Lanín volcano (39.5°S), Southern Andes: geology and morphostructural evolution

Luis E. Lara Servicio Nacional de Geología y Minería, Av. Santa María 0104, Santiago, Chile.
lelara@sernageomin.cl

José A. Naranjo jnaranjo@sernageomin.cl

Hugo Moreno Servicio Nacional de Geología y Minería, Cerro Ñielol s/n, Temuco, Chile.
hmoreno@sernageomin.cl

ABSTRACT

Lanín volcano is a compound stratocone, mainly effusive, made up by four units defined through morphological criteria. The first unit represents an ancient volcano; the youngest three units form the present stratocone built since the Middle-Late Pleistocene. Compositionally, volcanic rocks from Lanín Volcano are mainly basalts/basaltic andesites and dacites with scarce intermediate types. Postglacial pyroclastic deposits are also silicic and confirm a sharp bimodality of the magmas. Major oxides and REE patterns suggest a low-pressure magmatic evolution dominated by fractional crystallization of plagioclase and orthopyroxene with extraction of olivine, clinopyroxene and magnetite without complex interactions. The effusive eruptive cycles would be controlled by a short residence in a shallow magma chamber with rapid and coeval evacuation of dacites and basalts. In recent eruptions, viscous magma would have sealed the central conduit inducing the lateral drainage of basalts and, possibly, the partial collapse of the upper part of the cone. Nevertheless, the most active degradational processes are those related to the ice-cover condition of the present stratocone. The singular evolution of Lanín volcano, geochemically and morphologically intermediate between the monogenetic cones and the stratovolcanoes of the Villarrica-Lanín chain, could be related to its distance to the trench which causes low degree of partial melting in the source and the ascent of small batches of magma that would be stored in an ephemeral magma chamber.

Key words: Stratovolcano, Geochemistry, Morphostructure, Bimodal magmatism, Southern Andes.

RESUMEN

El volcán Lanín (39,5°), Andes del sur: geología y evolución morfoestructural. El volcán Lanín es un estratovolcán compuesto, predominantemente efusivo, para el que se han definido cuatro unidades según criterios geomorfológicos. La primera de ellas representa restos de una estructura ancestral; las tres siguientes constituyen el edificio volcánico actual construido esencialmente desde el Pleistoceno Medio-Superior. Composicionalmente, las rocas volcánicas del volcán Lanín corresponden, principalmente, a basaltos/andesitas basálticas y dacitas subordinadas con escasas variedades intermedias. Los depósitos piroclásticos post glaciales muestran también composiciones silíceas y confirman una estricta bimodalidad composicional de los magmas. Los patrones de tierras raras y elementos mayores indican una evolución magmática de baja presión controlada por fraccionamiento de plagioclasa y ortopiroxeno con extracción de olivino, clinopiroxeno y magnetita, sin interacciones complejas. Los ciclos volcánicos efusivos serían controlados por un reducido tiempo de residencia en una cámara magmática superficial con evacuación rápida y simultánea de dacitas y basaltos. En erupciones recientes, el sellamiento del conducto central con magma viscoso induciría el drenaje lateral de los basaltos y, eventualmente, el colapso parcial de la zona apical del cono. Sin embargo, los procesos de degradación más activos de la estructura volcánica actual se relacionan más bien con procesos exógenos ligados a la cobertura de hielo. La singular evolución del volcán Lanín, composicional y morfológicamente intermedio entre los conos monogénicos y los estratovolcanes de la cadena Villarrica-Lanín, se asociaría a su posición distal de la fosa que origina bajos grados de fusión en la astenósfera y reducidos pulsos de magma ascendente que se almacenarían en una cámara de actividad efímera.

Palabras claves: Estratovolcán, Geoquímica, Morfoestructura, Magmatismo bimodal, Andes del Sur.

INTRODUCTION

Quaternary volcanism in the Southern Volcanic Zone (SVZ; 33-46°S *sensu* López *et al.*, 1993; see Stern, 2004) has been organised in magmatic provinces related to first order features, like the crustal thickness (Hildreth and Moorbath, 1988). Thus, south of 37°S, a thickness of *ca.* 40 km appears to influence magma geochemical signatures and low-pressure magmatic evolution is dominated by fractional crystallization in closed systems. Nevertheless, at the volcanic arc scale, transversal chains formed by stratovolcanoes and scoria cones placed along crustal structures mainly define the volcano distribution. The Villarrica-Lanín volcanic chain has been studied for geochemical purposes (Hickey-Vargas *et al.*, 1989) and eruptive styles of the volcanic centres (H. Moreno)[1]. Nevertheless, because of its elevated activity, the Villarrica volcano has focussed the attention of scientists (Calder et al., 2004; Witter and Delmelle, 2004) and only comparative studies have been done on the other stratovolcanoes. The authors present here a detailed study of Lanín volcano describing the main stratigraphic units, its magmatic evolution, eruptive style and morphostructural features. The study of these topics in a transversal volcanic chain contributes to the knowledge of the relationship between volcanism and neotectonics in the volcanic arc.

THE VILLARRICA-LANIN VOLCANIC CHAIN

The Villarrica-Lanín volcanic chain (39°S) has a N50°W trend and 60 km length. It comprises the three major stratovolcanoes, Villarrica, Quetrupillán and Lanín and 5 deeply eroded Pleistocene volcanoes together with more than 20 monogenetic volcanoes, including two maars (Fig. 1). Villarrica volcano (39.3°S/71.9°W) is a compound stratovolcano that erupted mainly basalts and basaltic-andesites. Its volcanic structure consists of an external, 6.5 km across, elliptic caldera, which formed before the Last Glacial Maxima (LGM) in the region. While the whole last glaciation in Southern Andes was considered between 90-14 ky by Clapperton (1993), the LGM was the youngest (33.5-14 ky) glacial readvance (Lowell *et al.*, 1995). At the Villarrica lake basin, H. Moreno[1] and Clayton *et al.* (1997) confirmed the minimum age of the LGM. Within the Postglacial period, Villarrica volcano showed a remarkable explosive stage (14.000-1.600 yr BP) with two major basalt-andesitic ignimbrites (*ca.* 13.800 and 3.700 yr BP; H. Moreno[1]; Moreno *et al.*, 1994; Clavero, 1996). A more recent summit caldera, 2 km across, formed in the main edifice on the northwest edge of the older caldera. The present stratocone has been built inside the summit caldera by repeated strombolian eruptions. About 30 parasitic pyroclastic cones are located on its northeast and south flanks.

To the southeast, Quetrupillán volcano (39.5°S/71.7°'W) is a compound stratovolcano that comprises a basalt to dacite rock-suite. It has an extensive postglacial explosive record, which includes many pyroclastic flow and ash-fall deposits. Its morphostructural features show two nested calderas. As for Villarrica volcano, the first caldera structure is older than the LGM and the second one was

[1] 1993. Estudio geológico, estructural y evolutivo de la cadena Villarrica-Lanín (Unpublished). Informe Final Proyecto Fondecyt No. 1930885, Santiago,Chile.

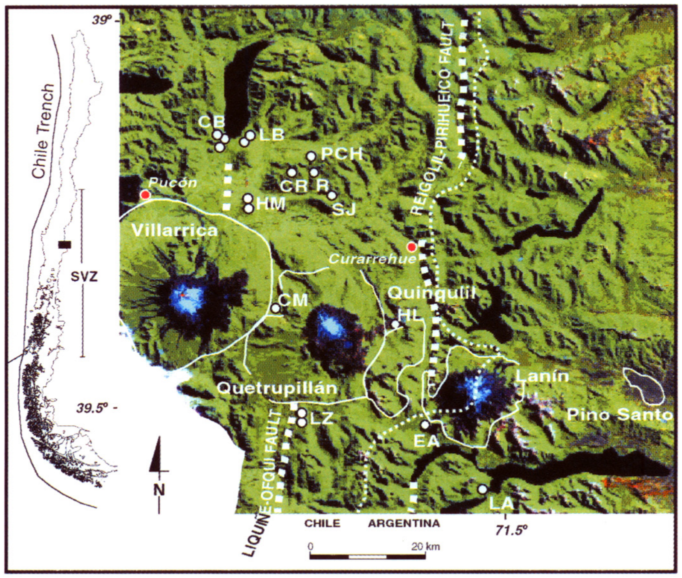


FIG. 1. Villarrica-Lanín volcanic chain. **CM**: Cordillera El Mocho; **H**: Huililco; **HM**: Huelemolles; **CB**: Caburgua; **LB**: La Barda **R**: Relicura; **CR**: Cerro Redondo; **PCH**: Pichares; **SJ**: San Jorge; **LZ**: Lizán; **EA**: El Arenal; **LA**: La Angostura.

formed during an explosive postglacial event. Domes and coulées surround the caldera walls while scoria cones are distributed in NE-SW and SW-NE directions (Pavez, 1997).

Cordillera El Mocho (39.3°S/71.8°W), Quinquilil (39.5°S/71.5°W), Laguna Los Patos (39.6°S/71.5°W), Carilafquén (39.7°S/71.6°W) and Pino Santo (39.8°S/71.2°W) are deeply eroded Pleistocene volcanoes located along the volcanic chain. Cordillera El Mocho is an eroded and small stratocone located between Villarrica and Quetrupillán volcanoes. Quinquilil volcano is a prominent neck surrounded by basaltic lavas, placed to the east of Quetrupillán volcano. Laguna Los Patos and Carilafquén centres are gently dipping volcanic sequences cut by feeder dykes, both located between Quetrupillán and Lanín volcanoes. To the east of Lanín, Pino Santo is a detritic-covered small volcano from which a noticeable lava flow fills the Malleo river valley.

Lanín volcano (39.7°S/71.5°W) lies at the southeastern end of the volcanic chain and was built mainly by basaltic and silica-rich andesitic/dacitic lavas, forming a simple large stratocone (Figs. 2, 3). Its summit reaches 3,747 m a.s.l. and is 2,500 m above the surrounding ground level. It covers an area of about 220 km^2 with an estimated volume of *ca.* 180 km^3. Lanín volcano has a near conical shape with steep slopes partially covered by glaciers. A dome that fed a blocky-lava flow fills the summit area on the northern flank. Glacial cirques cut the flanks and their heads approximately define the 'rimaya' (an ice fracture that separate the more stable glacier area on the summit from the flowing tongues over the mid slopes of the volcano). Near 2,600 m a.s.l. and more defined on the northwest flank (Figs. 2, 8), a slight break in the volcano slope roughly coincides with the heads of glacial cirques and seems to be the start line of the postglacial basalts.

Some authors (*e.g.*, Spaletti and Dalla Salda, 1996; Lara and Moreno, in press) have proposed that the Villarrica-Lanín volcanic chain is located along a pre-Andean crustal structure at the northern edge of the Loncoche tectonic block (Chotin, 1975). Moreno *et al.* (1994) suggested that this structure displaced the Liquiñe-Ofqui Fault with a left-lateral sense during the Late Cenozoic. Cembrano and Moreno (1994) proposed that the Villarrica-Lanín volcanic chain was a compressive domain within a volcanic arc affected by a simple dextral shear regime during the Quaternary. Recently, Lavenu and Cembrano (1999) showed, through microtectonic analysis that the Quaternary volcanic arc has been in a dextral transpressive regime as a whole.

FIG. 2. Lanín volcano, view to the south. Note the 'shoulder shape structure' on the flank (see text for details).

FIG. 3. Lanín volcano, view to the north.

LANÍN VOLCANO GEOLOGY

BASEMENT

The basement of Lanín volcano forms an uplifted structural block about 900 m higher than the base of the western Villarrica and Quetrupillán volcanoes. Towards the west, this block is limited by the Reigolil-Pirihueico Fault (Lara and Moreno, in press). The basement of Lanín volcano is composed of gneisses, felsic plutons and volcaniclastic sequences. The metamorphic rocks (Colohuincul Complex) have Precambrian protolithes (Dalla Salda *et al.*, 1991) and K-Ar Late Palaeozoic ages obtained by Lara and Moreno (in press) date the latest regional metamorphic event. Over these rocks rests a homoclinal Late Jurassic?-Early Cretaceous volcaniclastic sequence (Curarrehue Formation). This volcanosedimentary unit is intruded by tonalitic plutons (*ca.* 100 Ma) from the Northpatagonian Batholith along both sides of the Reigolil-Pirihueico Fault. At higher altitudes, the Mesozoic units are covered by a thin Pliocene sequence of lavas, tuffs and domes (*ca.* 5 Ma) correlated with the Estratos de Pitreño unit recognised by Campos *et al.* (1998) toward the south.

LANÍN VOLCANO

The volcanostratigraphy and the geological mapping of Lanín volcano (Fig. 4) have been made at 1:50,000 scale using essentially morphological criteria, which is common in glaciated areas (*e.g.*, Hildreth and Fierstein, 1995, among others). Indeed, with no radiometric data for the younger lavic units, the degree of glacial erosion and the 'cut and fill' relationships between the defined units were useful to establish a relative succession. Geomorphologic correlations allowed the authors to assign possible ages for these units as was done in other strato-

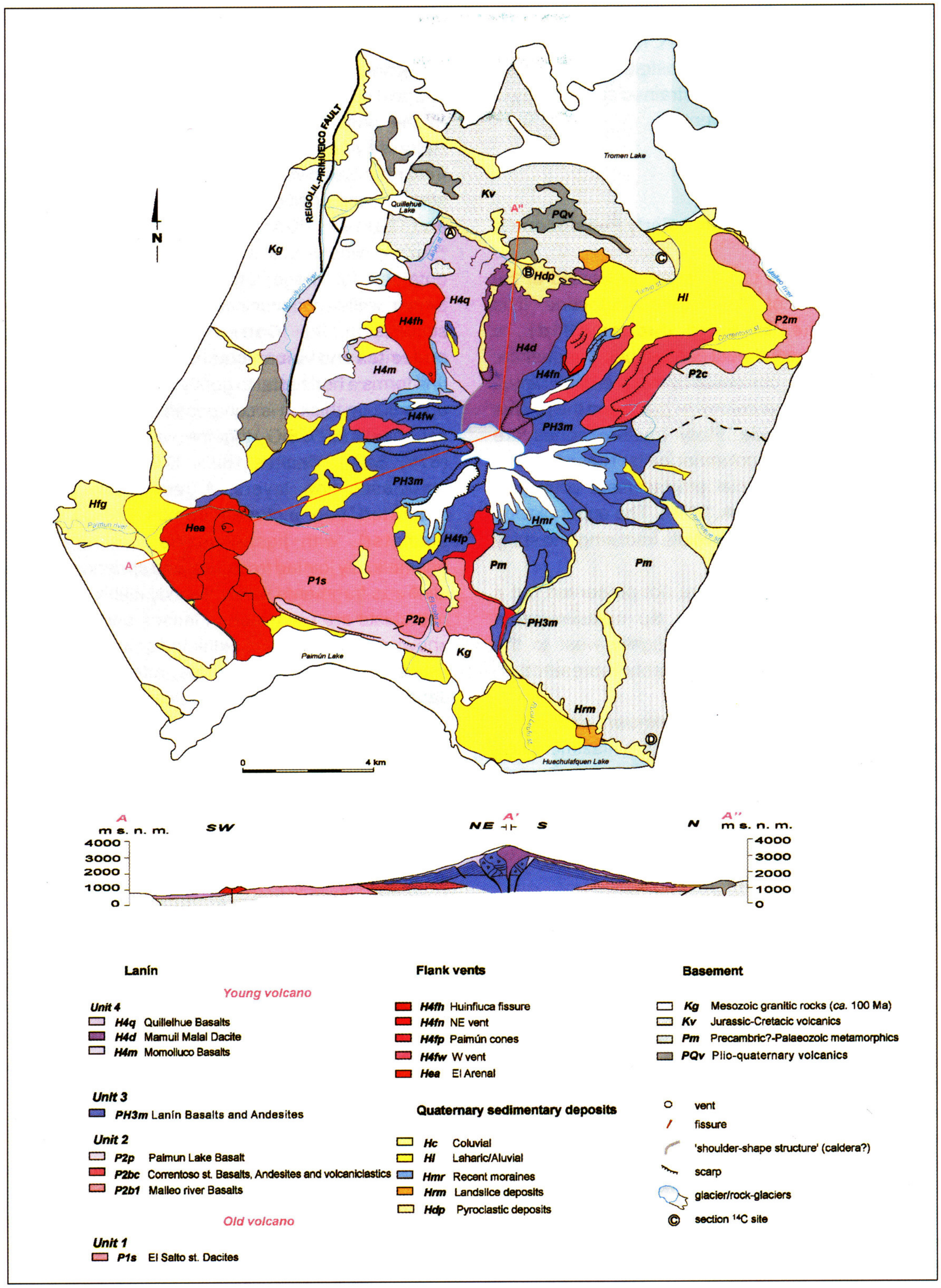


FIG. 4. Geological map of Lanín volcano (simplified from a 1:50,000 scale map by Lara, in press).

volcanoes from the SVZ (H. Moreno, J. Varela, L. López y F. Munizaga, 1985[2]; H. Moreno[1]; Naranjo *et al.*, 1993). ^{14}C ages from postglacial pyroclastic deposits enable a better constrained stratigraphy of the Holocene volcanic events.

OLD VOLCANO

Lanín unit 1 (Late Pliocene?-Early Pleistocene?)

The older Lanín unit 1, is mainly located at the southwest base of the modern stratocone. It is formed by the **'El Salto dacites (P1d)'**, a subhorizontal or southeast gently dipping sequence, up to 300 m thick, composed by massive dacitic lavas. All dacitic lavas show columnar joints and the prisms reach > 50 cm wide. Platy fracture zones are interbedded with the columnar joints. These features could indicate subglacial emplacement conditions (*e.g.*, Lescinsky and Fink, 2000). The upper blocky-lava flow show intense convolute fracturing and spiny surficial morphology.

The vents of this unit are not preserved but a simple restoration using the dip measurements suggests an emission zone slightly west to the present summit. This unit probably represents an older stratocone.

The age of this unit is unknown although it should be older than *ca.* 200 ky, the maximum age proposed for the Lanín unit 2. Nevertheless, its age could be still older and similar to some of the Late Pliocene-Early Pleistocene rocks that belong to eroded volcanic centres from the Southern Andes south of 38°S (Lara *et al.*, 2001).

YOUNG VOLCANO

Lanín unit 2 (Middle-Late Pleistocene?)

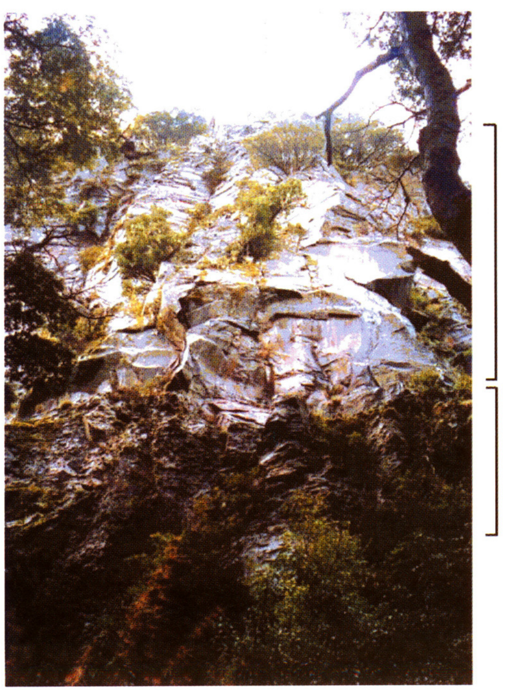
The Lanín unit 2 is formed by volcaniclastic sequences interbedded with basaltic lava flows that form the basal section of the present stratovolcano. All the outcrops of this unit show deep glacial erosion and crop out as gently dipping stacks or intracanyon lavas over Lanín unit 1 or basement. The lower subunit, labelled **'Malleo River Basalt' (P2m)**, crops out in the Malleo river valley as a massive olivine-rich basalt with platy interior fractures and deep glacial *striae* on surface. Nevertheless, the surface morphology of this lava flow, especially at its winding lava front, is well preserved, therefore the structures refered to above suggest subglacial emplacement. A few kilometres to the east of the mapped area, in Argentina, Rabassa *et al.* (1990) dated two basaltic-andesites from Pino Santo volcano, with similar morphological features and position on the valley floor, at 207±23 and 126±19 ky (K-Ar, whole rock). An unpublished $^{40}Ar/^{39}Ar$ whole-rock age of *ca.* 90 ky was also obtained for these latter basaltic-andesites (B. Singer, written communication, 2002). Upwards in the succession, the **'Correntoso stream basalts, andesites and volcaniclastic deposits' (P2c)** subunit forms a horizontal to gently dipping succession, up to 300 m thick. It is composed by clinopyroxene-rich basalts (52% SiO_2) together with some andesites (57% SiO_2), dacites (62% SiO_2), laharic and pyroclastic flow layers. A remarkable partially indurated bed includes bombs (20-30 cm in diameter), with jigsaw-puzzle structures and prismatically jointed fractures, and spherical coarse lapilli size fragments within a sandy matrix. The juvenile clasts are organised in lenses and the matrix shows a planar bedding deflected around the bigger clasts (Fig. 5). Such features, after Pierson and Janda (1994), are caused by 'volcanic mixed avalanches', a transition between pyroclastic currents and laharic flows, typical of extensively ice-covered stratovolcanoes. Another subunit, the **'Paimún lake basalt' (P2p)**, crops out as a thick subhorizontal lava stack, up to 100 m thick, forming a prominent scarp parallel to the Paimún lake shoreline with westward flow directions. Its large thickness, its surface located *ca.* 100 m over the lake and tributary streams level and the flow direction parallel to the present shoreline, suggest that this lava was once ponded against the El Salto Dacites (P1s) and the front of a westerly-derived glacier which disappeared forming the lake. Some key morphological features like platy joints, broad polygonal fractures in massive sections and the steep-walled rim of the lava flows (Lescinsky and Finks, 2000) can be interpreted as due to subglacial emplacement (Fig. 6).

Lanín unit 2 would be probably younger than the penultimate glaciation in the Southern Andes (262-132 ky after Clayton *et al.*, 1997). In fact, while the lower subunit 'Malleo River Basalt (P2m)' would be emplaced during the interglacial period before the

[2] 1985. Geología y riesgo volcánico del volcán Osorno y centros eruptivos menores. Proyecto Hidroeléctrico Central Petrohué. Informe OICB-06C (Unpublished), *Empresa Nacional de Electricidad S. A.-Corporación de Fomento de la Producción*, 212 p.

last glaciation, the younger subunits would have erupted during the intraglacial period, perhaps some of them at the main interstadial interval when the volcano was partially ice-covered. However, the upper levels of this unit must be older than the last glacial readvance in the region (33.5-14 ky after Lowell *et al.*, 1995) which promoted deep incisions on this volcanic sequence and left a thin cover of till and erratic blocks on surface.

Fig. 5. Pyroclastic deposit from 'Correntoso stream basalts, andesites and volcaniclastic deposits' (P2c). Note a prismatically jointed block (centre) in a juvenile-rich level and the coarse grained matrix with planar bedding deflected around the bomb.



Lanín unit 3

Unit 3 (Late Pleistocene-Holocene?) is formed by lava flows that shape the main inner structure of the present cone. However, its outcrops are discontinuous because they are partially covered by Lanín 4 younger flows. Lavas from Lanín unit 3 do not show glacial erosion features, but only deep river incisions and gravitational (volcanic) collapse scarps; probably formed during the Late-glacial stadial (*ca.* 12-10 ky; Clapperton, 1993). It is formed, among others, by the **'Lanín basalts and andesites' (PH3m)**, a lava sequence of olivine-rich basalts and silicic andesites, 150 m in thickness, exposed unconformably over Lanín 2 subunits (P2bc) on the north flank. In addition, there are single flows like those located in the Momolluco and Rucu Leufu rivers with similar morphology. Although they were probably erupted from the summit, their emission centres are unknown. The maximum age of this unit is *ca.* 14 ky because the absence of deep glacial erosion. Its minimum age is directly constrained by the oldest age of Lanín unit 4 of *ca.* 9,81 ky. Thus, the age of Lanín unit 3 coincides with the Late-glacial stadial in the Southern Andes.

Lanín unit 4

The upper part of Lanín volcano is formed by postglacial subunits grouped in Lanín unit 4. This unit is composed by multiple or single lava flows and pyroclastic deposits showing pristine features. Most parts of the stratocone, mainly the western and Southern flanks, are covered by the extense field of the **'Momolluco basalts' (H4m)**. Flow directions deduced from the channel ridges indicate that the multiple flows were extruded from the flank at *ca.* 3,000 m a.s.l. On the western flank, the basalt flows are overlying a 'shoulder shape structure' in the cone slope that defines a semi-elliptic contour that could be interpreted as a caldera collapse rim, a volcanic structure probably developed in the Lanín unit 3 (Fig. 2).

FIG. 6. Oblique view of a scarp showing megacolumns above platy fractures in massive interior section of 'Paimun lake basalt' (P2p). The columns diameter is *ca.* 5 m and the exposed thickness of the flow section is >50 m in this photograph.

On the northern flank of Lanín volcano the **'Mamuil Malal dacite' (H4d)** is exposed. This is a dacitic lava-dome (62% SiO_2) whose coulées extend up to 6 km. The feeder dome is located at the present summit and, together with the blocky-lava (about 25 m thick) has an estimated volume of *ca.* 0.45 km^3. The dome growth and its partial collapse would cause the emplacement of a block and ash flow deposit at the lava front, which has been dated by ^{14}C in 2,170±70 yr BP (Table 1) giving a good estimate of the age of 'Mamuil Malal Dacite' (H4d). The erosion channel recognised at the western margin of the blocky-lava starts at the dome collapse area and has been an active conduit for recent debris flows.

On the northern flank the **'Quillelhue basalts' (H4q)** are exposed. They correspond to an extensive basaltic field that reached the Quillelhue lake. They are multiple pahoehoe lava flows emitted from a hazy area located at *ca.* 2,600 m a.s.l. on the 'shoulder shape structure'. The overall volume of 'Quillelhue basalts' is *ca.* 0.1 km^3. The 'Quillelhue basalts' have features of 'shelly basalts' (Swanson, 1973) that are generally associated to fissural eruptions with lava tubes and coalescent channels 5-10 m high. Ropy *pahoehoe* structures at distal positions to the vent and tube-fed lavas suggest low effusion rates, less than 20 m^3/s (McDonald, 1972).

The maximum age of Quillelhue basalts is determined by the ^{14}C age of 2,170±70 yr BP obtained from samples of a pyroclastic deposit underlying the basalts near the Lanín creek. A minimum ^{14}C age (1,650±70 yr BP) for these lavas was obtained from a pyroclastic flow deposit that covers the basalts.

The Lanín unit 4 also comprises a few discrete pyroclastic deposits. These are piled as interfingering successions of flow and ash-fall deposits from both, Lanín and Quetrupillán volcanoes (Fig. 8). Thus, at the Lanín creek, a 2 m thick succession comprises laharic/alluvial deposits overlying pyroclastic deposits interfingered with the 'Quillelhue basalts' (H4q). Under a lava flow from H4q, the block and ash flow deposit related to the lava-dome (H4d) was dated in 2,170±70 yBP (site B, Fig. 4). On the other hand, near the southern shoreline of Tromen lake, a more complete pyroclastic succession includes an upper pyroclastic flow deposit dated in 2,460±70 yr BP (site C, Fig. 4). This layer covers a 40 cm thick ash fall deposit that includes ballistic bombs 20 cm in diameter. This pumice tephra show inverse grading from fine to coarse lapilli with a maximum diameter of 5 cm. Pumice and lithic pyroclasts are dacitic in composition. The lower part of the section includes a surge deposit overlain by a pyroclastic flow dated in 9,810±140 yr BP. To the southeast of Lanín volcano, at the northern coast of Huechulafquén lake, coarse alluvial, laharic and mudflow facies prevail and are covered by thin layers of ash fall and pyroclastic flow deposits, probably from Lanín and Quetrupillán volcanoes. At site D (Fig. 4), a pyroclastic flow deposit that covers a till was dated in 10,540±140 yr BP.

Flank vents

The occurrence of satellite eruptive centres is a common feature of stratovolcanoes at the SVZ. For example, Villarrica and Quetrupillán volcanoes have

TABLE 1. RADIOCARBON AGES FOR CHARCOAL SAMPLES.

Sample No./ Site	Type of deposit	Age (BP)*	Cal BC/AD age range** 1σ (68.3% confidence level)	Cal BC/AD age range** 2σ (95.4% confidence level)
160399-3E/A	pyroclastic flow	1,460±80	540 cal AD-655 cal AD	425 cal AD-690 cal AD
160399-3D/A	pyroclastic flow	1,650±70	340 cal AD-445 cal AD	240 cal AD-560 cal AD
160399-3A/A	pyroclastic flow	2,080±60	180 cal BC-30 cal BC	210 cal BC-55 cal AD
180399-4F/C	pyroclastic flow	2,460±70	775 cal BC-410 cal BC	795 cal BC-390 cal BC
190399-1/B	block and ash flow	2,170±70	365 cal BC-115 cal BC	390 cal BC-40 cal BC
180399-4C/C	pyroclastic flow	7,510±110	6,510 cal BC-6,160 cal BC	6,510 cal BC-6,160 cal BC
180399-4B/C	pyroclastic flow	9,810±140	9,335 cal BC-9,195 cal BC	9,690 cal BC-8,795 cal BC
180399-3G/D	pyroclastic flow	10,540±140	10,960 cal BC-10,350 cal BC	11,010 cal BC-9,970 cal BC

Data obtained at Beta Analytic Radiocarbon Dating Laboratory, Florida, USA. * conventional radiocarbon age $^{13}C/^{12}C$ ratio estimated.
** calibrated result (Stuiver and van der Plicht, 1998). Present=1950 AD (*e.g.*, Talma and Vogel, 1993). BC: Before Christ; AD: Annu Domini.
In italics Quetrupillán volcano deposits interbedded with Lanin products. Sites as in figure 4.

FIG. 7. Lanín volcano northern flank.

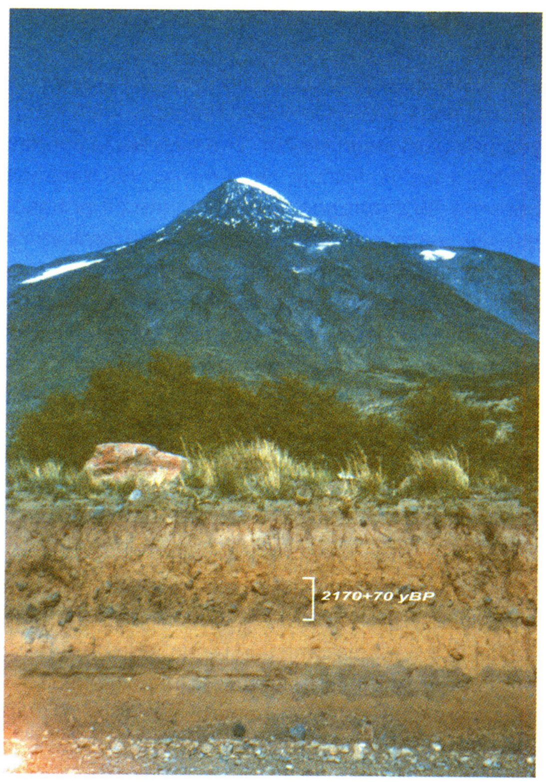


FIG. 8. Pyroclastic succession at the foothills of Lanín volcano, view to the south. Note the 'block and ash' deposit dated in 2,170±70 yBP over thin reddish pyroclastic flow deposit. 2 km west the Huinfiuca basalts (H4b2) cover this pyroclastic deposit. On surface, blocks from laharic deposits.

many postglacial pyroclastic cones, mainly aligned in a NE-SW direction. However, at Lanín volcano the flank vents are scarce and they are not aligned in a preferential direction.

The authors have recognised the **'Huinfiuca fissure' (H4fh),** a 300 m long failure with a small 'hornito' located at the lower tip. The fissure fed a field of 'shelly basalts' that reaches the Huinfiuca lake shoreline. A minimum age for this centre can be estimated from the juxtaposed 'Quillelhue basalts' (H4q) if they are younger than 2,170±70 yBP. On the northern flank of Lanín volcano, the **'N vent' (H4fn)** appears as a short fissure that fed two divergent lava flows and a local and irregular bed, up to 2 m thick, of agglutinated coarse-lapilli spatters and bombs that includes scoriaceous and banded pyroclasts with scarce partially molten granitic clasts. The eastern lava tongue shows the peculiarity that a pahoehoe flow was conducted through the central channel defined by the levées of a previous dacitic lava. The authors suggest that this feature tell about the near coeval extrusion of the two magma types during an eruptive episode.

On the southern flank of Lanín volcano, the **'Paimún cones' (H4ap)** are recognised. They correspond to small pyroclastic cones, 100-150 m in diameter, with well preserved craters and *ca.* 3.5 km long basaltic lava flow that descends to the Rucu Leufu stream. They are located on the rim of a major collapse amphitheatre filled by a rock-glacier tongue. On the western flank of Lanín volcano, lies an isolated basaltic lava field, the **'W basalts' (H4aw)**, with *tumulus* structures located, like the Paimún cones, near the rim of a collapse amphitheatre. Nor vent neither cinder cone morphology is recognised. Both the 'Paimún cones' and 'W basalts' are younger than the neoglacial moraine complex that radially extends on the flanks of the present volcanic edifice. The neoglacial events are not studied in the region of Lanín volcano but at a regional scale in Southern Andes, Clapperton (1993 and references therein) have recognised glacial advances at 8,200-8,100 yr BP; 4,700-3,300 yr BP; 2,500-1,300 yr BP and repeatedly during the last 1,200 years. For example, a major glacier on the eastern flank of Tronador volcano (41.2°S), more than 200 km southward but also at the Andean crestline, shows several readvances after the XIV century (Clapperton, 1993).

At the south-western foot of Lanín volcano is located a cluster of cinder cones called **'El Arenal cones' (Hea)**. The major pyroclastic cone is *ca.* 1.5 km diameter and has two nested craters. A smaller cone is located to the north. Both pyroclastic cones have fed a multiple lava flows that reached the Paimún lake. At the lake shoreline, medium lapilli size ash-fall layers are interfingered with surge beds. Tephras are basaltic in composition and form a thin succession of 2-5 cm thick horizons steeply dipping to the south. No phreatomagmatic features were recognised although Corbella and Alonso (1989) pointed out that vulcanian activity would be favoured by an embayment of Paimún lake, later dammed by the basalts of 'El Arenal cones'. Similar conditions could have developed at the La Angostura cone, between the Epulafquén and Huechulafquén lakes, 10 km southeast of the El Arenal cones (Fig. 1).

GEOCHEMISTRY

Lanín volcano has, as a main petrographic type, phenocryst-rich basalts (17-33%) with plagioclase (14-28%), olivine (2-5%) and opaque minerals. The more scarce basaltic andesites have plagioclase and pyroxene (5-10%) while the silicic-andesites/dacites are phenocryst-bearing (5-12%) with plagioclase (4-10%), orthopyroxene (5-10%) and opaques (1%), mainly magnetite. Unpublished microprobe data (C. Robin, written communication, 2002) show that silicic andesites/dacites have only orthopyroxene as mafic mineral. Pyroclastic-fall deposits are mostly dacitic with aphiric pumice and juvenile lithic clasts with 3-5% of phenocrysts (plagioclase and scarce pyroxene). Apatite is a common accessory as inclusion on plagioclase.

A prominent geochemical feature of the Lanín rock-suite is the bimodal silica content (Fig. 9). Indeed, from Lanín unit 2 basalts (*ca.* 52% SiO_2) and basaltic andesites prevail over silicic andesites/dacites. TiO_2 and alkali contents are typical of calc-alkaline suites. The linear trend of alkali contents (Fig. 9) shows a steeper slope compared to rocks from Villarrica volcano, a feature consistent with the distance to the trench and the depth of the magma sources (Dickinson, 1975). The high Na_2O content is also a typical feature as in the overall magmas from the SVZ (Moreno, 1976). On the other hand, basaltic magmas from both central and flank vents are not primary liquids because their low MgO (<4%) and Ni (< 25 ppm) contents. The linear trends of major elements are compatible with fractional crystallization in closed systems, probably dominated by plagioclase, olivine, pyroxene and magnetite. Remarkable high Al_2O_3 and CaO contents are recognised in some basalts, maybe indicating plagioclase accumulation. The MgO and CaO oxide contents suggest early crystallization of plagioclase, olivine and clinopyroxene in basalts.

From the rare earth elements (REE), a parental solid should melt in <4% to obtain a typical Lanín basalt in a fractional melting model (Fig. 10), if the authors assume a peridotitic composition (15% clynopyroxene/ 25% orthopyroxene/60% olivine) as was made in López and Frey (1976) and updated by Hickey-Vargas *et al.*, (1986). A slightly lower value was obtained from the Sr/Ca-Ba/Ca index by Onuma and López (1977). Melt estimates are strongly dependent of the applied model and the real composition of the parental solid. However, a comparative analysis between Villarrica and Lanín volcanoes, based upon the same assumptions, gave consistently lower melting degrees at the latter volcanic centre (Fig. 10), verifying previous results by Hickey-Vargas *et al.* (1989).

Silicic andesites/dacites show almost equal enrichment of all REE compared to Lanín basalts. In a fractional crystallization model based on the REE, the authors obtain *ca.* 50% of crystallization from basalts to silicic andesites/dacites (Fig. 10). Olivine, pyroxene and plagioclase can account for that enrichment due to their low mineral/melt partition coefficients for all REE in basaltic liquids (*e.g.*, Fujimaki *et al.*, 1984). Magnetite plays a minor effect on REE although for the 10% of silica enrichment from basalts to silicic andesites/dacites must be accounted for.

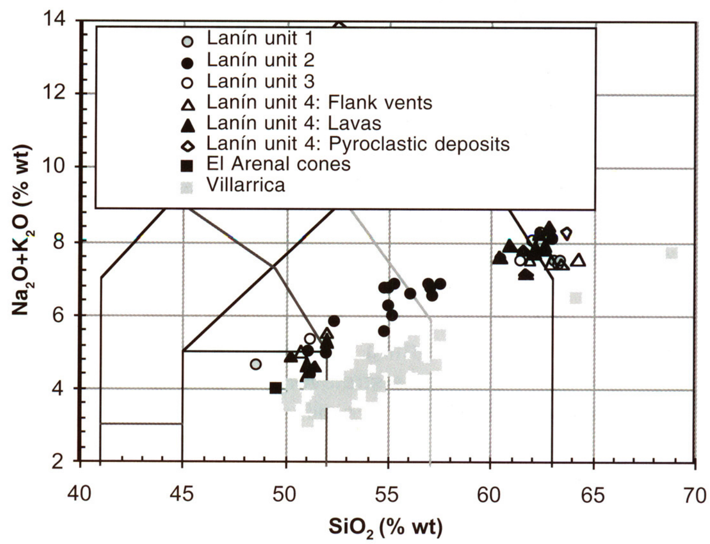


FIG. 9. Alkalis *versus* SiO_2 diagram for rocks and pyroclastic deposits from Lanín and Villarrica volcanoes. Data from table 2. Villarrica samples are from Hickey-Vargas *et al.* (1989) and H. Moreno (1993)[1].

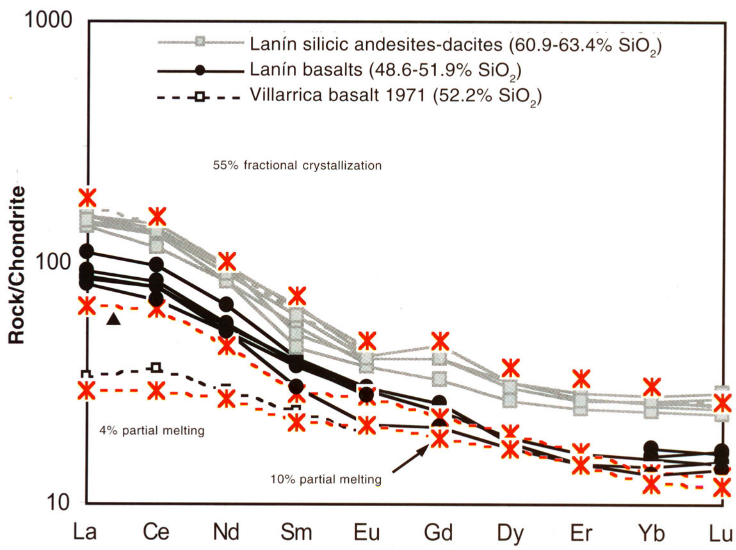


FIG. 10. Rare Earth Elements abundance for basalts and silicic andesites/dacites from Lanín volcano. For comparison, a typical basalt from Villarrica volcano is also included (Hickey-Vargas *et al.*, 1989). 10 and 4% partial melting models from peridotite are quoted. 50% curve of fractional crystallization for a basalt from Lanín volcano (L2-1*) shows homogeneous enrichment in all REE. Normalising values after Sun and McDonough (1989).

DISCUSSION

MAGMATIC AND MORPHOSTRUCTURAL EVOLUTION

New field and geochemical data show an outstanding evolution of Lanín volcano within the Villarrica-Lanín chain framework. For example, magmas from Lanín volcano have a sharp bimodal silica composition with dominance of basalts and basaltic andesites over silicic andesites or dacites. In addition, the lower pressure differentiation is mainly dominated by fractional crystallization while Villarrica and Quetrupillán volcanoes show field and geochemical features of hybridisation and magma mixing (*e.g.*, Hickey-Vargas *et al.*, 1986; Pavez, 1997). Moreover, the input of a high temperature basaltic magma would have triggered some explosive cycles in Villarrica and Quetrupillán volcanoes with related caldera collapse events (Clavero, 1996; Pavez, 1997). In addition, Lanín volcano has a contrasting morphostructural evolution. Lanín is a simple stratovolcano built by repeatedly effusive cycles. The diffuse 'shoulder shape structure' at the north and western flanks could represent a small 'Hawaiian-type' caldera even though glacial processes could cause similar morphology, as it has ocurred in other ice-covered stratovolcanoes of the Southern Andes. Finally, Lanín volcano does not show visible volcanic activity nor a 'historic' eruptive record (XVI to XX centuries) as the neighbouring volcanoes.

The authors speculate that the different morphostructural features and eruptive style of Lanín volcano are related to its dissimilar petrological evolution from the magma source to the magma chamber. For instance, basalts from Villarrica, Quetrupillán and Lanín volcanoes seem to have no common precursors and, different degrees of partial melting (decreasing eastward) are required in their petrogenetic models (López *et al.*, 1977; Hickey-Vargas *et al.*, 1986). A reasonable assumption is that lower degrees of partial melting in the astenosphere could supply smaller volumes of magmas to the crust. A roughly defined bulk emission rate (0.5-1.0 km^3/ky) for Lanín volcano could reflect small single pulses of magma from the mantle source following Fedotov (1981) and Takada (1994). Whilst, at Villarrica volcano the bulk emission rate (2-4 km^3/ky) could suggest a steady-state magma ascent. The latter assumption is supported by radioactive isotopes disequilibria measured in basalts from Villarrica volcano (Tormey *et al.*, 1991). Thus, a small batch of magma would reach the lower crustal levels where a higher pressure stage of fractional crystallization began. This early phase is well recognised in several long-lived stratovolcanoes of the Southern Andes as well (Hickey-Vargas *et al.*, 1986; 1989). Then, at shallow levels, a fractional crystallization model could explain the basalt-dacite transition throughout extraction of olivine, clinopyroxene and magnetite, coeval with the ongoing crystallization of plagioclase and orthopyroxene. Alternatively, the hypothesis of magma mixing was tested by Hickey-Vargas *et al.* (1989) obtaining an ambivalent result. Nevertheless, the eruptive style precludes that possibility in Lanín volcano, at least at a big scale, even though the replenishment of the magma chamber could produce mixing between basalts and dacites obtaining basaltic andesites.

On the other hand, the classic problem of the 'SiO_2 gap' (absence of intermediate compositions) could be explained throughout rheological arguments, as was done by Grove and Donelly-Nolan (1986) at Medicin Lake volcano or Tormey *et al.* (1989) at Planchón-Peteroa Volcanic Complex.

In addition, following Gudmundson (1986), we speculate that small magma batches feed small magma chambers that can be quickly drained. Field evidence from the Holocene eruptions of Lanín volcano seems to support the nearly coeval emplacement of basaltic and more silica-rich lavas. Silicic lavas would be erupted from the summit area while if the emptying of the chamber occur so fast, small 'Hawaiian-type' calderas could be formed.

Thus, discrete magma batches with short residence times and quickly drained, could cause the mainly effusive style of volcano building. The main erosive process, in turn, would be related to the glacier dynamics.

HAZARD ASSESSMENT

From the historical record (since XVI century) and the absence of visible current activity at Lanín volcano, a migration to the west of postglacial volcanic activity at Villarrica-Lanín chain was

TABLE 2. GEOCHEMICAL ANALYSIS OF LANIN VOLCANO.

Sample	140194-5	140194-4	140194-2	150502-3	170502-6	170502-5	170502-8	170502-7	151293-D	151293-C	151293-B	LN151293-A
Unit	P1s	P1s	P1s	P2b1	P2bc	P2bc	P2bc	P2bc	P2bc	P2bc	P2bc	P2bc
SiO_2	63,09	63,28	63,37	55,20	55,02	54,85	51,20	55,32	57,06	56,93	54,79	51,99
TiO_2	0,87	0,89	0,86	1,12	1,31	1,26	1,18	1,29	1,32	1,3	1,38	1,44
Al_2O_3	16,25	16,31	16,13	17,63	17,35	16,79	20,33	16,95	16,6	16,41	17,15	16,77
Fe_2O_3	5,89	5,83	5,76	8,60	8,31	8,86	8,46	8,37	9,06	9,33	10,28	12,02
MnO	0,15	0,15	0,15	0,18	0,21	0,19	0,15	0,19	0,17	0,18	0,17	0,15
MgO	1,66	1,54	1,59	2,79	2,51	2,64	3,61	2,50	2,59	2,61	3,26	4,02
CaO	3,93	3,87	3,94	7,78	7,74	7,84	10,07	7,77	5,47	5,44	6,61	7,88
Na_2O	5,05	5,01	5,03	4,55	4,70	4,67	3,39	4,83	4,83	4,9	4,09	3,85
K_2O	2,45	2,38	2,45	1,42	2,04	2,07	0,96	2,01	1,93	1,94	1,45	1,12
P_2O_5	0,34	0,34	0,33	0,34	0,42	0,42	0,24	0,38	0,56	0,54	0,4	0,34
Sc	13	13	13						20	22	25	26
V	63	64	61						86	88	162	260
Cr	5	5	5						5	5	5	5
Co	13	13	21						22	22	27	34
Ni	5	5	5						5	587	5	5
Zn	77	76	79						93		81	86
Ga										13		
Cu	8	8	5						14		29	45
K												
Rb												
Cs												
Sr	440	460	454						550	556	610	608
Ba	710	710	690						570	576	476	363
Y	33,9	33,3	34,5						38,8	40,2	31,7	29,9
Zr	216	221	226						167	177	145	108
Nb												
Hf	6,2	5,1	5,8						4,9	5,1	4,1	3,3
La	32	31	32						31	28	23	20
Ce	72	70	71						69	65	54	48
Nd	37	34	37						38	36	30	25
Sm	7,2	7,22	6,89						7,5	7,8	6,27	6
Eu	1,9	1,87	1,85						2,15	2,13	1,94	1,7
Gd	5,75	6	5,9						7,3	6,17	5,68	5,02
Tb												
Dy	5,5	5,66	5,63						6,37	5,86	5,25	4,75
Ho												
Er	3,3	3,3	3,26						3,55	3,42	2,89	2,65
Yb	3,3	3,25	3,21						3,47	3,36	2,92	2,61
Lu	0,51	0,5	0,51						0,54	0,53	0,45	0,37

Sample	51293-9	190194-C	160502-4	160502-1	LN130194-1	160502-2	160502-3	051293-1	LN81293-7	150193-5	150193-4	150193-2
Unit	P2bc	P2bc	P2p	P2p	P2p	P2p	P2p	PH3m	PH3m	PH3m	PH3m	PH3m
SiO_2	62,99	51,11	52,35	57,57	57,15	54,98	56,09	51,22	61,42	62,05	60,45	62,39
TiO_2	0,88	1,2	1,35	0,83	0,98	0,94	0,90	1,49	0,98	0,97	1,16	0,98
Al_2O_3	16,01	18,64	17,87	17,49	17,6	18,26	17,77	18,35	16,39	16,75	16,12	16,3
Fe_2O_3	6,53	10,55	9,59	6,70	8,25	7,91	7,36	10,77	7,14	6,36	7,16	5,88
MnO	0,16	0,15	0,18	0,18	0,16	0,17	0,18	0,15	0,17	0,16	0,18	0,15
MgO	1,35	4,3	3,51	2,09	2,52	2,50	2,40	3,80	1,54	1,34	2,08	1,29
CaO	3,24	8,39	8,56	7,35	5,91	8,05	7,88	8,02	4,07	3,49	4,44	3,63
Na_2O	5,12	3,8	4,36	4,93	4,95	4,60	4,79	4,01	4,92	5,25	5,13	5,42
K_2O	2,98	1,2	1,48	1,93	1,59	1,63	1,77	1,35	2,58	2,78	2,44	2,82
P_2O_5	0,34	0,27	0,35	0,53	0,5	0,58	0,47	0,43	0,38	0,45	0,44	0,4
Sc	16	27			11		11		18			
V	21	250			86		63		37			
Cr	5				5		6		5			
Co	12	41			13		11		5			
Ni	5	5			5		2		12			
Zn	90	76			77				6			
Ga									86			
Cu	8	44			14				9			
K												
Rb							35					
Cs												
Sr	385	650			730		691		451			
Ba	742	387			510				746			
Y	46,3				27,2		26		48,9			
Zr	274	119			43		114		243			
Nb							7					
Hf	7,2	3,5			3,9				7,5			
La	35	19			26		26		37			
Ce	80	42			59		55		83			
Nd	41	24			31		33		44			
Sm	9,12	4,6			6,05				10,1			
Eu	2,18	1,23			1,75				2,37			
Gd	7,41	4,31			5,39				9,19			
Tb												
Dy	7,14	4,3			4,5				8			
Ho												
Er	4,32	2,4			2,41				4,49			
Yb	4,34	2,25			2,43				4,43			
Lu	0,64	0,35			0,38				0,66			

Sample	L2-1*	L2-2*	GV164	180193-1	L3-1*	L3-2*	L3-3*	L3-4*	201281-01	200281-3	200281-05	LN71293-9
Unit	H4q	H4q	H4q	H4m	H4d	H4d	H4d	H4d	H4d	H4d	H4d	H4d
SiO_2	51,03	51,03	50,18	51,98	60,42	62,6	62,13	62,79	62,83	60,94	62,28	62,18
TiO_2	1,29	1,3	1,17	1,18	1,27	1,14	0,92	0,92	0,8	1,26	0,97	1,13
Al_2O_3	18,04	17,89	19,45	19,81	15,19	15,17	15,9	15,97	16,71	15,29	16,09	15,65
Fe_2O_3	10,83	10,92	9,82	8,64	8,71	7,74	7,45	6,24	5,96	7,81	6,37	7,17
MnO	0,19	0,18	0,21	0,14	0,23	0,22	0,21	0,18	0,14	0,2	0,16	0,18
MgO	4,92	4,66	5,05	3,72	1,67	1,2	1,33	1,25	1,01	1,81	1,51	1,47
CaO	8,6	8,57	8,5	8,49	3,95	3,19	3,58	3,49	3,48	3,83	3,62	3,57
Na_2O	3,18	3,42	3,68	3,99	5,18	5,19	5,01	5,62	5,54	5,45	5,45	5,30
K_2O	1,17	1,24	1,15	1,30	2,40	2,72	2,69	2,76	2,83	2,47	2,79	2,51
P_2O_5	0,36	0,4	0,36	0,34	0,57	0,43	0,37	0,39	0,31	0,54	0,37	0,45
Sc	29,3	28			19,9	17,9	15,7	17,2				18
V	216	219			32	17	19	15				32
Cr	19	23			8	6	8	3	10			5
Co	33,4	32			8,5	6,4	6,3	5,7	29			15
Ni	27	24			10	9	10	10				5
Zn	93	97			110	100	93	87				98
Ga	19,7	19,4			19,4	19,5	18	19,2				
Cu												8
K	9943	10462				23117		23455				
Rb	32,1	34,2			59,4	66,9	77,1	77,8				
Cs	1,81	1,9			2,3	3,03	3,5	3,9				
Sr	621	626			410	334	414	392				394
Ba	375	384			708	802	730	747				700
Y	27,3	27,4			43,1	45,5	40,9	42,3				49
Zr	154	157			270	311	285	302				218
Nb	6,3	6,6			11,3	13,3	11,1	10,8				
Hf	3,7	3,7			6,3	6,7	6,4	7,2				7,5
La	20,8	21,6	19,9		37,1	40,7	34,4	35,1	33	37	37	36
Ce	48,5	51,3	57		87,6	89,1	78,9	78,6	71	82	80	83
Nd	24	25,9	26		45,3	45,3	38,6	40,2	39	48	45	44
Sm	5,65	5,75	5,19		9,92	9,45	8,21	8,49	6,68	7,9	7,74	9,43
Eu	1,67	1,63	1,45		2,57	2,49	2,2	2,3	2,17	2,55	2,32	2,5
Gd									6,64	8,79	8,1	8,1
Tb	0,87	0,81			1,21	1,2	1,06	1,24				
Dy									6,78	7,78	8,09	7,22
Ho			1,3						1,19	1,42	1,38	
Er									4,1	4,58	4,75	4,37
Yb	2,7	2,85	2,8		4,56	4,57	4,35	4,32	4,06	4,43	4,81	4,44
Lu	0,42	0,41	0,46		0,65	0,68	0,63	0,66	0,6	0,67	0,74	0,67

Sample	LN81293-2	010393-2	180399-4D	180399-4E	90194-3b	90194-3a	90194-2b	90194-2a	81293-4	81293-3	180399-2B
Unit	H4d	Hdp	Hdp	Hdp	H4fn	H4fn	H4fn	H4fn	H4fn	H4fn	Hea
SiO_2	62,62	61,73	61,53	63,70	63,52	62,95	61,94	64,25	50,69	51,98	49,56
TiO_2	0,97	1,04	0,67	0,64	0,92	0,98	0,99	0,94	1,4	1,42	1,11
Al_2O_3	15,83	18,22	17,95	16,45	15,75	15,68	17,27	15,22	17,67	18,72	21,91
Fe_2O_3	6,74	5,95	6,71	5,69	6,06	6,29	6,91	6,13	11,14	10,81	9,6
MnO	0,17	0,16	0,17	0,17	0,52	0,15	0,17	0,15	0,17	0,17	0,14
MgO	1,56	1,54	1,22	1,24	1,52	1,67	1,28	1,42	4,78	3,30	3,28
CaO	3,55	3,42	3,2	3,14	3,6	4,06	3,1	3,59	8,33	7,25	9,8
Na_2O	5,00	4,44	4,99	5,30	4,55	4,55	4,78	4,58	3,62	4,20	3,32
K_2O	2,79	2,68	2,79	2,96	2,83	2,88	2,75	2,95	1,38	1,30	0,69
P_2O_5	0,37	0,41	0,38	0,29	0,35	0,39	0,42	0,38	0,43	0,43	0,19
Sc	17		17		15	15	15	16	29	25	23
V	30		24		49	53	24	47	235	190	
Cr	5		6		5	5	5	5	13	9	7
Co	12		2			13	12	12	37	26	23
Ni	5		2		5	5	5	5	17	9	2
Zn	92		93		75	75	92	79	85	90	68
Ga											
Cu	12				11	16	11	10	56	34	
K											
Rb			80								17
Cs											
Sr	340		345		381	370	340	362	613	641	753
Ba	670		707		702	677	680	680	392	370	246
Y	48,4		43		39,5	38,2	49,5	42,6	33,4	30	18
Zr	236		291		245	179	277	236	156	136	75
Nb			10								5
Hf	7,5				7,3	7,4	7,9	7,2	5,2	3,5	
La	35		37		31	32	37	33	25	21	12
Ce	82		84		72	73	85	78	58	47	27
Nd	42		42		36	36	47	41	33	29	20
Sm	9,23				7,56	7,36	9,72	8,36	6,96	5,8	
Eu	2,32				1,91	1,83	2,26	1,97	1,75	1,8	
Gd	8,1				6,67	6,98	8,66	7,35	5,76	5,2	
Tb											
Dy	7,68				6,38	6,28	8,28	6,8	5,78	5,02	
Ho											
Er	4,46				3,85	3,73	4,6	4,02	3,01	2,65	
Yb	4,57				3,82	3,79	4,63	4,13	2,98	2,73	
Lu	0,7				0,55	0,59	0,72	0,63	0,48	0,41	

Data obtained at Universidad de Chile, Departamento de Geología by J. Martinez and SERNAGEOMIN by F. Llona.
Dark grey pattern for data from Hickey-Vargas *et al.* (1989); light gray for data from López *et al.* (1977). Major oxides normalized to 99.6%.

proposed (H. Moreno[1]). Nevertheless, Lanín volcano had central eruptions at least until *ca.* 2000 yr BP, and that migration would be only apparent. Moreover, some parasitic cones are younger than the neoglacial deposits and could be, in turn, younger than *ca.* 700 yr BP. Lanín volcano was reported active after an earthquake in 1906 by a newspaper, but Sapper (1917) stated that the accounts were strongly disputed precluding that possibility. Thus, Lanín volcano would have been dormant for the last two centuries.

In the neighbouring area, 20 km to the southeast, the most recent volcanic event occurred as lava flows from El Escorial cone, which were dated in 200±90 yr BP (Inbar *et al.*, 1995).

Nevertheless, among the plausible volcanic unrest, the steep upper flanks, capped by thick glaciers and normally covered by snow, are clear features that can favour the formation of repeated debris flows as hazardous process. In addition, the instability of the main glacier front during the last decades, would be accelerated by their conspicuous retreat. Thick neoglacial moraine deposits are left as a suitable source for laharic debris flows. The areas that can be affected correspond to alluvial fans and aprons mainly located to the north and south.

Although Lanín volcano shows a poor stratigraphic record of explosive events, the presence of a summit dome which obstructs the central conduit may be a factor that favours an explosive eruptive process and/or sector collapse of the volcanic structure. Lanin is one of the highest stratocones of the Southern Andes and the main hazardous scenarios derive from its steep morphology and the aggradational processes that normally occur at ice-covered volcanoes.

CONCLUSIONS

Morphologic analysis and chronostratigraphic correlations allow to define a volcanostratigraphic succession of four units for Lanín volcano. All units from the present stratovolcano are monotonous sequences of basaltic/basalt andesitic lava flows and dacitic lavas with interbedded pyroclastic flow, ash fall and laharic/alluvial deposits. The Lanín unit 1 represents the building of an ancient stratocone in the Lower Pleistocene; the Lanín unit 2 form the basal section of the present stratocone and was probably erupted at the Middle-Late Pleistocene being deeply eroded by the last glacial event; the Lanín unit 3 forms the inner part of the present stratocone build up in the Late Pleistocene-Holocene and partially eroded at the Late-glacial stadial; and the Lanín unit 4 re-built the volcanic cone with postglacial emmisions in the Holocene.

The geochemical data characterise the Lanín basalts as a calc-alkaline type that can be modeled by *ca.* 4% of partial melting of a peridotitic mantle. The early fractional crystallization of olivine, clinopyroxene and magnetite and the later segregation of these phases, together with the ongoing crystallization of plagioclase and orthopyroxene, would have controlled the magmatic evolution as the authors can infer from the behaviour of major and trace elements.

The eruptive mechanism of each volcanic cycle is mainly effusive and should be closely related to the crystallization process in a shallow magma chamber. In a typical eruption, the pressure excess would allow the initial emission of a small volume ash cloud and ballistic bombs, followed by a viscous silicic lava flow sealing the central vent and forming an apical dome. Then, the major basaltic level of the chamber must be evacuated throughout ancient structures of the central vent or lateral fissures.

The authors propose that the volcanic behaviour of Lanín volcano, sharply different from the western stratovolcanoes, is related to magma source position far away from the trench and over a different tectonic block. Intermittent magma pulses that cause effusive eruptions followed by quiescence periods would build Lanín volcano. The size and steep morphology of Lanín make it a hazardous volcano, mainly from lahar debris-flows to sector collapse-forming processes, but probabilities are still are difficult to evaluate.

ACNOWLEDGEMENTS

Fieldwork and geochemical analyses were supported by Fondecyt 1930992 grant (HM; LEL). Fondecyt 1960186 grant (JAN; HM; LEL) supported the C^{14} dating and field revisions for crhono-stratigraphic discussion. Fieldwork was facilitated by Conaf (Corporación Nacional Forestal, IX Región), specially the Puesco district (Villarrica National Park) staff. The local hospitality is acknowledged to L. Quintún and his family. R.Cucci and J. Mendía provided high-quality vertical aerial photographs from SEGEMAR. R.S.J. Sparks, A. Demant and R. Hickey-Vargas made useful comments to this paper. This is a contribution to the Volcanic Hazard Program (Servicio Nacional de Geología y Minería, Chile).

REFERENCES

Campos, A.; Moreno, H.; Muñoz, J.; Antinao, J.; Clayton, J.; Martin, M. 1998. Area Futrono-Lago Ranco, Región de los Lagos. *Servicio Nacional de Geología y Minería, Mapas Geológicos,* No. 8. Santiago.

Cembrano, J.; Moreno, H. 1994. Geometría y naturaleza contrastante del volcanismo cuaternario entre los 38°S y 46°S: ¿Dominios compresionales y tensionales en un régimen transcurrente?. *In Congreso Geológico Chileno, No. 7, Actas,* Vol. 1, p. 240-244. Concepción.

Clapperton, C. 1993. Quaternary geology and geomorphology of South America. *Elsevier Science Publishers,* 779 p. Amsterdam.

Clavero, J. 1996. Ignimbritas andesítico basálticas postglaciales del volcán Villarrica, Andes del Sur (39°25'S). Tesis de Magister (Inédito), Universidad de Chile, Departamento de Geología, 112 p. Santiago.

Clayton, J.; Clapperton, C.; Antinao, J. 1997. Las glaciaciones pleistocenas en la cuenca del lago Villarrica, Andes del Sur. *In Congreso Geológico de Chile, No. 8, Actas,* Vol. 1, p. 307-311. Antofagasta.

Corbella, H.; Alonso, M. 1989. Post-glacial hydroclastic and pyroclastic deposits in the Lanín National Park. North-Patagonian Cordillera, Neuquén. *Revista de la Asociación Geológica Argentina,* Vol. 44, No.1-4, p. 127-132.

Chotin, P. 1975. Los Andes Meridionales et la Termination du Basin Andin. De Lonquimay (Chili) et le Neuquén (Argentine) (lat. 38°45'S). Ph.D. Thesis (Inédito), *Université Pierre et Marie Curie*, 306 p. Paris.

Dalla Salda, L., Cingolani C.; Varela R. 1991. El basamento pre-andino ígneo metamórfico de San Martín de los Andes, Neuquén. *Revista de la Asociación Geológica Argentina,* Vol. 46, No. 3-4, p. 223-234.

Dickinson, W.R. 1975. Potash-depth (K-h) relations in continental margin and intraoceanic magmatic arcs. *Geology,* No. 3, p.53-56.

Fedotov, S.A. 1981. Magma rates in feeding conduits of diffeent volcanic centres. *Journal of Volcanology and Geothermal Research,* Vol. 9, p. 379-394.

Fujimaki, H.; Tatsumoto, M.; Aoki, K. 1984. Partition coefficients of Hf, Zr and REE between phenocrysts and groundmasses. Proceedings of the Fourteenth Lunar and Planetary Science Conference, Part 2. *Journal of Geophysical Research,* Vol. 89, Supplement, B662-B672.

Grove, T.L.; Donelly-Nolan, J.M. 1986. The evolution of young silicic lavas at Medicine Lake volcano, California: implications for the origin of compositional gaps in calc-alkaline series lavas. *Contribution to Mineralogy and Petrology,* No. 92, p. 281-302.

Gudmundsson, A. 1986. Possible effect of aspect ratios of magma chambers on eruption frequency. *Geology,* Vol. 14, 991-994.

Hickey-Vargas, R.; Frey, F. Gerlach; D.; López, L. 1986. Multiple sources for basaltic arc rocks from the southern volcanic zone of the Andes (34°-41°S): trace element and isotopic evidence for contributions from subducted oceanic crust, mantle and continental crust. *Journal of Geophysical Research,* Vol. 91, p. 5963-5983.

Hickey-Vargas, R.; Moreno, H.; López Escobar, L.; Frey, F. 1989. Geochemical variations in Andean basaltic and silicic lavas from the Villarrica-Lanín volcanic chain (39.5°S): an evaluation of source heterogeneity, fractional crystallization and crustal assimilation. *Contributions to Mineralogy and Petrology,* Vol. 103, p. 361-386.

Hildreth, W.; Moorbath, S. 1988. Crustal contributions to arc magmatism in the Andes of Central Chile. *Contributions to Mineralogy and Petrology,* Vol. 98, p. 455-489.

Hildreth, W.; Fierstein, J. 1995. Geologic map of the Mount Adams volcanic field, Cascade Range of Southern Washington. *U.S. Geological Survey, Miscellaneous Investigation Series,* Map I-2460.

Inbar, M.; Risso, C.; Parica, C. 1995. The morphological development of a young lava flow in the South Western Andes-Neuquén, Argentina. *Zeitschrift Geomor-*

phologie, N.F., Vol. 39, No. 4, p. 479-487.

Lara, L.; Moreno, H. (in press). Geología del área Liquiñe-Neltume. *Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica,* No. 83.

Lara, L. (In press). Geología del volcán Lanín, IX y X regiones. *Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica.*

Lara, L.; Rodríguez, C.; Moreno, H.; Pérez de Arce, C. 2001. Geocronología K-Ar y geoquímica del volcanismo plioceno superior-pleistoceno de los Andes del Sur (39°-42°S). *Revista Geológica de Chile,* Vol. 28, No. 1, p. 67-90.

Lavenu, A.; Cembrano, J. 1999. Compressional and transpressional-stress pattern for Pliocene and Quaternary brittle deformation in fore arc and intra-arc zones (Andes of Central and Southern Chile). *Journal of Structural Geology,* Vol. 21, p.1669-1691.

Lescinsky, D.; Fink, J. 2000. Lava and ice interaction at stratovolcanoes: use of characteristic features to determine past glacial events and future volcanic hazards. *Journal of Geophysical Research,* Vol. 105, No. B10, p. 23711-23726.

López, L.; Frey, F. 1976. Las rocas volcánicas cuaternarias de Chile central-sur (33°-41°S): modelos petrogenéticos sugeridos por las tierras raras. *In Congreso Geológico Chileno, No. 1, Actas,* Vol. 2, p. F223-F255. Santiago.

López, L.; Kilian, R.; Kempton, P.D.; Tagiri, M. 1993. Petrography and geochemistry of quaternary rocks from the Southern Volcanic Zone of the Andes between 41°30' 46°00'S, Chile. *Revista Geológica de Chile,* Vol. 20, No. 1, p. 33-56.

Lowell, T.V.; Heusser, C.J.; Andersen, B.G.; Moreno, P.I.; Hauser, A.; Heusser, L.E.; Schlüchter, C.; Marchant, D.R.; Denton, G.H. 1995. Interhemispheric correlation of Late Pleistocene Glacial Events. *Science,* Vol. 269, p. 1541-1549.

McDonald, G.A. 1972. Volcanoes. *Prentice Hall, Englewood Cliffs,* 510 p. New Jersey.

Moreno, H. 1976. The Upper Cenozoic volcanism in the Andes of Sothern Chile (from 40°00' to 41°30'S.L.). *In IAVCEI International Symposium on Volcanology, Proceedings,* p. 143-173. Santiago.

Moreno, H.; Clavero, J.; Lara, L. 1994. Actividad explosiva postglacial del Volcán Villarrica, Andes del Sur (39°25'). *In Congreso Geológico Chileno No. 7, Actas,* p. 329-333. Concepción.

Naranjo, J.A; Moreno, H.; Emparan, C.; Murphy, M. 1993. Volcanismo explosivo reciente en la caldera del volcán Sollipulli (39°S). *Revista Geológica de Chile,* Vol. 20, No. 2, p. 167-191.

Onuma, N.; López, L. 1977. Possible contribution of the astenosphere, below the subducted oceanic lithosphere from the Andean southern volcanic zone (33°-46°S). *Journal of Volcanology and Geothermal Research,* No.33, p. 283-298.

Pavez, A. 1997. Geología e historia evolutiva del Complejo Volcánico Quetrupillán, Andes del Sur, 39,5°S. *In Congreso Geológico Chileno, No.8, Actas,* Vol. 2, p. 1443-1447. Antofagasta.

Pierson, T.; Janda, R. 1994. Volcanic mixed avalanches: a distinct eruption-triggered mass-flow process at snow-clad volcanoes. *Geological Society of America, Bulletin,* Vol. 106, p. 1351-1358.

Rabassa, J.; Evenson, E.; Clinch, J.; Sclieder, G.; Zeitler, P.; Stephens,G. 1990. Geología del cuaternario del valle del río Malleo, Provincia del Neuquén. *Asociación Geológica Argentina,* Vol. 45, No.1-2, p. 55-68.

Sapper, K. 1917. Katalog der geschitlichen Vulkanausbrüche, 358 p. Strabburg.

Spalletti, L.A.; Dalla Salda, L.H. 1996. A pull-apart volcanic related Tertiary basin, an example from the Patagonian Andes. *Journal of South American Earth Sciences,* Vol. 9, Nos. 3-4, p. 197-206.

Sun, S.S.; McDonough, W.F. 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. *In* Magmatism in the Ocean Basins (Saunders, A.D.; Norry, M.J.; editors). *Geological Society, Special Publications,* No. 42, p. 313-345.

Stern, C.R. 2004. Active Andean Volcanism: its Geologic and Tectonic Setting. *Revista Geológica de Chile,* Vol. 31, No. 2, p. 161-206.

Stuiver, M.; van der Plicht, H. 1998. INTCAL98 Radiocarbon age calibration. *Radiocarbon,* Vol. 40, No. 3, p. 1041-1083.

Swanson, D. 1973. Pahoehoe flows from the 1969-1971 Mauna Ulu eruption, Kilauea volcano, Hawaii. *Geological Society of America, Bulletin,* Vol. 84, p. 615-626.

Takada, A. 1994. The influence of regional stress and magmatic input on styles of monogenetic and polygenetic volcanism. *Journal of Geophysical Research,* Vol. 99, No. B7, p. 13563-13573.

Talma, A.; Vogel, J. 1993. A simplified approach to calibrating 14C dates. *Radiocarbon,* Vol. 35, No. 2, p. 317-322.

Tormey, D.; Frey, F.; López, L. 1989. Geologic history of the Azufre-Planchón-Peteroa volcanic center (35°15'S, Southern Andes), with implications for the development of compositional gaps. *Revista de la Asociación Geológica Argentina,* Vol. 44, p. 420-430.

Tormey, D.; Schuller, P.; López, L.; Frey, F. 1991. Uranium-thorium activities and disequilibrium in volcanic rocks from the Andes (33-46°S): petrogenetic constraints and environmental consequences. *Revista Geológica de Chile,* Vol. 18, No. 2, 11 p.

Witter, J.B.; Delmelle; P. 2004. Acid gas hazards in the crater of Villarrica volcano (Chile). *Revista Geológica de Chile,* Vol. 31, No. 2, p. 273-278.

Manuscript received: February 3, 2003; accepted: August 20, 2003.