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The two major postglacial (13-14,000 BP) pyroclastic eruptions of Llaima and Villarrica volcanoes (Southern Andes) : A comparison

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1. Introduction

Llaima (38°45'S) and Villarrica (39°25'S) are Upper Pleistocene-Recent composite stratovolcanoes located in the Central Southern Volcanic Zone of the Andes (López-Escobar *et al.*, 1993). The predominant products of both volcanoes are basalts and basaltic andesites. Presently, they are the most active volcanoes in Chile and have had an important postglacial (< 14,000 years) explosive activity, characterised by voluminous deposits of mafic (basaltic to andesitic) ignimbrites (Naranjo & Moreno, 1991; Moreno *et al.*, 1994). In order to investigate the eruptive causes of such uncommon products, a study has been undertaken in an IRD-GEA-SERNAGEOMIN-University of Chile collaborative project (Ecos-Conicyt C01U03). In this abstract, we present the petrographical, mineralogical and geochemical characteristics of the two major ignimbritic deposits which are close in age (13,800 and 13,500 years; the Licán ignimbrite at Villarrica volcano and the Curacautín ignimbrite at Llaima, respectively), within the context of the history of each volcanic complex.

2. Summarized postglacial stratigraphy of Llaima and Villarrica

2.1. Llaima volcano

Postglacial activity at Llaima began with a violent explosive eruption that generated the Curacautín ignimbrite (estimated 24 km^3, non-DRE). This event marks the beginning of an explosive period which finished around 7,500 years B.P. and was followed by a mainly effusive activity of basaltic andesites that has lasted until today (Naranjo & Moreno, 1991).

Curacautín ignimbrite : Field studies and ^{14}C-datings allow to distinguish two main units in the Curacautín ignimbrite. The lower unit (Curacautín 1) is widely distributed around the volcano. Massive beds (up to 10 m thick) consist of scoria bombs, juvenile and accidental lapilli in a fine, often indurated ashy matrix. This thick unit is followed by surge deposits. Degassing pipes in the ignimbrite stop abruptly at the contact with these surge deposits. Progressive changes in colour (from dark grey to light brown), correlated with a transition from massive to diffusively stratified layers, and the sudden presence of vitreous quenched lapilli are observed towards the top of the ignimbrite. The upper unit (Curacautín 2) consists of a 2 to 5 m thick sequence of ash and scoria flow deposits (7 successive deposits). This sequence is discordant with unit 1 and refills drainages formed by the erosion of the Curacautín 1 unit. It ends with a 3-4 m thick sequence of surges. Discordance and reworked deposits indicate a significant time interval between the eruption of both units. ^{14}C-datings indicate an age of

~13,500 years B.P. (2 datings) for Curacautín 1 whereas the age of Curacautín 2 is ~12,600 years B.P. (3 datings).

Post-Curacautin activity: The Curacautín ignimbritic deposits are overlain by a sequence of subplinian airfall deposits which alternate with paleosoils. Two ^{14}C-datings in these paleosoils (10,610±180 years B.P. and 9,930±70 years B.P.) give an idea of the interval (minimum 2,700 years) which separates the two Curacautín events from a large plinian eruption whose bi-coloured (black and light grey) pumice deposit extends to the SE. Some grey lapilli from this fallout tephra show bands of darker material which becomes dominant towards the top. This unit is overlain by two surge deposits which are relatively fine and poorly sorted. The upper one has been dated in 7,420±180 B.P. (Naranjo & Moreno, 1991).

2.2. Villarrica volcano

The Upper Pleistocene development of Villarrica volcano is marked by the formation of a 6.5 x 4.2 km elliptical caldera ca. 100,000 years ago (Clavero & Moreno, 2004). A collapse produced by the emission of the Licán ignimbrite (~10 km^3, non-DRE; Clavero, 1996) has rejuvenated this older structure. This event occurred about 13,800 years ago (average of 4 datings, including 2 dates by Clavero (1996) and two new datings).

Licán ignimbrite. A massive breccia deposit (up to 3.5 m thick) with metric bombs of dense scoria (up to 20%) at the foot of the cone (~8 km from the summit) represents the lower unit of the observed Licán ignimbrite. This unit is overlain by a fine, clay-rich altered ash deposit, a fallout lapilli layer and finally scoria flow deposits. In the SW, at least three flows, probably related to the latter, have been recognized (Clavero, 1996; our observations). Surge deposits (1-2 m), widespread to the SW, mark the end of the eruption. This sequence is characterised by colour changes (dark grey to light brown) and an increase in lithic content towards the upper part of the section.

Post-Licán activity. Subsequently, a new edifice was built, which was truncated 3,700 years ago by a similar eruption which generated the less voluminous Pucón ignimbrite (~3 km^3, non-DRE; Silva *et al*., 2004). Other postglacial volcanics consist of smaller pyroclastic flow deposits, thick lava flow sequences, fallout deposits and numerous lahars. At least 14 postglacial pyroclastic flow units have been recognized at Villarrica, including the Licán and Pucón deposits (Moreno *et al*., 1994).

3. Discussion of petrologic data : relationships between the ignimbrites and the Holocene volcanic series

3.1. Relationships between the Curacautín ignimbrite and lower Holocene volcanics at Llaima volcano

Geochemistry. Compared to the fallout and surge deposits erupted between ~ 10,000 and 7,500 years B.P., the Curacautín ignimbritic deposits are less differentiated (53-59 % SiO_2 versus 60-69% SiO_2) and show higher TiO_2, Fe_2O_3, CaO, Cr and Ni contents. On the other hand, Holocene lava flows are basalts and basaltic andesites, less differentiated than the ignimbrites. It is important to note that, whereas Curacautín represents the emptying of a large stock of relatively homogeneous magma, the subsequent sequences correspond to the emission of a zoned magmatic chamber whose composition varies rapidly from 69 to 59 % silica. In the plinian fallout deposit, the occurrence of lapilli formed by black and white bands indicates that magma mixing could be an important factor in triggering the explosive eruption. Considering the thick reworked material on top of Curacautín, the time interval between Curacautín 2 and the next pyroclastic event (~2,000 years) and the composition of the tephra related to the latter (63% SiO_2), two scenarios are possible: either these evolved products result from the differentiation of a Curacautín-like residual magma in the reservoir, or they result from the differentiation of a new, more mafic magma which refilled the chamber after the Curacautín eruptions. All magmas are probably related by fractional crystallization (indicated by variation diagrams), and crustal assimilation does not seem to have been an important process as no increments in ratios such as Rb/La, Rb/Ba, K/Ba, K/La have been observed (McMillan *et al.*, 1989). This is also supported by the subparallel chondrite normalized REE patterns.

Mineralogy. Until now, only a few samples have been studied. Pre-Curacautín lava flows are relatively rich in phenocrysts (7%), with plagioclase (An_{80-21}), olivine (Fo_{83}) and orthopyroxene (En_{80-72}) as major phases. Plagioclase cores show normal or oscillating zoning, but thin, more sodic rims are always present. Olivine and orthopyroxene are not or normally zoned. In contrast, juvenile bombs coming from the Curacautín ignimbrite deposit are quite aphyric (0,5-2%), with plagioclase as the main phase (An_{91-39}; at least two groups), and less clinopyroxene. Zoning in plagioclase is much more complex than in lava flows: normal, reverse and oscillating zoning as well as unzoned crystals are observed. Augitic microphenocrysts show variable core compositions. The groundmass is composed of plagioclase (An_{59}), olivine (Fo_{68-39}), augite and glass.

Post-Curacautín lava flows are similar to pre-Curacautín lava flows, but with mainly plagioclase and olivine as the main phases and only traces of pyroxene.

3.2. Relationships between the Licán ignimbrite and lower Holocene volcanics at Villarrica volcano

Geochemistry. The Holocene eruptive activity of Villarrica volcano can be divided into two periods : the first (14,000 to 4,000 years B.P.) starts with the eruption of Licán ignimbrite followed by the construction of the cone until the eruption of Pucón ignimbrite. The second period develops since the latter event till nowadays. Licán ignimbrite juvenile material ranges from 50 to 58% SiO_2, being the most evolved samples the most abundant. The silica content in rocks decreases from the base to the top of the sections. A decrease in TiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Sc, V, Cr and Ni with increasing differentiation indicates the fractionation of olivine, pyroxene, plagioclase and Fe-Ti oxides. Up to the emission of the Pucón ignimbrite (which also has more differentiated material), post-Licán deposits are less evolved than the Licán juvenile material.

Mineralogy. Juvenile clasts from the Licán ignimbrite are, generally, almost aphyric (only 2% phenocrysts), highly vesicular scoria. Phenocrysts are plagioclase (An_{90-40}), clinopyroxene (augite and pigeonite) and orthopyroxene (enstatite and ferrosilite). The groundmass contains plagioclase (An_{58-51}), augite, olivine (Fo_{66}), magnetite and glass. Granitic xenoliths are common. Plagioclase phenocrysts show complicated zoning patterns (reverse, oscillating, non-existent, normal) and different populations have been observed. Some orthopyroxenes have ferrosilitic cores and enstatitic rims.

Post-Licán lava flows are relatively rich in phenocrysts (15%) and consist mainly of plagioclase (An_{90-57}), with less pyroxene (enstatite and augite) and olivine (Fo_{83-75}). The groundmass is composed of plagioclase, Fe-Ti oxides, clinopyroxene, olivine and traces of glass. In general, plagioclase and olivine phenocrysts are normally zoned.

4. Concluding remarks : Comparison between the postglacial magmatisms at Llaima and Villarrica

Curacautín and Licán pyroclastic deposits represent the major postglacial explosive eruptions of Llaima and Villarrica volcanoes respectively. Juvenile material of both deposits exhibit a relatively low degree of differentiation (50-58% SiO_2) and both catastrophic events are of similar age (13,500 and 13,800 B.P.), close in time to the end of the last ice age (around 14,000 B.P.). Nevertheless, whereas the Licán eruption seems to have occurred as a single event just after the end of the glaciation, the Curacautín deposit belongs to two large eruptions separated by a 1,000 year time interval. Scoria bombs of both ignimbrites are quite aphyric and the study of the scarce phenocryts indicates strong mineralogical zoning which suggests disequilibria due, for example, to magma mixing. Other causes such as differences in water contents may also explain this phenomenon (McCurry & Schmidt, 2001). Changes in colour due to palagonitization of matrix glass, enrichment in lithics towards the upper parts of each ignimbritic sequence, and the presence of large surge deposits indicate also strong water intervention, at least during the late phases of the eruptions.

At Llaima, the post-Curacautín volcanism consists of a series of subplinian deposits which culminate in a large plinian eruption of mixed (andesitic and rhyodacitic) magmas. On the contrary, at Villarrica, volcanics subsequent to the Licán ignimbrite consist mainly of lava flows and minor pyroclastic flow deposits which are less evolved than the juvenile Licán clasts, at least up to the lavas which preceded the Pucón eruption (i.e. up to about middle Holocene). Such a difference in eruptive dynamics and compositional evolution suggests two opposite internal magmatic systems and developments. Whereas the Llaima magma seems to have evolved in a closed magma reservoir (which is tapped occasionally), at Villarrica, new mafic batches of magma do not differentiate very much before they are expelled to the surface. Moreover, on variation diagrams, Villarrica volcano shows much steeper K_2O and Rb versus SiO_2-slopes than Llaima. As isotopic studies exclude significant crustal assimilation (Hickey-Vargas *et al.*, 1989), we will favour in our forthcoming studies, the hypothesis of differently sized reservoirs and/or residence times related to a distinct tectonic regime in both volcanoes.

5. References

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