# Insights on the Effects of the Hydrothermal Alteration in the El Laco Magnetite Deposit (Chile)

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## INTRODUCCIÓN

The understanding of the origin of the recent (ca. 2 Ma) El Laco deposit (Fig. 1), with near 1 Gt of almost pure magnetite/hematite, is considered critical for the interpretation of the Kiruna type magnetite-apatite style of mineralization, an end-member of the IOCG group of deposits. Despite the abundant studies conducted in the last decades on El Laco, with little erosion, well preserved volcanic features and excellent conditions of exposure, there is no agreement between models that support a genesis related to the hydrothermal replacement of preexisting andesitic rocks (Rhodes & Oreskes, 1999; Rhodes et al., 1999) and those which interpret the deposit as magmatic flows and dikes product of the crystallization of an iron oxide melt (Frutos & Oyarzun, 1975; Nyström & Henríquez, 1994; Naslund et al., 2002; Henríquez et al., 2003; Tornos et al., 2011). To solve this fascinating controversy is crucial to understand the problem from a global point of view, integrating geological and geochemical data of the magmatic and hydrothermal rocks present in the area.

The hydrothermal alteration is widespread in El Laco deposit and covers an area of several km2; despite having a relationship with the magnetite ore, not always the magnetite is hosted within the alteration halo.

## THE TEXTURAL FEATURES OF THE MAGNETITE

A key question in the interpretation of the genesis of these deposits is the characterization of the mineralogical changes undergone by the iron oxide ore after crystallization and the recognition of the extent of the hydrothermal alteration on both the orebody and the host rocks. Except for some dikes, most of the magnetite orebodies (Laco Sur, Laco Norte, S. Vicente Alto, S. Vicente Bajo, Rodados Negros, Laquito) occur as stratiform bodies interbedded with andesite flows. Selective etching shows that the massive magnetite is made up of 0.1 mm sized grains that show common 120° dihedral boundaries and development of subgrains, something interpreted as related with annealing during cooling of a melt. This mosaic texture (Fig. 2a) confirms widespread recovery and recrystallization after the deposition thereby destroying much of the evidences of primary deposition.

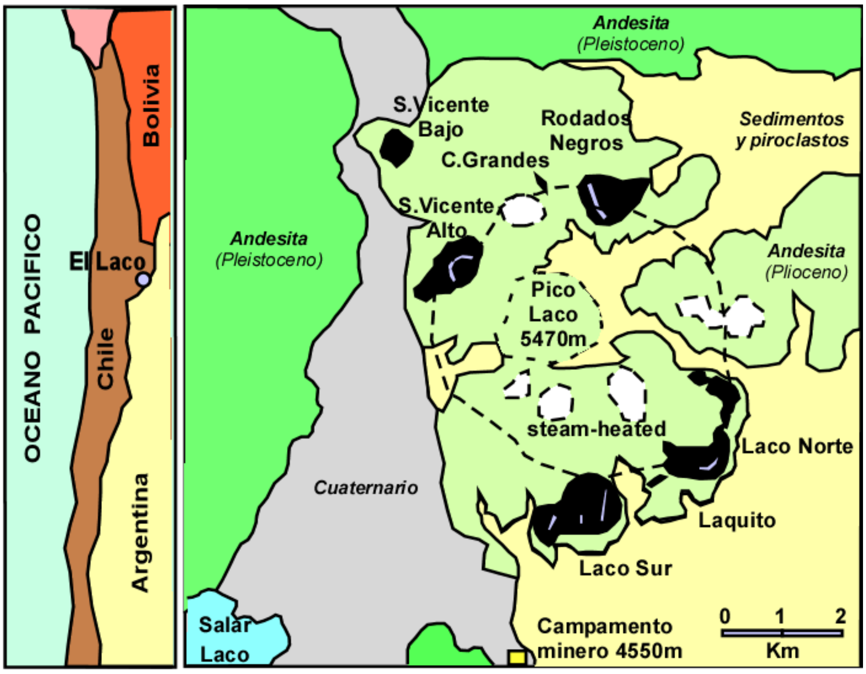


*fig. 1* Schematic geological map of the magnetite orebodies (black) at the El Laco district hosted in the Plio-Pleistocene andesitic volcanic arc, northern Chile (modified from Frutos & Oyarzun, 1975).

The stratiform bodies are crosscut by numerous pipes or degassing tubes, several meters long and up to 40 cm diameter. The walls of these pipes are carpeted by octahedral magnetite crystals (size mm to several cm) intergrown with prismatic-acicular diopside growing perpendicularly to the walls. Here, chemical etching shows the presence of well defined zoned crystal growth (Fig. 2b), with continuous individual zones some μm in thickness; they are interpreted as representing pulses of precipitation from a supersaturated low density fluid with very limited capability of transport of Fe that exsolved from the crystallizing melt and also indicates that their growth postdate the previous annealing.

## ALTERATION SEQUENCE

Regional mapping and geochemistry allow to distinguish four stages of hydrothermal activity at El Laco:

*palabras clave:* El Laco, Yacimiento magnetita, Alteración hidrotermal. | *key words:* El Laco, Magnetite deposit, Hydrothermal alteration.


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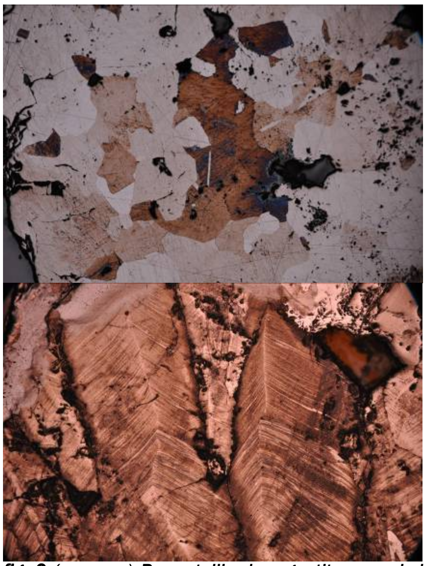

**fig. 2** *(a, upper) Recrystallized magnetite annealed during cooling; (b, lower) Detail of euhedral magnetite with zonal growth pattern barely discernable after etching. Width of fields is 2.0 mm. Polished sections etched with HCl.*

- a) an early high-temperature hydrothermal lining of the degassing tubes by euhedral magnetite and diopside with local scapolite, sanidine, albite, and anhydrite;
- b) likely at the same time ocurred the widespread high temperature and early alkaline pervasive hydrothermal alteration of the andesite underlying the magnetite orebody, which includes the replacement by albite, diopside, magnetite, biotite-phlogopite, quartz and marialite and abundant veins with the same assemblage. The melt and fluid inclusions in the diopside crystals suggest the relationship with hypersaline brines at circulating at 710-840ºC (Broman et al., 1999).
- c) a pervasive low temperature (<250ºC) stratabound but fault-controlled acid alteration that caused the replacement of the andesite, including the previous alkaline alteration by crystalline and amorphous alunite with minor amounts of cristobalite and anatase synchronously with the widespread oxidation of magnetite to hematite (nuts); there are no evidences of iron oxide precipitation during this stage. In this zone, there are very little clays representative of the argillic or propyllitic alteration zones. The mineralogy and the morphology of the this acid alteration zones suggest that they were produced by steam-heated processes (Sillitoe & Burrows, 2002), related with reaction of a SO2, P and F-rich gas with surficial waters and the host rock. The observed extreme acid alteration caused the complete leaching of all cations (except the Si and Ti) from the andesite. Minor amounts of pyrite precipitate during this stage; the low proportion of sulfides here is probably related with the highly oxidized nature of the melts, with low $H_2S/SO_4$ ratios. This acid alteration affected the alkaline alteration with dissolution or replacement of the anhydrite by gypsum, of plagioclase by alunite, formation of Fe-rich smectite clays (nontronite) and the replacement of the diopside by saponite and magnetite by hematite.
- d) late and local silicification, with formation of tridymite, amorphous silica, and rutile-anatase, replacement of the alunite by jarosite and growth of zones with gypsum (rubbly gypsum), silica and sulfur with minor variscite. This late process was related with channelized fumarolic activity.

The formation of the above hydrothermal minerals graded to common supergene products such as the replacement of magnetite to hematite and pyrite to goethite.

## CONCLUDING REMARKS

The geology of El Laco deposit shows the existence of a large zone of stratabound steam heated hydrothermal alteration which is part of a continuum with the extrusion and crystallization of the iron melts, a deeper alkaline alteration and vigorous degassing of the melts. This acid alteration is interpreted as related with the replacement of the andesite by acid fluids resulting from the mixing of vapour degassed from the water-rich iron oxide melts during their crystallization and mixing with surficial waters, likely of nival derivation. Such a large and unusual alteration zone, almost exclusively made up of alunite, can only be interpreted as related with extremely aggressive and unusually advanced alteration. The underlying alkaline alteration is here interpreted as related with the circulation of the accompanying condensed brines that separated from the vapour.

Field evidences and petrographic data suggest that these three types of hydrothermal activity represent a continuous alteration process that took place from high to low temperatures and alkaline to acid conditions related to the liquid-gas separation of fluids degassed from crystallizing iron oxide melts.

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