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NEVADO DE LONGAVÍ VOLCANO (SVZ - 36.2°S): AN UNUSUAL 'ADAKITIC' COMPONENT PARTICIPATING IN A MAGMA-MIXING DOMINATED SYSTEM

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INTRODUCTION

The Southern Volcanic Zone (SVZ) of the Andean arc has been divided geographically into three segments related to the position of the volcanic front (segmentation scheme of Wood & Nelson, 1988; Dungan *et al.*, 2001); (Fig.1). From north to south these segments are: Tupungato-Maipo (TMS: 33°-34.5°S), Palomo-Tatara (PTS: 34.5°-36.1°S) and Longaví-Osorno (LOS: 36.2°-41.1°S) segments. Volcanoes within segments are commonly similar in composition, whereas across segment boundaries abrupt chemical and mineralogical changes are observed.

Nevado de Longaví Volcano (36°12'S-71°10'W, summit altitude 3,242 m) is the northernmost center of the LOS, whose front is located some 15-18 km closer to the trench than the adjoining Palomo-Tatara Segment (PTS). Nevado de Longaví (NL) volcano unconformably overlies folded continental volcaniclastic and sedimentary strata of Eocene-Early Miocene age (Cura-Mallín Formation), which are in turn intruded by Miocene granitic plutons. NL is located just to the north of the Plio-Pleistocene basaltic to basaltic-andesitic Villalobos Volcanic Complex (Cola de Zorro Formation; Muñoz & Niemeyer, 1984).

NL is a Quaternary stratovolcano composed mainly of thick andesitic flows that radiate from the summit area. Pyroclastic rocks are almost absent from the main cone, but they are dominant during Holocene activity and are well preserved on the eastern side of the volcano. Holocene piroclastic deposits are represented by a subplinian pumice fall dated at 6,835±65 years B.P. (^{14}C-AMS[*], this study) and an overlying block and ash flow deposit, associated with the extrusion of a dacitic dome near the summit (see Sellés *et al.*, this volume).

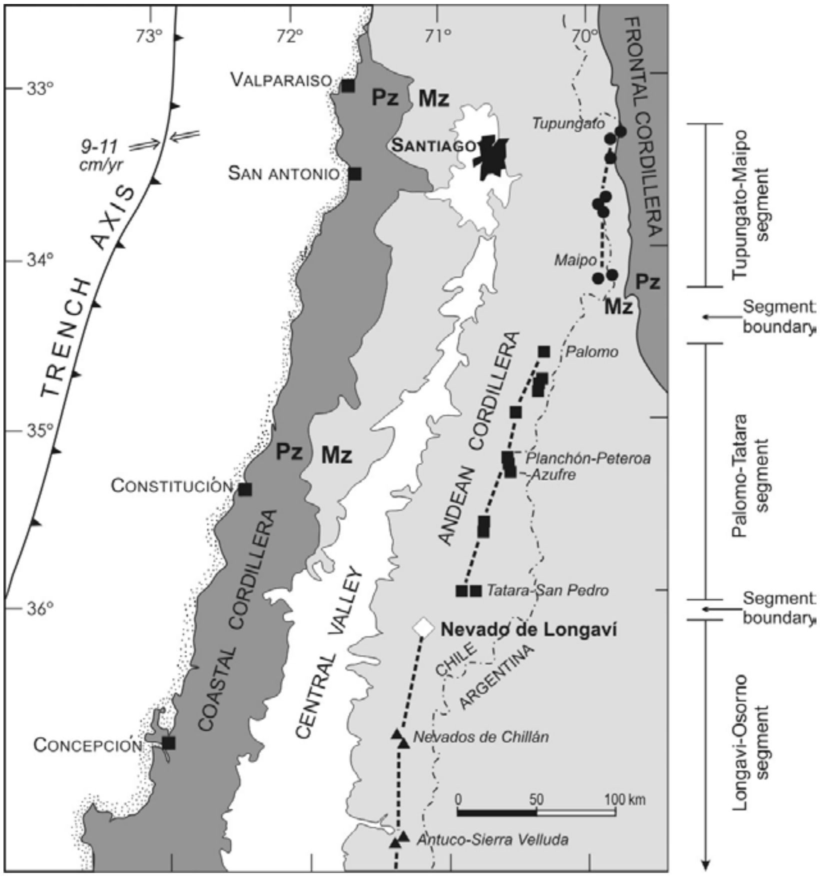

Figure 1: Location Map of Nevado de Longaví volcano and segmentation scheme for Southern Volcanic Zone (SVZ) of Wood & Nelson (1988).

WHOLE-ROCK CHEMISTRY: NEVADO DE LONGAVI IN THE CONTEXT OF THE SVZ

NL lavas range from basalt (52 wt% SiO_2) to dacite (65 wt% SiO_2) (Fig. 2), defining a medium–K suite (Fig. 3). In the regional context of the SVZ, the chemistry of NL magmas is characterized by markedly low concentrations of incompatible elements in both major (K_2O, P_2O_5, TiO_2) (Fig. 2, 3) and trace elements (Nb, Y, Rb, Ba, Zr, Ce, REE, etc) (Figs. 4, 5, 7), as well as high Sr and Al_2O_3 values for given rock types. These features (*i.e.*, low incompatible element enrichments with increasing silica) are most pronounced towards the dacitic end of the spectrum, whereas basaltic magmas have incompatible element contents broadly similar to other basalts in the LOS.

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[*] Necessary preparation and pre-treatment of the sample material for radiocarbon dating was carried out by the ^{14}C laboratory of the Department of Geography at the University of Zurich (GIUZ). The dating itself was done by AMS (accelerator mass spectrometry) with the tandem accelerator of the Institute of Particle Physics at the Swiss Federal Institute of Technology Zurich (ETZ).

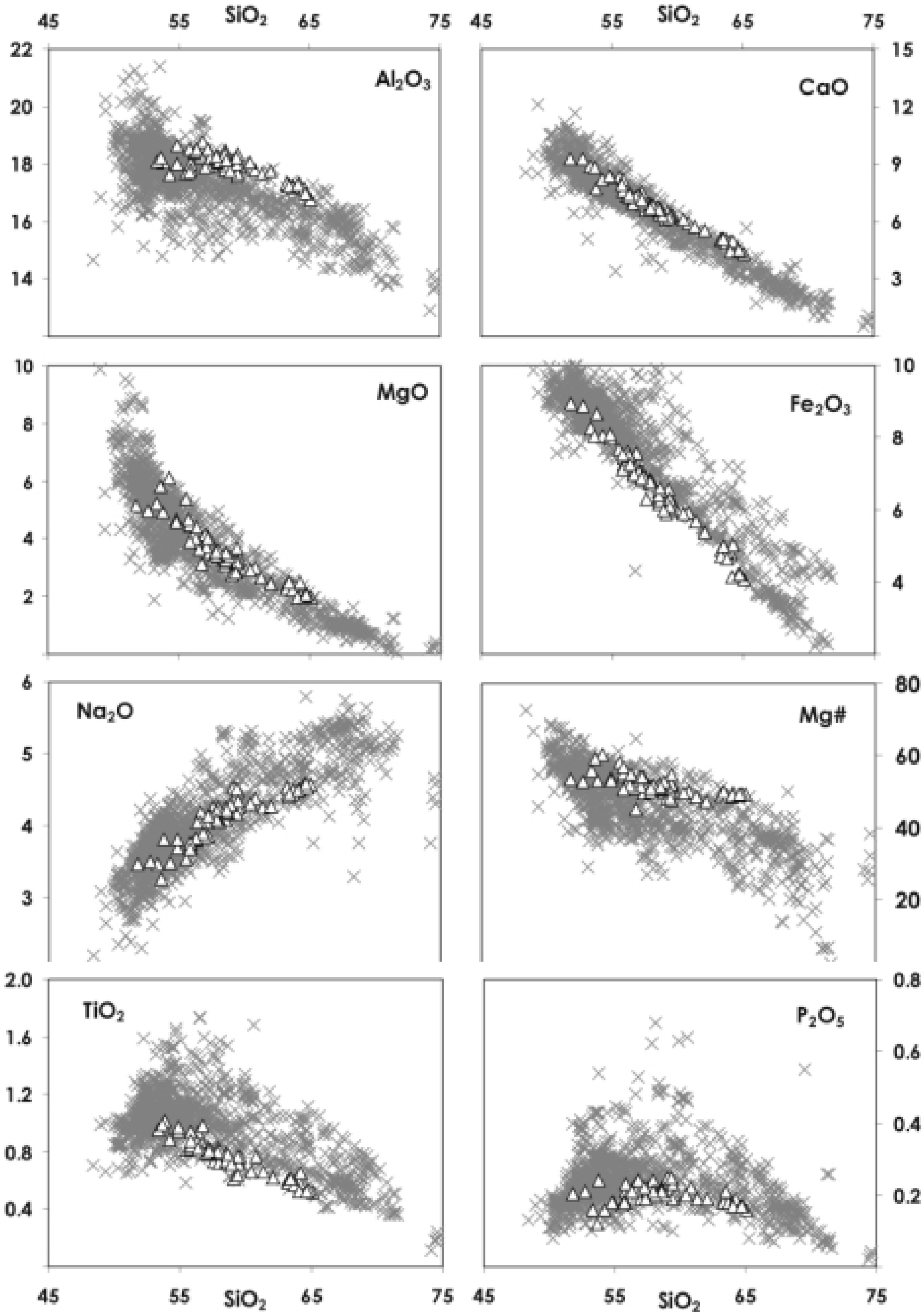


Figure 2: Harker diagrams for NL samples (triangles) compared with magma compositions in the SVZ (crosses). Only data from volcanic centers between Palomo and Osorno volcanoes (34.5°-41°S) are shown.

MAJOR ELEMENTS

Major element arrays defined by NL lavas (Figs.2 and 3) are distinctly different in many respects compared to the typical fractional crystallization (FC) dominated trends of others suites from SVZ. Mg# in NL rocks, for example, does not decrease substantially with increasing silica, in contrast to the steep decreasing trend recorded in Puyehue volcano, a typical case of FC-dominated evolution (Gerlach *et al.,* 1988). Elements such as TiO_2 and P_2O_5 define flat trends versus SiO_2, without early increases followed by depletions due to fractionation of FeTi-oxides and apatite respectively. Unsually low K_2O (<1.5 wt%) in intermediate to silicic NL rocks (Fig.3), along with some samples from Choshuenco volcano, are among the lowest values found in the LOS; being notably lower than K_2O concentrations recorded at the neighboring Chillán and San Pedro volcanic centers. Conversely, Al_2O_3 (>16 wt %) and Mg# (45-62) values at NL are on the high end of the SVZ spectrum.

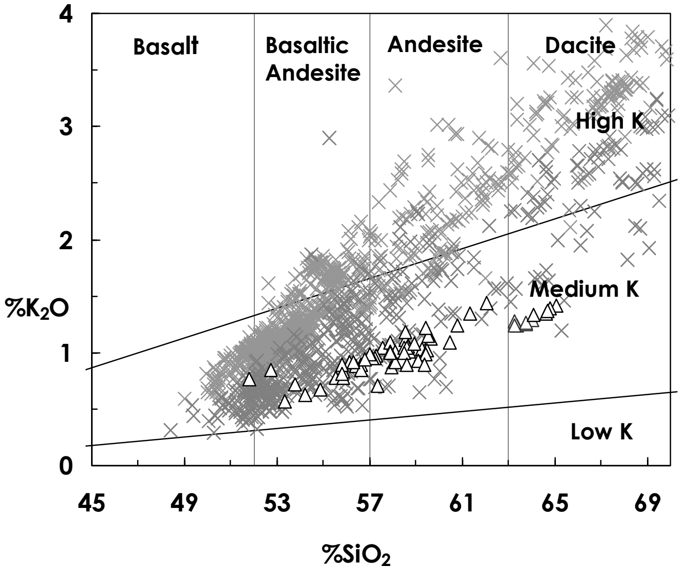


Figure 3: Diagram K_2O vs silica for NL rocks (triangles) and SVZ (crosses). Subdivisions of Le Maitre *et al.* 1989.

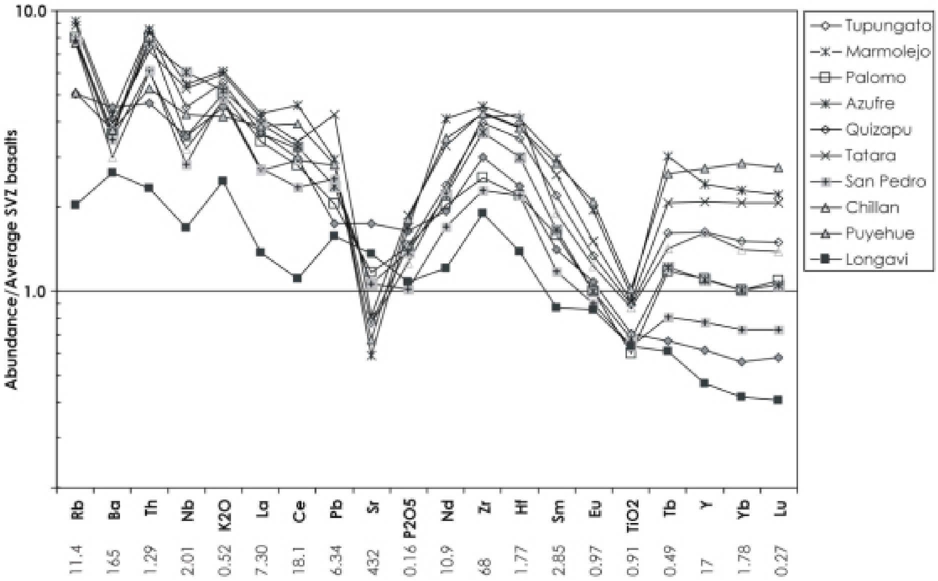


Figure 4: Spider diagram for dacites of SVZ (63-64% SiO2). Samples were normalized to the average of 32 basalts from SVZ (normalization values in diagram under element). For a clear presentation, only one representative sample was considered per volcanic center. Data from: Gerlach *et al.*, 1988; Tormey *et al.*,1995; Ferguson *et al.*,1992; Costa & Singer, 2002; Déruelle & López-Escobar, 1999; Hildreth & Moorbath, 1988.

TRACE ELEMENTS

The most evolved products of NL volcano are Holocene dacites, which show extreme impoverishment in incompatible elements in relation to its silica content, representing a unique case in this regard within the SVZ. A comparison of NL dacites to broadly similar rocks from the SVZ (63-64 wt% SiO_2) (Fig. 4) shows that NL dacites have a flatter pattern, with notably lower contents for almost all incompatible elements: Rb, Ba, Zr, Hf, Th, Nb, Ce, La, etc. Extremely low values (normalized values <1 with respect to average SVZ basalts) are found for middle and heavy REE; only some samples from Tupungato and San Pedro volcanoes also show this signature, but in these rocks HREE depletion is coupled with high concentrations of LREE and other incompatible elements. Although Y and HREE decrease with increasing SiO_2 in the TMS, these volcanoes are located on much thicker crust where garnet should be stable in deep crustal lithologies (Hildreth & Moorbath, 1988).

Other notable differences between NL rocks and the most SVZ volcanoes, can be observed in the arrays defined by certain trace elements and their ratios. The most dramatic case is Y (and HREE) contents that *decrease* with increasing silica, contrary to what is observed in the SVZ (at least south of Maipo volcano) wherein Y and HREE behave as incompatible elements and *increase* from basalt to dacite-rhyolite. The NL values for Ce/Y and Sr/Y (Fig. 5) form a linear array at high angles to mafic-silicic trends at volcanoes located to the south and north of NL (PTS and LOS). The marked increase in Sr/Y toward dacite is in part due to the absence of a strong Sr-depletion with increasing SiO_2. The strontium concentrations observed in NL dacites (550-600 ppm) are higher than for most basalts at volcanoes south of NL (Chillán-Osorno) and are not observed in any intermediate or highly evolved magmas at such volcanoes (*e.g.,* Gerlach *et al.,* 1988). Some Tupungato samples, in which plagioclase may not have been a fractionating phase at high pressure, have comparable Sr content.

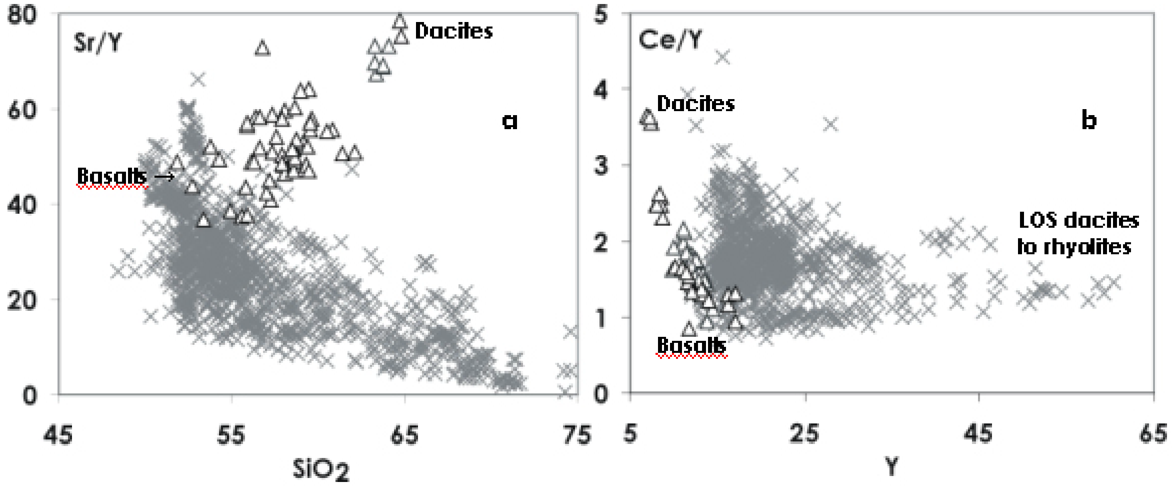


Figure 5: Sr/Y vs silica (a) and Ce/Y vs Y (b); NL rocks (triangles) in comparison with LOS and PTS centers (crosses). Note the divergent trend for NL samples with respect to the normal SVZ array. These diagrams include samples from all temporal units of the volcano, showing that magmatism in NL is consistent in both its source and evolution.

ORIGIN OF THE NL DACITES

Identification of the source is a fundamental requirement for understanding the petrogenesis of NL dacites. Petrographically, NL dacites are dominated by abundant plagioclase (30% vol) and amphibole (10% vol), with lesser amounts of orthopyroxene, Fe-oxides, and apatite in a glassy matrix. These magmas are mingled with fine-grained basaltic-andesitic to andesitic enclaves (5% vol. with respect to the dacite host). The less evolved compositions at NL are represented by sparse basalts (51.7-52.7 wt% SiO_2) and the enclaves. The mineralogy of basalts is dominated by plagioclase (55% vol), olivine (10% vol), pyroxene (30% vol), without hydrous minerals. In contrast, mafic enclaves (53-56 wt% SiO_2), present in Holocene dacites, are dominated by plagioclase (40% vol.) and amphibole (30-35% vol.), with less orthopyroxene and olivine.

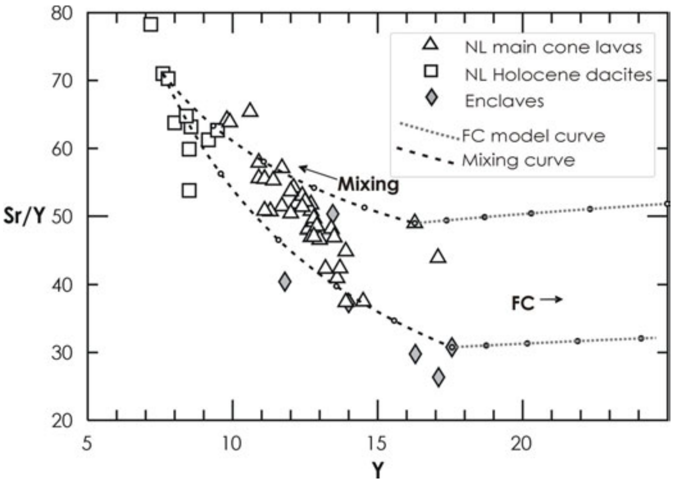


Figure 6: Sr/Y vs Y showing FC and mixing models, starting from basalt (without hydrous minerals) and an enclave (amphibole rich) found in dacites. NL main cone samples plot between both mixing curves. FC trend is opposite to the observed evolution pattern. Ticks every 20% of mixing, and 10% FC. FC models consider a typical calc-alkaline mineralogical association: plg, px, amp and ol, but no garnet.

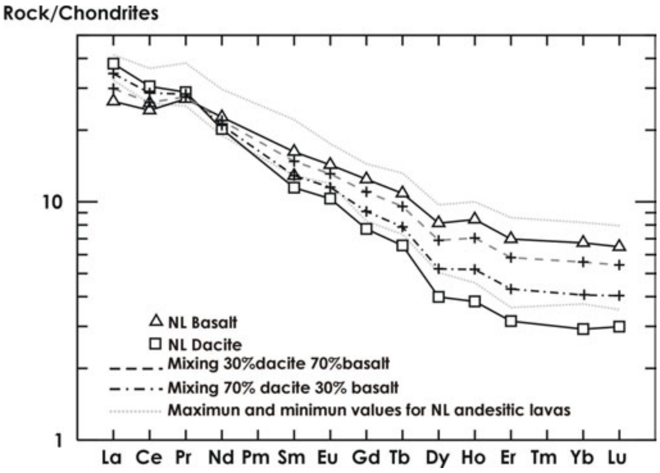


Figure 7: REE pattern for NL dacites, basalt and range of intermediate lavas. Note the extreme low content of MREE and HREE in dacite. Two mixing models included show good consistency with observed contents. Normalization values from Nakamura, 1974.

A direct genetic relationship between these diverse mafic end-members and the dacites is doubtful. Fractional crystallization of typical calc-alkaline assemblages (plagioclase-pyroxene-olivine-amphibole) from basaltic parent magmas would lead to evolved liquids similar to dacites found elsewhere in the LOS, where this type of evolution is considered to be dominant, but would fail to generate the incompatible element-poor compositions observed in NL dacites. At the same time, extensive plagioclase fractionation would lower Sr and Al_2O_3 values. Assimilation of granitic crustal material would generate evolved liquids enriched in incompatible elements to even higher levels. Although some characteristics can be explained by assuming fractionation involving a high-pressure mineral assemblage (e.g. fractionation of garnet to explain decreasing Y, Ulmer *et al.*, 2003), no single phase can explain the depletion in virtually all incompatible elements. A genetic relationship between basalts and dacites through FC or AFC is therefore considered highly unlikely, and we suspect that the origin of these dacites is actually linked to a source different from that of the basalts.

Magma mixing, as is suggested by the presence of enclaves and the chemical patterns noted above, is considered to be a possible mechanism for the observed array of NL magmas. Pre-Holocene andesitic lavas from the NL main cone can be modeled as mixtures between two end-members (Fig. 6). These lavas plot in a field bounded by two mixing curves, showing an unexpected but significant participation of the amphibole-rich enclave-forming component. Conversely, the spectrum from basalt to dacite (Fig. 7) in NL rocks is marked by impoverishment of middle and heavy REE, inconsistent with the enrichments that would arise through FC involving typical calc-alkaline mineral assembleges. The sparse NL andesites with higher REE than basalts can be explained by minor degrees of FC. Nevertheless, NL andesites with lower REE contents than basalts seem to reflect mixing with more evolved, low-REE dacitic magma.

The preliminary model results suggest that dacite represents an important component of NL magmas whose source seems to be different from that of the basalts. NL basalts, that seem to respond to the latitudinal systematic variations predicted by Hildreth & Moorbath (1988), represent the other end member in the mixing dominated NL system. These two extreme magmas derived from two separate sources, have probably coexisted and mixed throughout most of the history of NL volcano, even though dacites was rarely erupted as a discrete magma prior to the Holocene. Another factor that seems to be relevant in NL magmatism is the water content, represented by highly variable contents of hornblende in the mafic extreme.

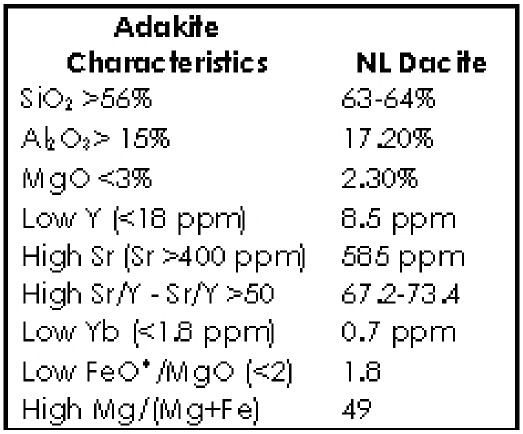
XENOLITHS

Two types of centimeter- to decimeter-sized plutonic xenoliths are present in lava flows in the NL system: 1) quartz-biotite granitoids, and 2) hornblende gabbroids. Granitoid xenoliths are probably related to known Miocene-aged basement that crops out in the area, as these do not show any reaction with the magmas and, therefore, were problably incorporated at high crustal levels. Gabbroic xenoliths contain amphibole as the dominant mafic mineral (up to 80% vol), and they usually display evidence of variable degrees of post-entrainment partial melting, such as glass channels and pockets, and textures of amphibole dehydration breakdown. Unlike granitoids, gabbroic xenoliths can not be associated with any known geological unit, but seem to be deep hydrous cumulates, possibly related to NL magmas (see Sellés *et al.*, this volume). If hornblende-bearing xenoliths and NL magmas have a cogenetic relationship, the high water activity required to stabilize amphibole in the system is a critical factor to study (Sisson & Grove, 1993; Naney, 1983).

ADAKITIC AFFINITY

The closest analogs to NL dacites are found in adakitic magmas. Adakites have been defined as intermediate to acidic calc-alkaline volcanic or hypabyssal rocks with low-, medium- or high-K_2O affinities; high Al_2O_3 and Sr, and low Y and HREE contents (the main characteristics are summarized in Table 1). Fractional crystallization origin from calc-alkaline basaltic magma is precluded by trace element characteristics. Defant and Drummond (1990) proposed that adakites derive from partial melting of subducted oceanic crust at high-pressures (≥ 1-1.2 GPa) where the slab is young (<5 My) and hot enough to attain the wet basaltic solidus (Peacock *et al.* 1994).

Since this definition was first proposed, a number of cases of andesites and dacites with the geochemical characteristics of adakites have been reported worldwide in arc settings that are not associated with a young oceanic slab. Alternative mechanisms to achieve slab melting of older oceanic crust (*e.g.,* flat subduction; Gutscher *et al.,* 2000) as well as alternative high pressure basaltic sources have been proposed to explain adakite-like occurrences. Alternative sources include basic material underplated at the base of a thickened orogenic crust (*e.g.,* Petford *et al*., 1996; Kay & Mpodozis, 2002) and tectonically eroded lower forearc crust slivers (Kay, 2002).



Adakite Characteristics	NL Dacite
SiO_2 >56%	63-64%
Al_2O_3> 15%	17.20%
MgO <3%	2.30%
Low Y (<18 ppm)	8.5 ppm
High Sr (Sr >400 ppm)	585 ppm
High Sr/Y - Sr/Y >50	67.2-73.4
Low Yb (<1.8 ppm)	0.7 ppm
Low FeO*/MgO (<2)	1.8
High Mg/(Mg+Fe)	49

Table 1 : Summary of characteristics of adakites and contents of NL dacite.

Slab melting, as an explanation for the adakitic signature of NL dacites, finds little support in the geodynamic setting of the volcano. Early Tertiary oceanic crust is currently being subducted steeply beneath this center (Herron, 1981; Bevis & Isacks, 1984; Barazangi & Isacks, 1976), and the age of the oceanic crust impinging on the trench becomes younger to the south, while the tendency for Sr/Y decreases as a function of increasing silica becomes progressively more marked to the south. Alternative mechanisms for developing an adakitic signature, such as partial melting of underplated basaltic rocks or pre-existing crustal lithologies, are geodynamically more plausible. Detailed geological and geophysical studies in this area that might constrain crustal structure, character, and thickness are however, lacking. This study is oriented toward establishing constraints on the nature of the source region and the evolution of Holocene magmas erupted at NL volcano.

DISCUSSION

NL magmas are characterized by anomalously low contents of most incompatible elements, strong 'adakitic' signatures in evolved magmas, and an amphibole-rich mineralogy that differs markedly from that of other SVZ volcanoes, particularly those located to the south, despite the fact that thickness and/or nature of the underlying crust beneath neighboring centers is not expected to vary significantly. FC and/or AFC, which are thought to dominate the evolution of SVZ magmas at many other centers (e.g. Hildreth & Moorbath, 1988); fail to reproduce evolved NL magmas because such mechanisms would lead to incompatible element enrichments. Fractionation of accessory phases should not be discarded *a priori* as a factor that might contribute to the unusual NL dacite trace element signatures, but it cannot alone explain the depletion of such a diverse spectrum of elements. NL 'evolution trends' can however be better explained as mixing products of basalt with an anomalous dacite magma, whose origin seems to be different from that of the basalts. The establishment of constraints on the nature of the source of this intriguing silicic component, however, will have to deal with the critical question of why this behavior is almost entirely restricted to NL volcano.

An important crustal-scale feature that could be exerting an influence on the nature of magmas generated at NL, is the oceanic Mocha Fracture Zone which projects beneath the volcano. Subducted oceanic fractures constitute propitious zones for the development of serpentinite bodies via hydration of deeper layers of the oceanic lithosphere. Serpentinites could transport substantial amounts of water into the subduction zone (they contain about 13% H_2O versus 3% in hydrated mafic oceanic crust) and then release it at depths below 70 km. (Ulmer & Trommdorff 1995; Wunder & Schreyer, 1997; Ringwood, 1990; Bonatti & Crane, 1984). This focused contribution of water could produce localized hydrous metasomatism in the overlying mantle wedge, thereby providing a source for wet magmas with Nb/Zr ratios similar to those from less hydrated mantle (*e.g.* Johnson *et al.*, 1996; Peacock, 1993; Tatsumi *et al.*, 1986; Proteau *et al.*, 2001). Dacites from other volcanoes situated over the projection of subducted oceanic fractures zones have somewhat similar chemical characteristics, although not as extreme as NL. The Mocho-Choshuenco complex lies over the Valdivia Fracture Zone whilst Calbuco volcano is spatially associated with the Chiloé Fracture Zone. In both cases, some dacites show similar tendencies towards enrichment in Al_2O_3 and Sr, and lower TiO_2, K_2O and incompatible elements compared with nearby centers (McMillan *et al.*1989; Hickey-Vargas *et al.*, 1995; López-Escobar *et al.* 1995).

Constraints on the time-scales involved in the evolution of the magmatism at NL will be particularly valuable to evaluate the hypothesis of a "Mocha Fracture Zone-modified" source. In summary, we suspect that proximity to the subducted Mocha Fracture Zone may be related to high contributions of water to the wedge under NL volcano, explaining the local character of the anomalous low-incompatible contents, adakitic affinity and the water rich features of NL magmas and xenoliths included.

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