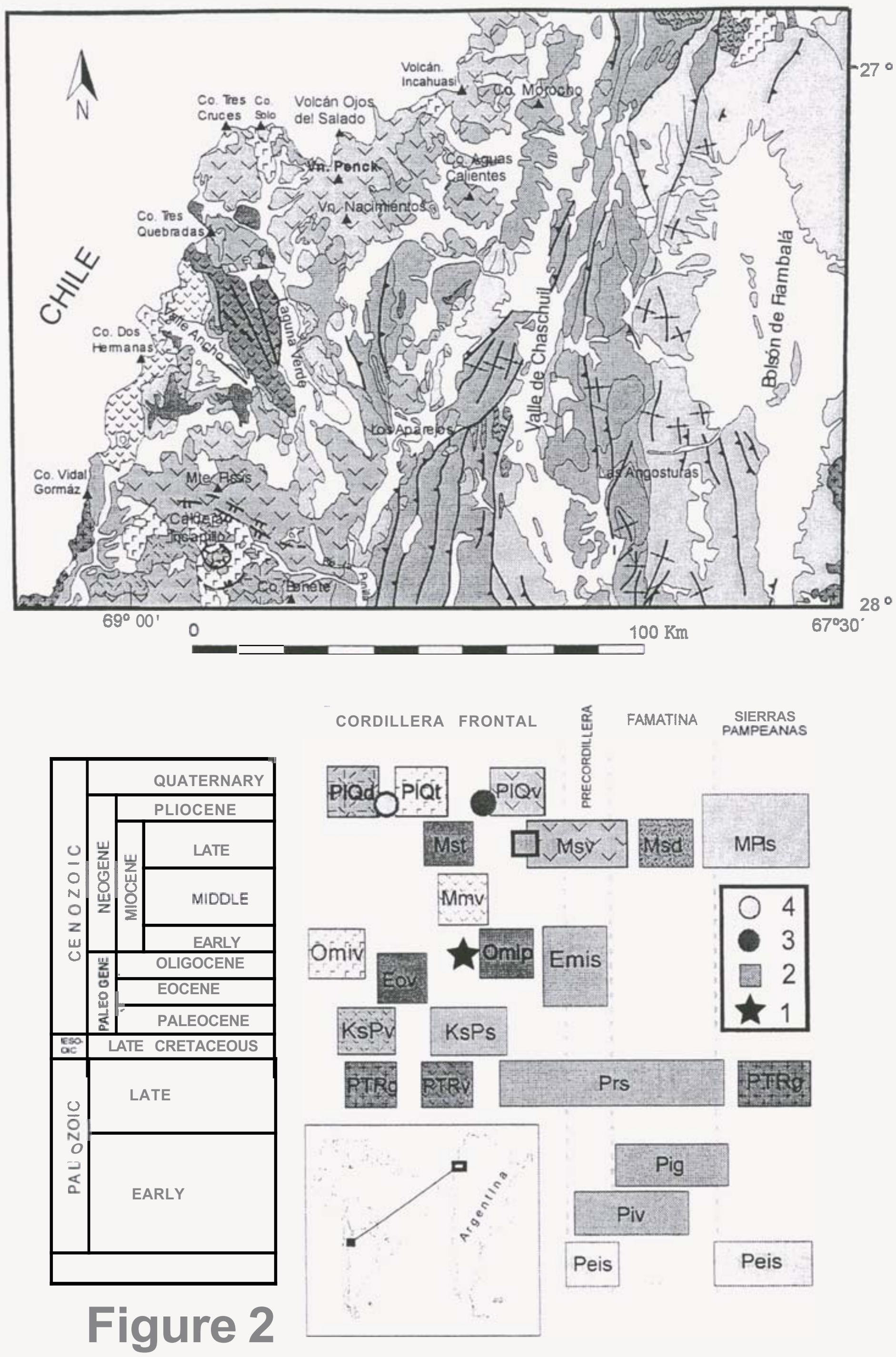

Figure 2

Figure 2: Regional overview of Andean geology between 27° and 28°S in Argentina.

Pre-Cenozoic units: Peis: Low to medium grade metamorphic rocks; **Piv:** Marine sedimentary rocks with interbedded volcanic sequences, locally mafic and ultramafic rocks; **Pig:** Intrusive rocks (540–420 Ma); **PTRg:** Intrusive rocks (420–200 Ma); **PTRv:** Volcanic and volcano-sedimentary rocks.

Cenozoic volcanic and volcano-sedimentary units: KsPv: Volcanic and volcano-sedimentary rocks (80-55 Ma); **EOv:** Intermediate volcanic rocks (40-28 Ma); **Magmatic stage 1=OMip:** Intrusive rocks and porphyries (27-17 Ma); **OMiv:** Volcanic and volcano-sedimentary rocks (27-17 Ma); **Magmatic stage 2=Mmv:** Intermediate volcanic rocks (17-11 Ma); **Mmt:** Pyroclastic rocks (17-11 Ma); **Msv:** Intermediate volcanic rocks (11-5 Ma); **Mst:** Pyroclastic rocks (11-5 Ma); **Magmatic stage 3= PlQv:** Intermediate to mafic volcanic rocks. Include debris flows (<5 Ma); **Magmatic stage 4= PlQd:** Domes and domes complexes (<5 Ma), **PlQt:** pyroclastic rocks (<5 Ma).

Sedimentary rocks: Prs: Marine and continental sedimentary rocks; **KsPs:** Continental sedimentary rocks; **EMis:** Continental sedimentary rocks with evaporite intercalations; **MPls:** Continental sedimentary rocks with pyroclastic intercalations.

3.4 Magmatic Stage 4

From the Pliocene to Quaternary (<5 Ma), the volcanic arc contracted and **is** now active only in the present border area between Argentina and Chile. It is comprised of felsic domes (PlQd), pyroclastic rhyolitic-dacitic flows (PIQt) and dacitic-andesitic volcanic rocks (PlQv). During the Quaternary some rare intermediate and basic lavas were erupted (e.g.Volcán Incahuasi) and explosive activity has occurred. At the present time volcanism is represented by fumarolic activity on Nevado's Ojos del Salado volcano ***(6864*** m).

3.5 Chemical composition

The Cenozoic magmatic units belong to a high-K calc-alkaline series and ranges from basaltic andesite to rhyolite. The geochemistry of major and REE elements (Figure **3** and **4)** can serve as a guide to relative crustal thickness. Increasing Sm/Yb ratios mostly reflect pressure-dependant changes from clinopyroxene to amphibole to garnet in the mineral residue in equilibrium with evolving magmas (Kay ***et al.***, 1999).

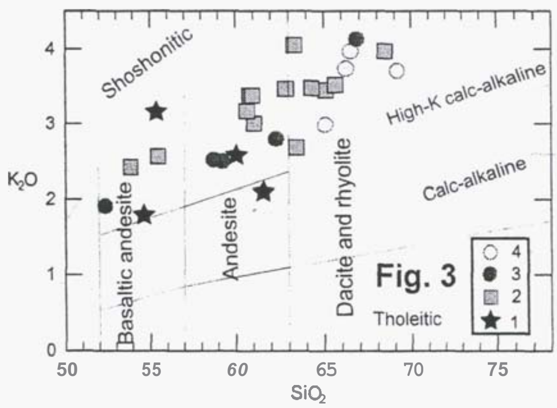

Figure **3:** Plot of K_2O versus SiO_2 (Peccerillo and Taylor, 1976). The Cenozoic magmatic units **belong** to a high-K calc-alkaline series and ranges **from** basaltic andesite to rhyolite.

Sm/Yb ratios can serve as a guide to relative crustal thickness. REE patterns of volcanic rocks **from** the first magmatic stage (Omiv) suggest amphibole-bearing lower crustal residues as the origin (Figure **4)** consistent with a thickened crust over a shallower subduction zone (Kay ***et al.,*** 1999). This followed by the release of fluid in conjuction with breakdown of the amphibole-bearing crystal assemblages in the crustal melt zones during subhorizontal shortening and thickening of the crust. During the mineralization **stage** the amphibole breaks down to garnet in a thickening lower crust in response to increasing pressures. The REE pattern for these volcanic rocks show garnet residual in the source phase (Kay et al., 1999).

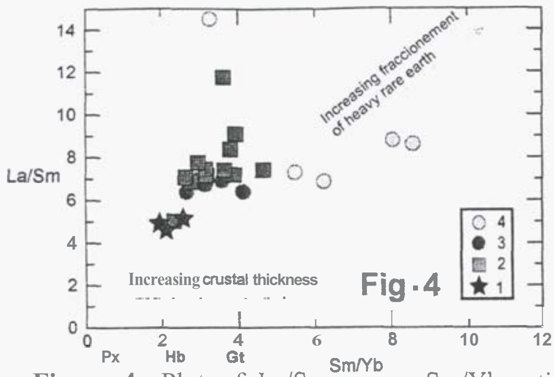

Figure 4: Plot of La/Sm versus Sm/Yb ratios monitoring the behaviour of the slopes of the light and heavy REE, respectively. Increasing heavy REE ratios are attributed **from** pyroxene (Px) to increasing amounts of amphibole (Hb) and garnet (Gt) in the mineral residue of the magmas (symbols are the same **as** in Figure **3).**

4. DISCUSSION

The Andean segment between 27° -28° S is **an** interesting region for studying magmatic arc migration and expansion because it: 1) includes development of the Cenozoic magmatic arc across different geological provinces or morpho-structural units; b) represents the southern end of the CVZ of the Central Andes, with a transition, towards the south to the zone of flat-slab subduction; and c) includes important epithermal deposits and Cu-bearing porphyries associated with the Cenozoic volcanism.

This region also includes Cenozoic and Holocene pyroclastic deposits that are exceptionally well preserved. Some eruptive centres are also potentially active (volcanoes Ojos del Salado, Tres Cruces, Incahuasi, Incapillo, etc).

Petrologic and a regional studies associated the magmatism in this region with changes in the subduction angle (Coira and Kay, 1993).

These characteristics could reflect changes in the subduction geometry (Mpodozis ***et al.,*** 1995; Sasso and Clark 1998; Kay ***et al.*** 1999).

During Late Miocene time, deformation ceased in the Cordillera Frontal and Altiplano, when the tectonically active domain was displaced to the east, upon the initiation of compressive deformation at the foreland front. Cenozoic foreland basins and a fold and thrust belt accompanies the volcanic arc migration towards the east and broadening of the arc in the Neogene to reach the Pampean Ranges. This phenomenon has been considered a consequence of crystalline basement thermally weakened by the Late Cenozoic magmatism.

Uplift and deformation of Cordillera Frontal, Precordillera, Famatina and Sierras Pampeanas follows the eastward propagation of arc magmatism. This relationship implies that uplift and deformation are more likely related to thermal weakening and crustal anisotropies than to

fluctuations in horizontal compressive stress (Ramos *et al.,* 2002). Eastward propagation of magmatism to the foreland since Late Miocene should have played an important role in the thermal crustal history. The crust developed brittle-ductile transitions allowing uplift of an old basement-cored block.
Variations in subduction geometry during Cenozoic time were responsible for a broadening of the magmatic arc during the Late Miocene and therefore higher thermal gradients. These high gradients favoured softening of the lower crust and later, and importantly, thickening and uplift of the basement cored Pampean Ranges to the east.
The chemical, spatial and temporal distribution of late Oligocene to Recent magmatism in the CVZ can be broadly explained by changes in the dip of the subducting Nazca Plate and the thickness of the lithosphere mantle and crust beneath this segment of the Andes (Coira and Kay, 1993).
Temporal changes in lithosphere and crustal thickness were tracked by using REE elements as guides to pressure-sensitive residual minerals and source melting percentages (Kay *et al.,* 1999).
As a rough guide in mafic lavas, clinopyroxene is dominant at depths of <35 km, amphibole from ca 30-45 km and garnet at >45-50 km. Kay *et al.* (1999) present a model in which mineralization is linked to changes in crustal and lithospheric thickness induced by evolving geometry of the subducting Nazca plate.
The mineralization stages are linked to the evolution of fluid phases in conjuction with breakdown of the amphibole-bearing crystal assemblages in the crustal melt zones during subhorizontal shortening and thickening of the crust. As a result of amphibole breakdown and mineralization, garnet is stable in a thickening lower crust in response to increasing pressures. The REE pattern for volcanic rocks derived from melting these source rocks show garnet residual in the source phase (Kay et al., 1999).

5. CONCLUSION

A recent regional geological compilation and new field work has added petrologic and geochronologic data, increasing our understanding of this region and permitting a more detailed reconstruction of the volcanic history of the region.
The Cenozoic magmatic history began with the development of a Paleogene volcanic arc in Chilean territory (40-28 Ma). Neogene volcanism started about 26 Ma, and migrated to the east fkom 17 to 12 Ma. At that time, the flat subduction zone developed in the northern Puna (Coira and Kay, 1993).
REE patterns of the first magmatic stage suggest amphibole-bearing lower crustal residues as the origin (Figure 4) consistent with a thickened crust over a shallower subduction zone (Kay *et al.,* 1999). Andesitic units that erupted in the second magmatic stage have higher light/heavy REE ratios consistent with a more garnet-rich residual mineralogy at deep levels of a thicker crust. Near the end of this second magmatic stage a mineralization episode linked to the emplacement of 14-12 Ma "gold porphyries'? at Maricunga Belt (Sillitoe *et al.,* 1991) occurred. REE pattern of these magmas indicate also an amphibole-bearing residue.
The final mineralization in the Andean segment between 27" -28°S occurred at 9-6 Ma in the Farallon Negro Volcanic Complex to the east (Sasso and Clark, 1998). Since the Pliocene, uplift of the Pampean Ranges (sierras de Aconquija and Ambato) in the east (Figure 1) has occurred.
During the Quaternary, some rare intermediate and mafic lavas were erupted and explosive activity has occurred in the Cordillera Frontal. At the present time volcanism is represented by fumarolic activity on Nevado's Ojos del Salado volcano (6864 m).

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