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Garnet phenocrysts in Early Miocene intrusives in Central Chile: Evidence for a crystal fractionation origin of adakite-like magmas

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Introduction

Adakitic-like rocks are andesitic to dacitic hydrous magmas that exhibit fractionated REE patterns (high La/Yb) consistent with garnet involvement as well as evidence for lack of plagioclase in the residual assemblage (high Sr, no Eu anomaly). Compared to normal evolved arc magmas, adakitic rocks tend to have slightly higher contents of compatible elements (Mg, Cr, Ni), but have similar or lower concentrations of incompatible elements. Adakite-like magmas in arcs are often interpreted as melts derived from crustal sources (oceanic or continental) that have either reacted with the mantle wedge or interacted with primitive arc basaltic magmas. There is general agreement that, to produce adakitic melts, the crustal sources involved must be mafic (basaltic) in composition and at a depth within the stability field of garnet. In general, it is difficult to identify the oceanic or continental nature of the source involved, as it is to explain the very local occurrence, both in space and time, of adakitic magmatism within volcanic arcs. An alternative process to explain adakitic magmas by crystal fractionation (Kleinhanns *et al.*, 2003, Sellés *et al.*, 2004) relies on recent high pressure experimental results which have demonstrated that garnet can be a primary igneous phase in arc magmas at conditions close to base of the crust, if the melts are hydrous and oxydized (Müntener *et al.*, 2001; Ulmer *et al.*, 2003). We present whole-rock, mineral chemistry, and isotopic data from Miocene adakitic-like andesites and dacites that probably were derived from more mafic water-rich parent magmas, and thus do not need crustal sources to be involved.

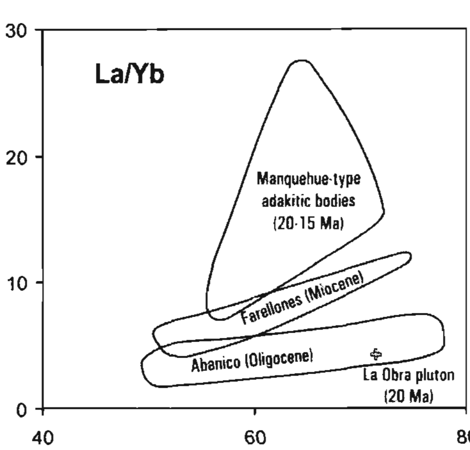

Fig. 1: SiO_2 vs. La/Yb plot for Tertiary units near Santiago. Farellones Fm. data from Kay et al. (2004). Other data from Sellés (1999).

Geological setting

Oligocene magmatism of the Abanico Formation (=Coya-Machalí Fm.) constitutes a tholeiitic suite generated during a period of crustal thinning and mantle upwelling. MORB-like REE patterns together with low $^{87}Sr/^{86}Sr_i$ ratios and high ε-Nd values are consistent with relatively dry mantle-derived magmas that did not assimilate important amounts of crustal material and that evolved dominantly by low-pressure fractional crystallization. In the area of Santiago (33-34°S), the volcanic sequence is cross-cut by coeval to slightly younger subvolcanic intrusive bodies, most of which are isotopically and chemically similar to the effusive rocks and can be considered the plutonic roots of the Oligocene arc. However, a subset of slightly younger intrusive bodies (20-15 Ma; Manquehue-type stocks) shows a distinctive adakitic chemical signature that is not observed in previous or subsequent volcanics

(Fig 1). The front of the volcanic activity shifted eastwards immediately after or simultaneously with intrusion of these adakitic stocks, coinciding with the beginning of a period of increased convergence rate and progressive crustal thickening and uplift. Compared to the Oligocene lavas, the Miocene arc magmas (Farellones Fm.) are wetter and they incorporated higher proportions of crustal material as evidenced by isotopes and incompatible element concentrations, and the residual mineral assemblage suggests higher pressures of fractionation with the involvement of some amphibole but no garnet. At the latitude of Santiago, no other Neogene magmatic unit is known to show a residual garnet signature, and it is only in Quaternary times that the volcanic arc, located above a ~60 km thick crust, indicates again garnet involvement coupled to crustal contamination. In the El Teniente Area (34°S), however, intrusive units related to porphyry copper mineralization show garnet signature during the latest Miocene to Pliocene (6-4 Ma; Kay *et al.*, 2004).

Petrography and Geochemistry

The adakitic Manquehue-type stocks in the area of Santiago are low- to medium-K andesites to dacites (56-72% SiO_2). They are commonly porphyritic in texture, with plagioclase and amphibole as the main phenocrysts. They have a distinctive chemistry relative to other magmas of the area in having low incompatible element contents (K, Rb, Zr, etc.), high Sr and positive Eu anomalies, and high La/Yb and Ce/Y ratios. Compared to the modern SVZ, Manquehue-type stocks have very modest increases in incompatible elements relative to silica, similar to the trend depicted by Nevado de Longaví volcano low-Rb magmas (Sellés *et al.*, 2004). Both Manquehue and Longaví differ from Quaternary volcanics of the northern Southern Volcanic Zone (SVZ) in that high La/Yb ratios are not accompanied by substantial enrichments of incompatible elements, which argues against crustal sources for the garnet signature. Interestingly, the less evolved compositions are broadly similar to mafic magmas from the SVZ (Fig. 2), suggesting a common mantle source but different evolutionary paths. The absence of significant crustal contamination is further demonstrated by Sr and Nd isotopic ratios. ε-Nd values of Manquehue-type stocks are within the range of Abanico lavas (+6 to +5), although initial $^{87}Sr/^{86}Sr$ ratios are slightly higher (0.7038-0.7042; Fig. 3). Sr isotopic compositions are moreover uncorrelated with increasing La/Yb.

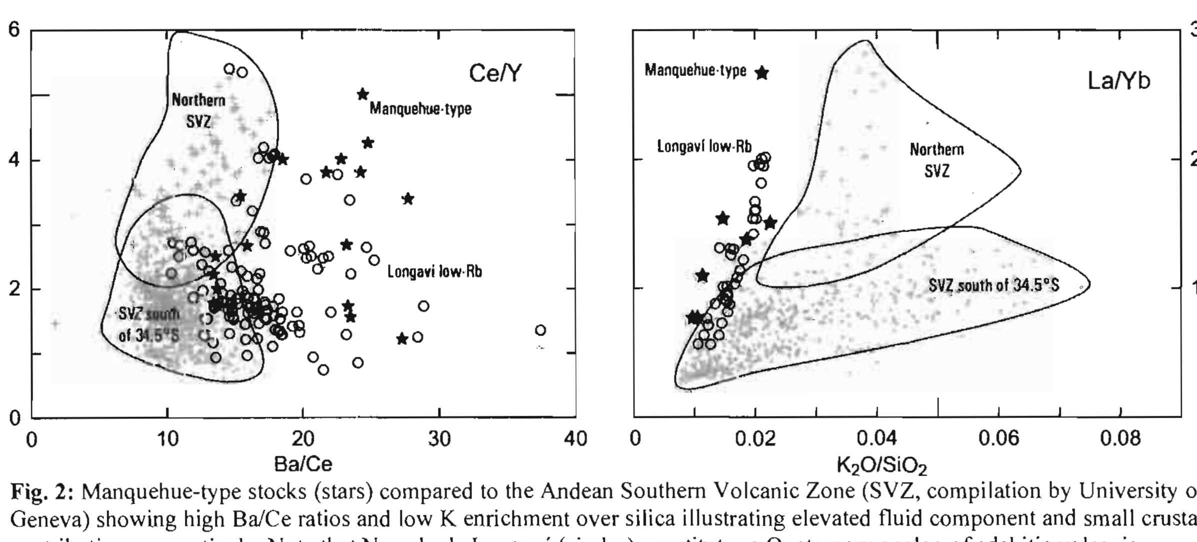

Fig. 2: Manquehue-type stocks (stars) compared to the Andean Southern Volcanic Zone (SVZ, compilation by University of Geneva) showing high Ba/Ce ratios and low K enrichment over silica illustrating elevated fluid component and small crustal contributions respectively. Note that Nevado de Longaví (circles) constitutes a Quaternary analog of adakitic volcanism.

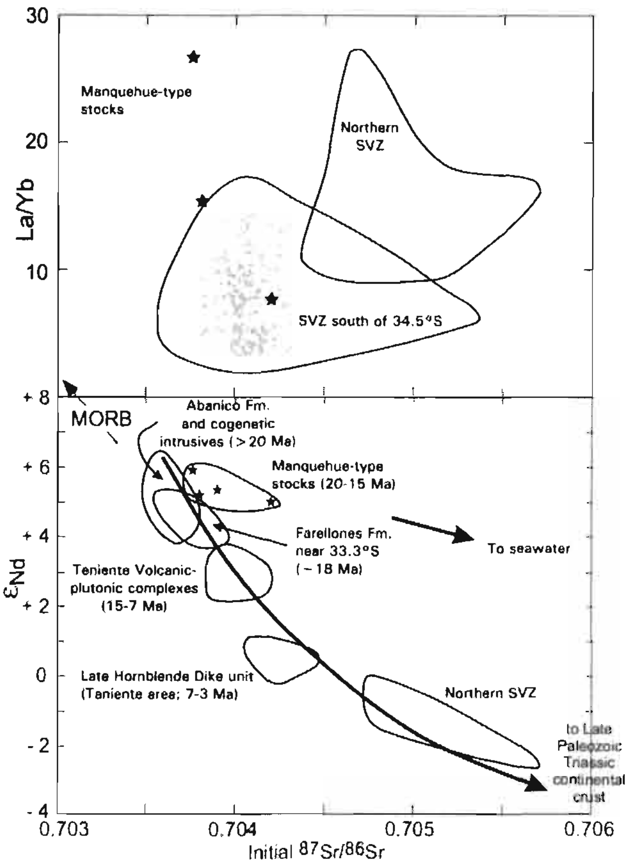

Fig. 3: Sr and Nd isotopic composition of Manquehue-type stocks compared SVZ magmas (top) and Cenozoic magmatic units at 34°S (bottom, modified from Kay *et al.*, 2004). Isotopic determinations were obtained at the laboratories of the Geological Survey of Canada in the framework of the collaborative SENAGEOMIN-MAP project.

Although garnet is often inferred to make part of residual assemblages of continental arc magmas, it is rarely actually observed because it will tend to fractionate from the host magma or will be resorbed at low pressure conditions. One of the Manquehue-type stocks preserves euhedral to subhedral garnet crystals up to 2 mm in diameter. The host rock is almost aphanitic in texture, the only phenocrysts being ~1% garnet and ~5% plagioclase ($An_{40\text{-}35}$). Despite this particular mineralogy, this body is chemically similar to the amphibole-bearing stocks. Garnet crystals are unzoned, almandine-rich (Al_{73}-Py_{11}-Sp_6-Gr_{10}), and contain abundant randomly oriented inclusions, mainly needle-like apatite and minor iron-rich orthopyroxene and Fe-Ti oxides. Garnets of similar composition were described by Harangi *et al.* (2001), which they interpreted as a primary phase crystallizing from hydrous mantle-derived calc-alkaline melts. Recent experiments have proven that garnet can crystallize at moderately high pressures (≥8 kbar) from hydrous and oxidized andesitic magmas (e.g. Ulmer *et al.*, 2003).

Discussion

Previous interpretations on the petrogenesis of these stocks have assumed that garnet was a restitic phase, either from a subducted slab source (Sellés, 1999; Yañez *et al.*, 2002) or from crustal slivers dragged down by subduction erosion (Kay *et al.*, 2004). Newly acquired isotopic data and petrologic observations suggest that garnet was a primary phase, crystallizing from intermediate hydrous mantle melts evolved at lower to middle crustal pressures. The hydrous character of Manquehue-type magmas is suggested by the abundance of amphibole and paucity of pyroxene phenocrysts. Also, high Al_2O_3, Sr and positive Eu anomalies indicate that plagioclase did not thoroughly fractionate, which is also expected to happen in hydrous melts. Moreover, enrichments of fluid-mobile trace elements over less mobile ones suggest important participation of slab-derived fluids. In the Quaternary Nevado de Longaví volcano, similar characteristics are interpreted to be consequence of the subduction of an oceanic fracture zone that can host serpentinized bodies, potentially efficient water carriers to the subarc mantle. Fluids released upon serpentine breakdown should have the isotopic composition of sea water, which could explain the relatively elevated Sr isotopic ratios displayed in Fig. 3. Elevated fluid flux to the mantle generates high-degree hydrous melts that evolve mainly by fractionation of amphibole, keeping incompatible element contents low.

One additional constraint to the genesis of these intrusives comes from the available radiometric ages. K-Ar and $^{39}Ar/^{40}Ar$ ages (Gana & Wall, 1997) suggest a pattern of decreasing ages to the south, from 20 Ma at 33°S (Cerro Grande de Chacabuco) to 15 Ma at 33.6°S (Sellés & Gana, 2001). Although the amount and precision of the ages are limited, they suggest that adakitic magmatism was diachronous in the area, which would be consistent with a southward-migrating subducted linear feature (such as a fracture zone) but not with a major, regional-scaled tectonic event.

The recognition of two independent cases of water-rich, mantle-derived adakitic magmas in the Andean context opens new perspectives in the interpretation of these rocks.

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