



# Comparative study of lahars generated by the 1961 and 1971 eruptions of Calbuco and Villarrica volcanoes, Southern Andes of Chile

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## ABSTRACT

The Villarrica and Calbuco volcanoes, of the Andean Southern Volcanic Zone, are two of the most active volcanoes in Chile and have erupted several times in the XX century. The 1961 eruption at Calbuco volcano generated lahars on the North, East and Southern flanks, while the 1971 eruption at Villarrica volcano generated lahars in almost all the drainages towards the north, west and south of the volcano. The deposits from these eruptions in the Voipir and Chaillupén River (Villarrica) and the Tepú River (Calbuco) are studied. The 1971 lahar deposits on Villarrica volcano show a great number of internal structures such as lamination, lenses, grading of larger clasts and a great abundance of large floating blocks on top of the deposits. The granulometry can be unimodal or bimodal with less than 5% by weight of silt + clay material. SEM images reveal a great variety of forms and compositions of clasts. The 1961 lahar deposits on Calbuco volcano have a scarce number of internal structures, steeper margins and features of hot emplacement such as semi-carbonized vegetal rests, segregation pipes and a more consolidated matrix. The granulometry usually is bimodal with great quantities of silt + clay material (>10% by weight). SEM images show a uniformity of composition and forms of clasts.

Differences on deposits reveal different dynamics on both lahars. The Villarrica lahar was generated by sudden melt of ice and snow during the paroxysmal phase of the 1971 eruption, when a high fountain of lava was formed. The melted water flowed down on the flanks of the volcano and incorporated sediments to become transition flows, highly energetic and were emplaced incrementally. Dilution of the flows occurs when the lahars reached unconfined and flatter areas. In cases where the lahar flow found large water streams, dilution is enhanced. The Calbuco lahars were generated by the dilution of block and ash pyroclastic flows by flowing over the ice or snow or by entering active rivers, transforming to debris flows. The differences on dynamics of both flows show the importance to understand initiation processes of lahars in order to make better hazard assessment due to lahars flows.

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## 1. Introduction

Villarrica volcano is a compound stratovolcano located in the Southern Andes of Chile (39.5°S) (Fig. 1) and is considered to be one of the most active volcanoes in South America (Petit-Breuilh and Lobato, 1994; Moreno, 1993). Its historical eruptive activity has been mainly effusive with few explosive eruptions, with more than 60 documented eruptions since 1558 (Petit-Breuilh and Lobato, 1994; Clavero and Moreno, 2004). The volcano is covered by a glacier and a seasonal snow cap. The glacier has a surface of 30.3 km<sup>2</sup> and an approximate

volume of 2.3 km<sup>3</sup>, mainly distributed toward the south and east, where it can reach a thickness of up to 150 m (Rivera et al., 2006). The seasonal snow cap has been estimated in 1.2 km<sup>3</sup> at the end of the 1992 winter season (Moreno, 1993). These data yield to an approximate water-equivalent volume of 2.7 km<sup>3</sup> at the end of the winter season. The generation of lahars is the most recurrent process in historical times and one of the main hazards for the population living on its surroundings (Moreno, 1993; Naranjo and Moreno, 2004; Moreno and Clavero, 2006).

Calbuco volcano, on the other hand, is a composite stratovolcano located at 41.3°S in the Southern Andes (Fig. 1), near 220 km south of Villarrica volcano. Its historical eruptions have been mainly vulcanian to subplinian with ashfall, lava flows and block and ash pyroclastic flows as the main products (Moreno, 1999). The last recorded eruptions occurred in 1893–95, 1906–7, 1911–12, 1917, 1932, 1945, 1961 and 1972 (Petit-Breuilh, 1999). The glaciers in the volcanic edifice have a very small volume and a seasonal snow cap above

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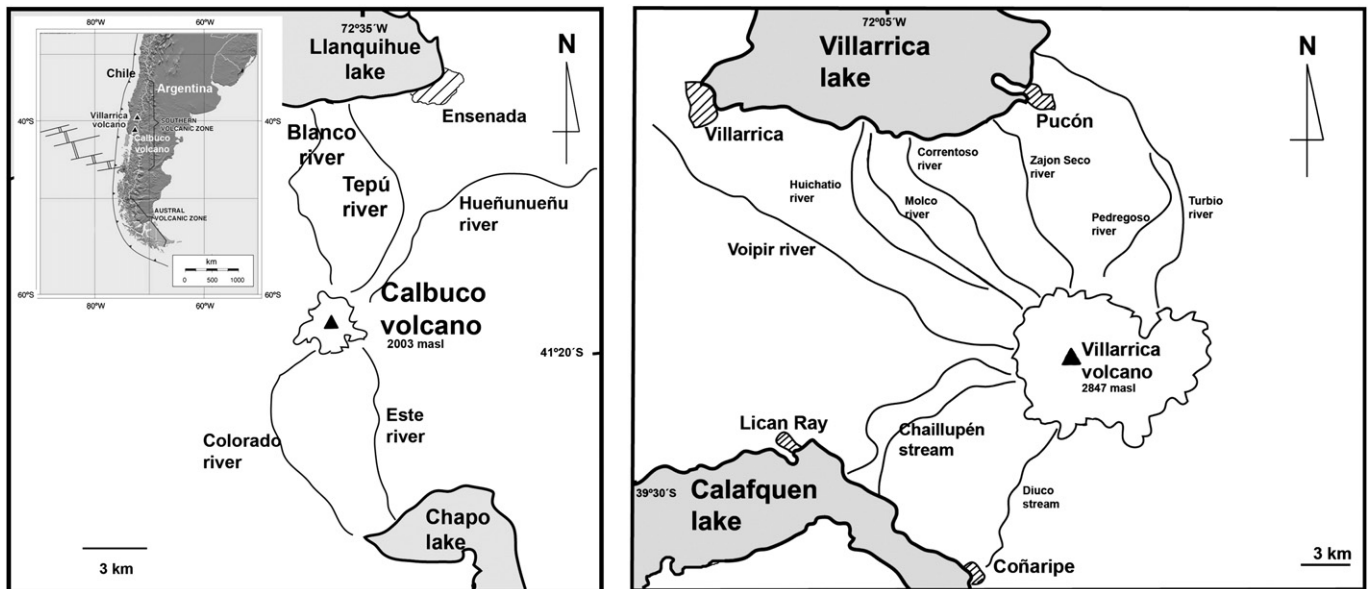


Fig. 1. Major streams draining from Villarrica and Calbuco volcanoes. The Voipir River and the Chaillupén stream are in the western flank of the Villarrica volcano. Tepú river is in the N flank of Calbuco volcano.

1000 masl. (Lahsen et al., 1985). The generated lahars, have been reported mainly as “hot” (Moreno et al., 2006), opposed to the vast majority of the others volcanoes in the Southern Andes.

Despite of this, little work has been done regarding the main characteristics of lahar deposits at both volcanoes and the hazard related to these volcanoclastic flows. Only Naranjo and Moreno (2004) described the lahar deposits of 1971 eruption on the northern flank of the Villarrica volcano, where the town of Pucón is located. In this paper, the lahar deposits associated to the 1971 eruption of the Villarrica volcano (the last eruption that generated lahars) on the western flank (Voipir River and Chaillupén stream, Fig. 1), and the deposits of the 1961 eruption of the Calbuco volcano in the northern flank (Tepú River, Fig. 1) are described, with special attention to the internal structures of the deposits, their grain-size distribution and the microscopic characteristics, establishing a conceptual flow dynamics model for both types of lahars.

## 2. Geological setting

Villarrica is an active volcano that started its eruptive activity ca. 600,000 years ago, whose evolution has been divided into three main units (Moreno and Clavero, 2006). The oldest, Villarrica 1 (ca. 600,000 to 14,000 y BP), is characterized by abundant basaltic andesite lavas, as well as lahar and pyroclastic deposits. Recent studies (Gaytán et al., 2005) have shown that Villarrica 1 unit also includes recurrent explosive activity during the last Glaciation. Villarrica 2 and 3 units (14,000–3700 y BP and 3700 y BP to the Present, respectively) consist of an alternating sequence of basaltic andesite lavas and pyroclastic (fallout, flow and surge) and lahar deposits. The two major eruptive events in Villarrica's history recognized so far, Licán and Pucón eruptions that formed large basaltic andesite ignimbrites (Clavero and Moreno, 2004) belong to Villarrica 2 unit. In historic times (last 500 years) at least 60 eruptive events have been documented, most of them of Hawaiian to mild strombolian type (e.g. Clavero and Moreno, 2004).

Calbuco is an active volcano whose evolution is characterized by the emission of lavas and domes mainly of silicic andesite composition and their associated pyroclastic and lahar deposits, the latter being described as “hot” by Moreno et al. (2006). The volcano has generated at least two sector collapses directed towards the north and northwest during the Holocene (Clavero et al., 2008), as well as a

series of dome-forming eruptions with their associated, pyroclastic flow, block-and-ash flow, blast and lahar fans, mainly directed to the north, west and south of the volcano. In historic times (since middle XIX century in the area) Calbuco has had at least 3 major eruptive cycles (1893–1895, 1929, 1961), with the emission of lava flows, fallout and block-and-ash flows, from strombolian to subplinian, with a major eruptive event in 1893–1895 (Petit-Breuilh, 1999).

## 3. Methodology

### 3.1. Field mapping

Field mapping of the deposits was carried out at 1:25,000 scale. Twenty four stratigraphic columns were made at the Chaillupén valley and sixteen at the Voipir valley (Villarrica volcano), and fourteen at the Tepú River (Calbuco volcano), with emphasis on the internal structures such as grading of the larger clasts, bedding/lamination, lenses and clast orientation.

### 3.2. Grain-size analysis

Samples (1–2.5 kg) of the different lahar unit deposits were collected at different locations along the channels. Only material finer than 6.4 cm ( $-6\phi$ ) in diameter was sampled, but the abundance (% in volume) of larger clasts was noted in the field. The samples were later analyzed in the laboratory by standard dry sieving techniques at  $1\phi$  intervals, down to  $4\phi$ .

### 3.3. Largest blocks analysis

The volumes of the 3 to 5 largest blocks in each site were estimated measuring the 3 main axis of each block. The volume was obtained approximating it to an ellipsoid. Two different kinds of blocks were measured: The largest block immersed on the deposit (“I-type”) and the largest floating block on top of the deposit (“F-type”), usually much bigger than the I-type blocks.

### 3.4. SEM analysis

Analyses were made through the Scanning Electronic Microscope (SEM) at the facilities of the Católica del Norte University. 3 samples

from the Voipir River (Villarrica volcano) and 4 from the Tepú River (Calbuco volcano) were analysed in the range [1, 4] in the phi scale. Special attention was made regarding the composition, texture and morphology of the clasts.

**4. Results**

**4.1. 1971 Lahar deposits on the western flank of Villarrica Volcano**

**4.1.1. Voipir River system**

The Voipir River is located on the northwestern flank of Villarrica volcano (Fig. 1). It's a long and relatively flat River system which has been a recurrent lahar path in historical times. The 1949 lahars went down this valley and reached its junction with the Toltén River, ca. 45 km downstream. The 1971 deposits cover an area of more than 11 km<sup>2</sup>, with an estimated volume of 10<sup>7</sup> m<sup>3</sup> (Fig. 2).

The deposits have been divided into several facies according to their petrographic and structural characteristics, as well as to the distance from their origin. These facies are: proximal (<14 km), where the lahars were confined inside a narrow channel and the terrain slope is >5°. Medial (14–22 km) where the lahars were no longer confined and the terrain slope is <5°, and distal (>22 km), where the lahar deposits are discontinuous and the terrain slope is <1°, central and lateral facies were defined according to lateral location with respect to the main channel at any given distance (Fig. 3).

The deposits consist of poorly-sorted mixtures of centimetre-to-metre sized blocks set within a fine to coarse sandy matrix. The deposits vary between 0.3 and 1.7 m in thickness, showing 1 to 3 flow units, a flat surface and are composed mainly of basaltic-andesitic lava fragments.

The proximal facies extends up to 14 km from the main crater and is characterized by 0.5–1.7 m thick massive deposits (Fig. 4A), with 50–60% (vol.) of clasts larger than 6.4 cm. The larger clasts consist of angular to sub-angular basaltic-andesitic lava fragments up to ca. 55 cm in diameter (0.15 m<sup>3</sup> I-blocks). The matrix is mainly composed of coarse-to-very coarse sand of the same composition, with small

amounts of silt and clay (<3 vol.%). The presence of large floating blocks (F-type blocks) up to 110 cm (ca. 1.5 m<sup>3</sup>) on top of the deposit is common. Internal structures are scarce and consist mainly in a clast orientation parallel to the flow and, occasionally, in a ~10 cm-thick basal layer without clasts larger than 5 cm.

The medial facies extends from 14 to 22 km from the main crater. The unconfined flow in this flat area, generated an inundation area up to 1000 m wide (perpendicular to flow direction). The deposits are 0.6–1.2 m thick, with 10–60 vol.% >6.4 cm clasts. The larger clasts are sub-angular to sub-rounded, mainly basaltic-andesite lava fragments which are more abundant towards the central parts of the deposits. The matrix is similar in composition to the proximal facies deposits. The abundance and volume of F-type blocks are greater than in the proximal facies, with diameters up to 3 m (volumes up to 13.2 m<sup>3</sup>), while the I-type blocks are up to 70 cm (0.3 m<sup>3</sup>). Internal structures consist in parallel and cross bedding, clast orientation, lenses with coarser fragments and reverse grading. The number of structures increases towards the lateral parts of the deposits.

Overflow deposits, located 3 m higher than the main channel, occurs at the beginning of this facies, with deposits up to 50 cm thick, with a fine sand matrix, absence of clasts larger than 5 cm and some intercalated mud beds (silt + clay), less than 2 cm thick.

Sudden lateral changes can occur in this facies, both in grain-size and in the presence of internal structures. At 20 km from the crater, the channel facies consists in 1–1.2 m thick deposits with a great concentration of large, rounded blocks (~50 vol.% >6.4 cm in diameter) up to 70 cm in diameter, immersed in a coarse sand matrix, with reverse grading (Fig. 4B). At ca. 10 m from this site (perpendicular to flow direction), the deposits are 0.9–1 m thick, without clasts larger than 3 cm in diameter, with 5–10 cm thick parallel lamination and 1–10 cm thick coarsed-grained (2–3 cm in diameter clasts) lenses within a fine sand matrix (Fig. 4C).

The distal facies extends beyond 22 km from the main crater. In this facies the remaining deposits are scarce and isolated, with 1 to 3 individual flow units and a total thickness of 0.3–0.5 m. The largest I-type blocks are much smaller (<2 cm. in diameter) than those

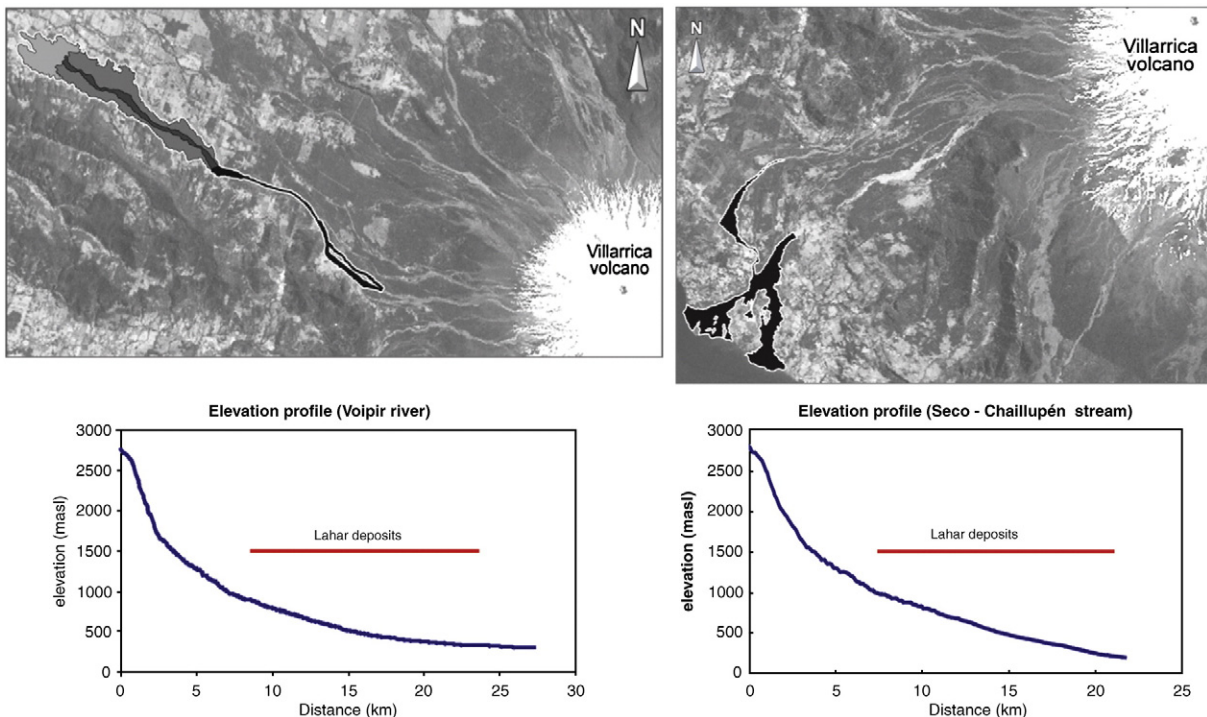


Fig. 2. Lahar deposits from the 1971 eruption at Voipir River and Chaillupen stream. Altitude profiles are shown below.

# Granulometry Voipir river, Villarrica Volcano

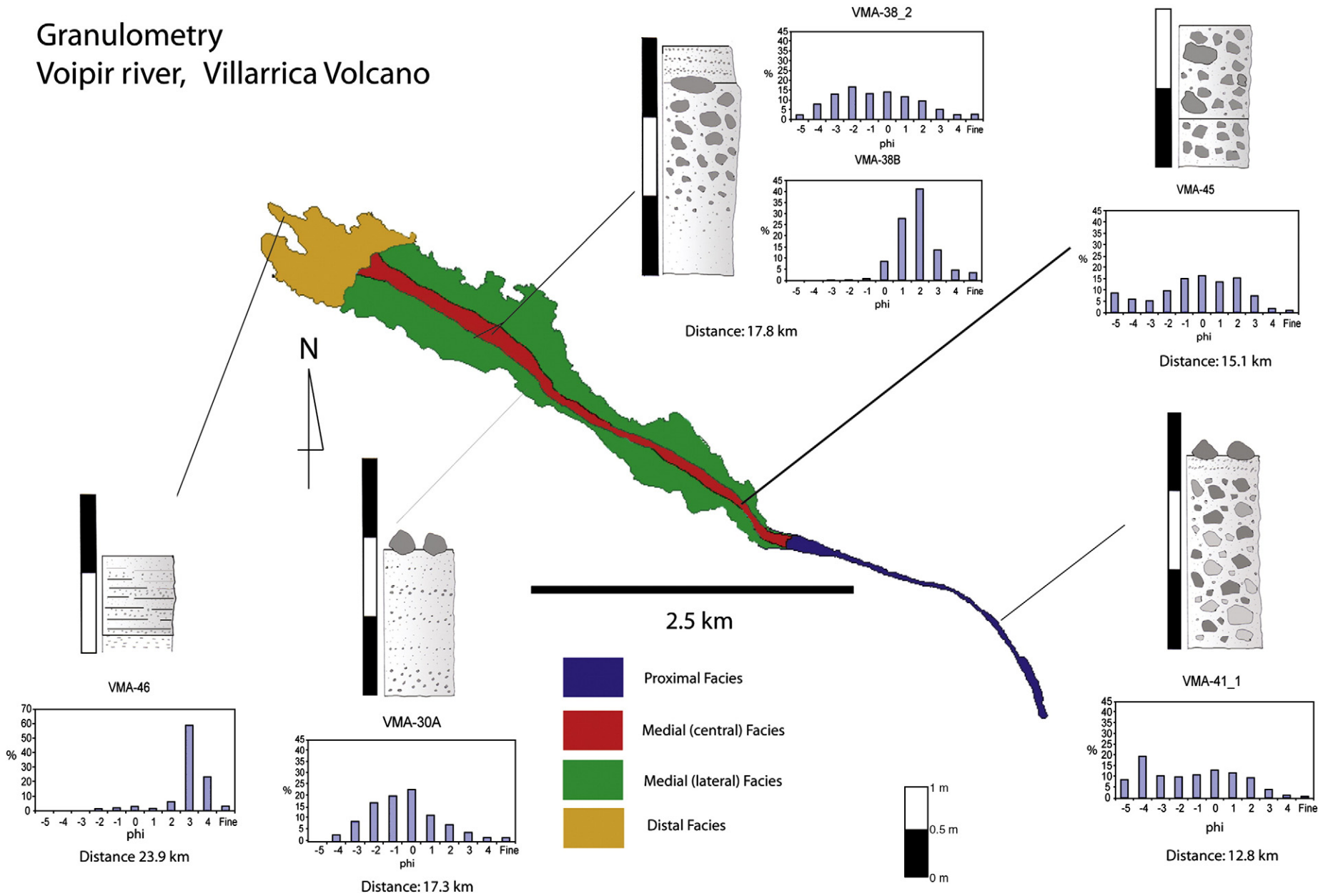
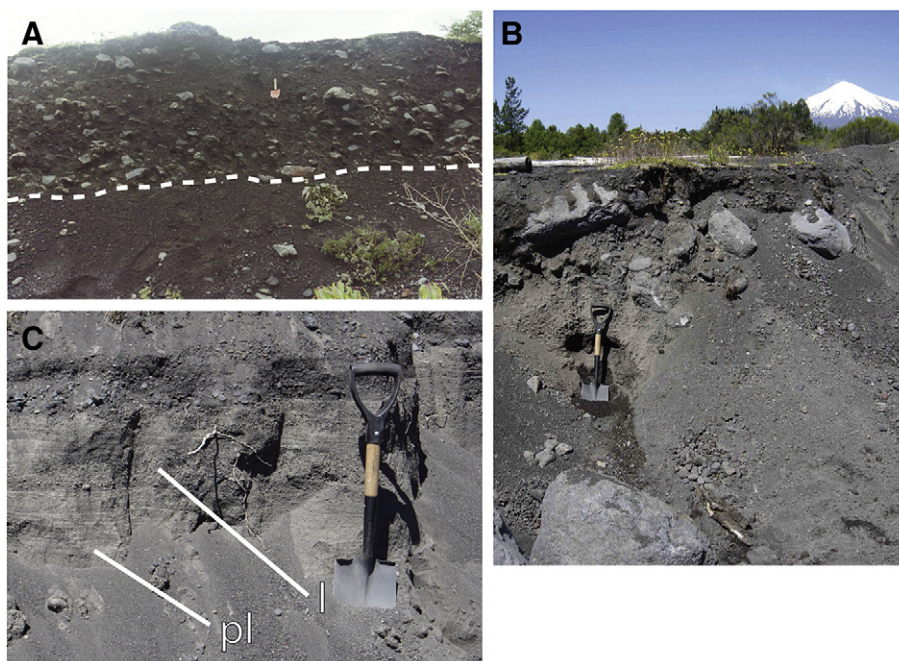


Fig. 3. Facies, granulometry and schematic columns from selected sites in the Voipir River deposits.





**Fig. 4.** Laharic deposits at the Voipir river (A) Site VMA-41. Deposit of the proximal facies, showing massive deposit, matrix supported, with angular clasts up to 30 cm in diameter. (B) Site VMA-38. Medial facies deposit in the Voipir River showing reverse grading with blocks up to 70 cm in diameter near the top of the deposit. (C) Site VMA-38b Lahar deposit, 10 m away, perpendicular to the flow, from the deposit showed in (B). The deposit is composed by a fine to very fine sand matrix, without clasts larger than 10 cm in diameter, with parallel lamination (pl) and lenses with coarser fragments (l).

found in the other facies and the matrix is composed of fine to very fine sand with a more variable composition with andesitic fragments with different crystallinity and texture and some clay aggregates. The F-type blocks are scarce and very small in volume ( $<10^{-3} \text{ m}^3$ ) and internal structures, such as parallel and cross bedding (2–10 cm thick beds), clasts orientation and lenses with coarser fragments (1–5 cm thick, 10–100 cm long) are ubiquitous.

#### 4.1.2. Chaillupén system

The Chaillupén River is a more complex system than the Voipir River. It has 2 main streams and several secondary ones (Fig. 1). It has an irregular slope, with several slope breaks, as well as numerous bends and topographic barriers (Fig. 5). It is important to note that the 1971 lahars that originated the deposits in this valley reached the Calafquén Lake, therefore an unknown part of the deposits consists of still unobserved subaqueous facies. Also, the associated lava flow from the same eruption buried the proximal and medial lahar deposits in the main stream. The area covered by the subaerial deposits is about  $4 \text{ km}^2$ , with an estimated minimum volume of  $6.5 \times 10^6 \text{ m}^3$  (Fig. 2).

The deposits have been divided into several facies according to the distance to their origin, in a similar way than the Voipir River: proximal ( $<15 \text{ km}$ ), medial (15–18 km) and distal facies (18–21 km). However in the medial facies, another facies has been defined, named impact facies, due to the impact with a topographic barrier (Fig. 5). The distal facies has been subdivided itself in channel facies, lateral facies and overflow facies, in accordance with the nomenclature used by Quinteros (1991).

The proximal facies extends up to 15 km from the main crater and consists mainly of isolated deposits in the central part of the stream. The deposits show several flow units (up to 5) with individual thickness varying between 4 and 30 cm and a total thickness of 1.1 to 1.4 m. The units are usually massive (Fig. 6A) although occasionally they show reverse grading towards the top, with clasts  $>6.4 \text{ cm}$  up to 30%. The larger clasts, mainly of basaltic andesite lavas are angular to subrounded and the matrix is composed of coarse sand fragments of the same origin. Locally, the flows inundated adjacent areas,

generating 1–2 m thick overflow deposits, with reverse-normal grading from the base to the top, with a 50–60 cm thick, central part with abundant large blocks (40–50 vol.%  $>6.4 \text{ cm}$ ).

The medial facies extends from 15 to 18 km from the main crater and shows deposits with several different features. It can be subdivided into central and lateral facies, and the impact facies in the Estero Seco (Fig. 5). The central and lateral facies have deposits up to ca. 4 m thick, with a well-developed reverse-normal grading, from base to top, with a  $\sim 1\text{--}2 \text{ m}$  thick central part with abundant subrounded large blocks (50–60 vol.%  $>6.4 \text{ cm}$ ) up to 70 cm in diameter ( $0.34 \text{ m}^3$ ). Towards the top, it shows well-developed structures such as lenses (5–15 cm thick, 50–200 cm long) and planar bedding (with 5–30 cm thick beds) (Fig. 6B). The F-type blocks can be up to 150 cm in diameter ( $3.3 \text{ m}^3$ ).

In the impact facies, the deposits show several special characteristics. In the direct impact site, the deposit is relatively thin (60–70 cm thick), massive and with a large concentration of I-type blocks (50–60 vol.%  $>6.4 \text{ cm}$ ) up to 80 cm in diameter ( $0.51 \text{ m}^3$ ). The F-type blocks are abundant and are up to 180 cm ( $5.3 \text{ m}^3$ ). Approximately, 200 m upstream of this site, the deposits are 1.2–1.4 m thick with up to 4 flow units (0.2–0.5 m individual thickness). The average grain size is smaller than in any other location at this system (see also Section 4.1.2.1), without clasts larger than 3 cm in diameter within a very fine sand matrix. Internal structures are abundant and consist in parallel bedding (1–5 cm thick), lenses with coarse clasts (15–20 cm thick, 60–120 cm long), clast orientation in flow direction and wavy bases, with a 15 cm amplitude and a 50–80 cm wavelength (Fig. 6C). The F-type blocks are scarce and are only up to 55 cm.

The distal facies extends from 16 km from the crater up to the Calafquén Lake shoreline, at 21 km from the crater. In this facies, the Chaillupén stream bifurcates into 2 branches: a northwest branch and a southeast one. The northwest branch is an initially channelized, 50 m wide stream, which progressively opens towards the Lake, where the deposits form a  $\sim 1 \text{ km}$  wide delta in the Calafquén Lake shoreline. In this branch the deposits have been divided into channel, lateral and overflow facies. The southeast branch is an essentially an unconfined plain.

# Granulometry Chaillupén - estero Seco, Villarrica volcano

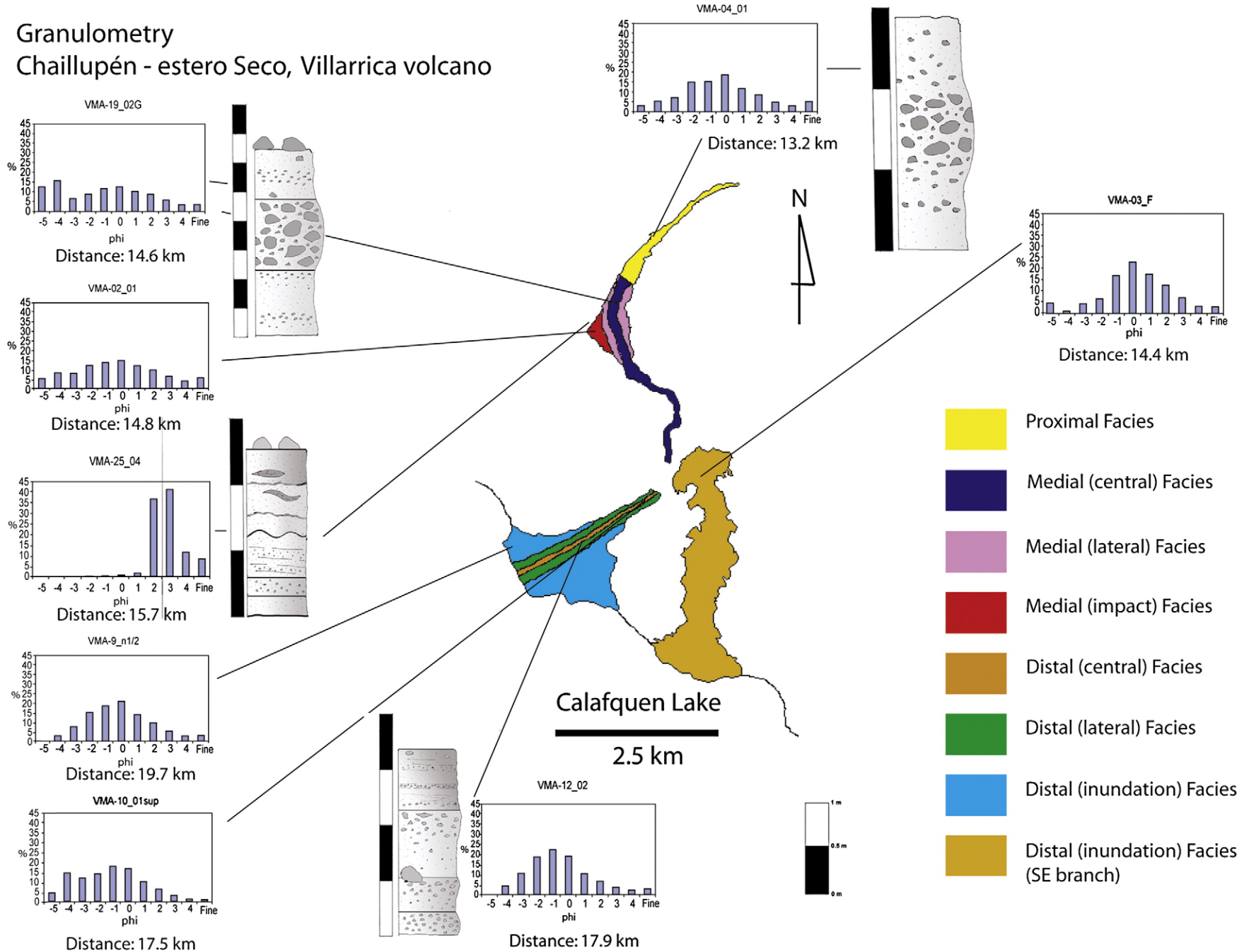
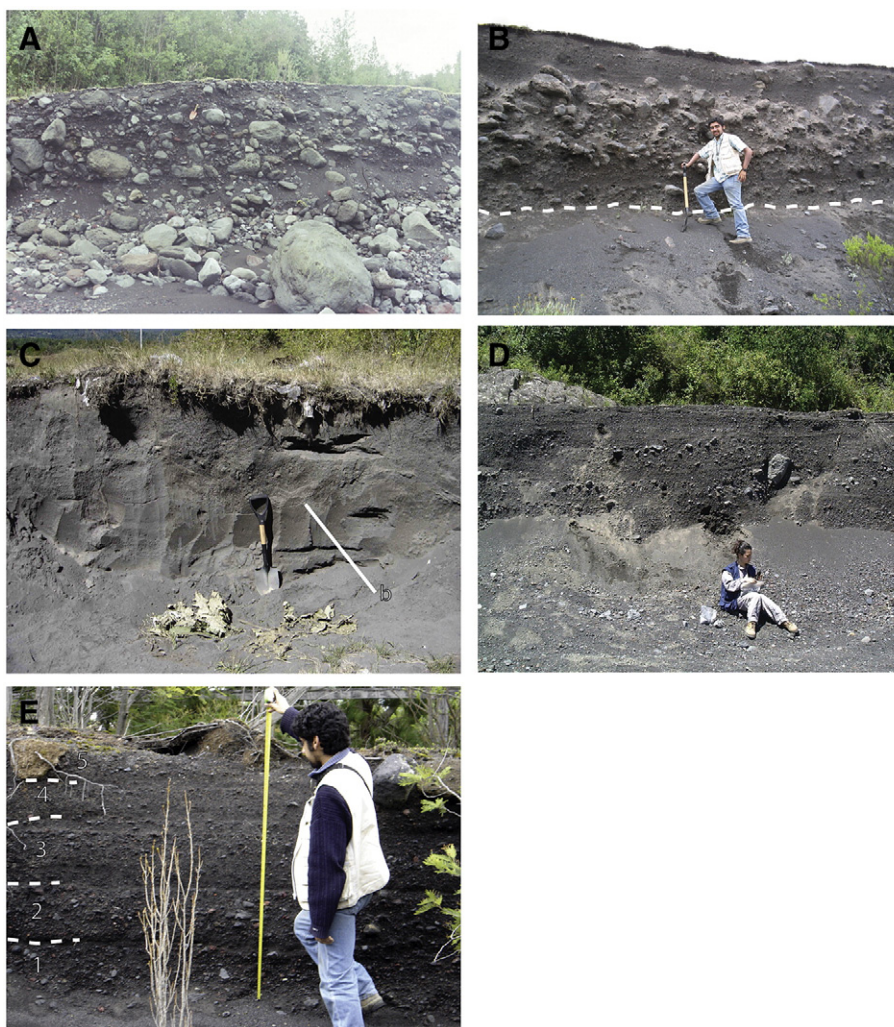


Fig. 5. Facies, granulometry and schematic columns of the Chaillupén-Estero Seco stream deposits.





**Fig. 6.** Laharcic deposits at the Chaillupén system (A) Proximal facies deposit, showing a massive deposit with more than 50% by vol. of semi-angular clasts larger than 6.4 cm. (B) Site VMA-19. Central facies deposit, showing reverse-normal grading from base to the top. Near the top, the deposit shows internal structures such as lenses and parallel lamination. (C) Site VMA-25. Impact facies deposit, with many structures such as lenses, lamination and wavy bases, with a medium to fine sandy matrix. (D) Site VMA-12. Lateral sub-facies deposit, showing internal structures such as lenses with coarser fragments, and parallel lamination. (E) Site VMA-1. Lateral distal facies showing 5 flow units, each with a reverse grading.

**Northwest branch:** In the channel facies, the deposits can be up to 5 m thick, but commonly are only 0.7–1 m thick. The deposits are commonly massive showing, locally, some minor structures such as parallel and cross bedding (10–15 cm thick) and small lenses (10 cm thick, 20–30 cm long) towards the top of the deposits. The abundance of subrounded clasts larger than 6.4 cm in diameter is variable (20–50 vol.%). Few (<1 vol.%), but not present upstream, small (up to 5 cm in diameter) granitoid fragments occur within the deposits of this facies. The F-type blocks are abundant and are up to 50 cm (ca. 0.2 m<sup>3</sup>) and can be granitic in composition. In the lateral facies, the deposits are composed by 3 or 4 flow units and have a higher abundance of internal structures, such as cross and parallel lamination (10–50 cm thick), lenses (0.5 m thick, 2 m long) with large blocks (up to 40 cm in diameter) and lesser fragments >6.4 cm. (10–30 vol.%) (Fig. 6D). The F-type blocks are up to 70 cm (0.34 m<sup>3</sup>), but are scarcer than in the central facies. In the overflow facies the deposits are 0.3–0.5 m thick, showing 1 to 5 flow units, with clasts smaller than 3–4 cm in diameter, within a fine sandy matrix, showing an inverse grading and a faint parallel lamination (Fig. 6E). The scarce F-type blocks may be up to 1.6 m (3.8 m<sup>3</sup>).

**Southeast branch:** In this zone, the deposits thicknesses range from 1.5 m to only 18 cm, showing a progressive decrease in thickness downstream. Internal structures consist in parallel lamination (5–

15 cm thick beds, with different grain-size, from 0.5 to 4 cm in diameter), lenses with coarser fragments up to 10 cm in diameter and clast orientation in the direction of the flow. The abundant F-type blocks can be up to 1.5 m in diameter (4 m<sup>3</sup>).

**4.1.2.1. Granulometry and SEM analysis.** All the analysed samples of the Villarrica volcano are clay-poor (<5% by weight <4  $\phi = 0.063$  mm) and are typically unimodal, with the main mode at 0 to  $-1 \phi$  (Figs. 3 and 5). Some samples, especially at proximal and at the beginning of medial facies are bimodal with the second mode at  $-4$  to  $-5 \phi$ . The mean grain size ( $M_z$ ) and the sorting ( $\phi$ ) of the samples are illustrated in Fig. 7. The matrix of the deposits can be well or poorly-sorted and falls in the field of debris flow, transition flow and hyperconcentrated streamflow (Pierson and Scott, 1985). The samples from Chaillupén have a small variation, both in  $M_z$  and  $\phi$ , with the exception of the samples from the impact facies which show a much better sorting and a smaller mean grain size (Fig. 7). The samples from Voipir River show a higher variation both in  $M_z$  and  $\phi$ , related to a better sorting and a decrease in mean grain size with distance from the origin of the flow.

The volume variations with distance of F and I-type blocks in both River systems are different. At the Voipir River, initially, the proximal channelized facies shows an increase in the volume of F-type blocks with distance. At the start of the unconfined medial facies, the F-type

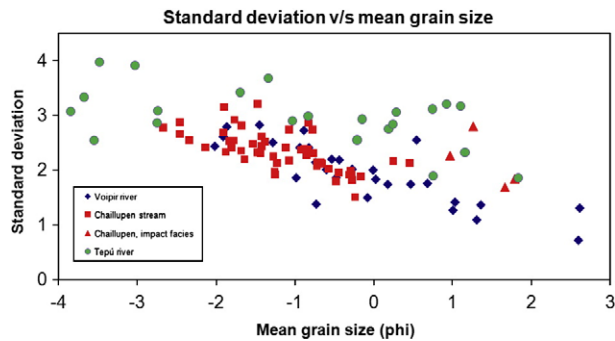


Fig. 7. Standard deviation versus mean grain size for samples from Villarrica and Calbuco volcanoes.

blocks reach their largest volumes, decreasing with distance later in the distal facies. At the Chaillupén system, the volume variations are more complex, due to the numerous channels that cross each other. The patterns followed by the I-type blocks are more irregular, but the F-type blocks are always larger in volume than the I-type blocks at any given distance from the origin of the flows.

Samples from proximal, medial and distal facies of the Voipir river were analysed in the range 0.063–1 mm with the SEM. At the proximal facies, the fragments are mainly subangular scoria with different vesicularity and surfaces (flat and irregular) and free crystals. At the medial and distal facies, the variety of fragments is much greater and appears some clay conglomerates and scoria with very high differences in crystal content and rugosity and more rounded borders that in the proximal facies.

#### 4.2. 1961 Lahar deposits on the north flank of Calbuco Volcano

##### 4.2.1. Tepú River

Tepú River is located in the north flank of the Calbuco volcano. It reaches the Llanquihue Lake at 16.5 km away from the crater. In the first 9 km, the River is channelized with a mean width of 150 m. Downstream the valley is wider with a width greater than 2 km. The 1961 lahar deposits cover an area of about 4 km<sup>2</sup> with an estimated subaerial volume of  $5 \times 10^6$  m<sup>3</sup> (Fig. 8).

The deposits have been divided into proximal (channelized, >5° terrain slope) and distal facies (unconfined, <5° terrain slope) and into central, lateral and inundation according to the lateral distance to the centre of the channel, in a similar way in which the Villarrica volcano facies were defined (Fig. 9).

The proximal facies extends up to 9 km of distance from the crater, with an altitude between 400 and 180 masl. The deposits are between 1.3 and 2 m thick. The internal texture of the deposits is massive, without structures, although sometimes appears a slight orientation of the clasts in the flow direction and a bed 10 cm thick at the bottom of the deposits without clasts larger than 5 cm in diameter. The deposits have commonly more than 60 vol.% of dense, angular andesitic clasts larger than 5 cm in diameter, with a maximum of 75 cm (Fig. 10A). The deposits are clast-supported and can show sudden lateral variations as shown in the Fig. 10A and B, with deposits without clasts larger than 5 cm, 5 m away from the central portion. The matrix is composed of fine ash, with a high proportion of silt and clay and composed of andesitic clasts and free crystals (plagioclase and pyroxene). The F-type blocks are abundant and can reach up to 2 m in diameter (6 m<sup>3</sup> in volume, Fig. 10C).

The distal facies extends from 9 to 14.5 km at the Llanquihue shoreline, with an altitude between 180 and 70 masl. The west branch deposits are 0.9–1.3 m thick. The blocks can be up to 40 cm in diameter, with a 40–50% of blocks greater than 5 cm (Fig. 10D). The blocks are mainly andesitic in composition and can be angular to

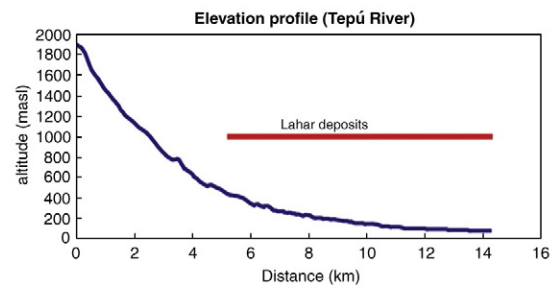
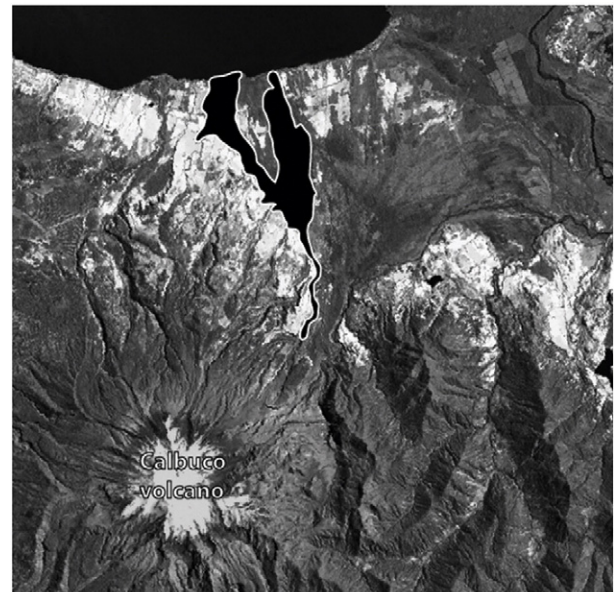


Fig. 8. Lahar deposits from the 1961 eruption at the Tepú river, altitude profile are showed below.

rounded. The deposits are matrix-supported and massive, but a 5 cm thick bed without blocks greater than 1 cm can appear.

The east branch deposits are smaller, with thickness of 0.4–0.5 m. There is no clasts greater than 6 cm in diameter, but the concentration in the range 3–6 cm is very high (>50 vol.%), and with a very angular morphology, forming a clast-supported deposit (Fig. 10E). The matrix is composed of fine ash, similar to proximal deposits. The abundance of F-type blocks are less than in the proximal facies, with volumes less than 140 cm (2 m<sup>3</sup>).

The inundation facies are 0.4–0.8 m thick. The abundance of internal structures is greater than in the other facies, with parallel lamination, (2–4 cm thick beds), lenses with different grain size, 10 cm thick and 30 cm long. In some places a reverse grading is also present. In this facies, evidence of hot deposition is common, as the presence of semi-burned vegetation, prismatic jointed blocks and a more compacted matrix compared to the Villarrica deposits.

**4.2.1.1. Granulometry and SEM analysis.** The analysed samples of the Calbuco volcano, have a greater content of fine material (>10% by weight <4  $\phi = 0.063$  mm) and are typically bimodal with the two main modes at  $-4$  to  $-3 \phi$  and  $2$  to  $-3 \phi$  (Fig. 7). The mean grain size and sorting are illustrated in the Fig. 7 and it can be appreciated that are notably less well sorted than the Villarrica samples, with a mean grain size between  $-4$  and  $2 \phi$ . The volumes of both the F-type and the I-type tend to decrease with distance.

All analysed samples with the SEM present a very high uniformity in composition, mainly with andesitic fragments with crystals of plagioclase and pyroxene. All samples show a similar vesicularity (40–50 vol.%) with spherical to oval vesicles. The fragments have a slightly elongated form, with borders that are usually angular to subangular.



Matrix granulometry of laharic deposits  
Tepú River, Calbuco volcano

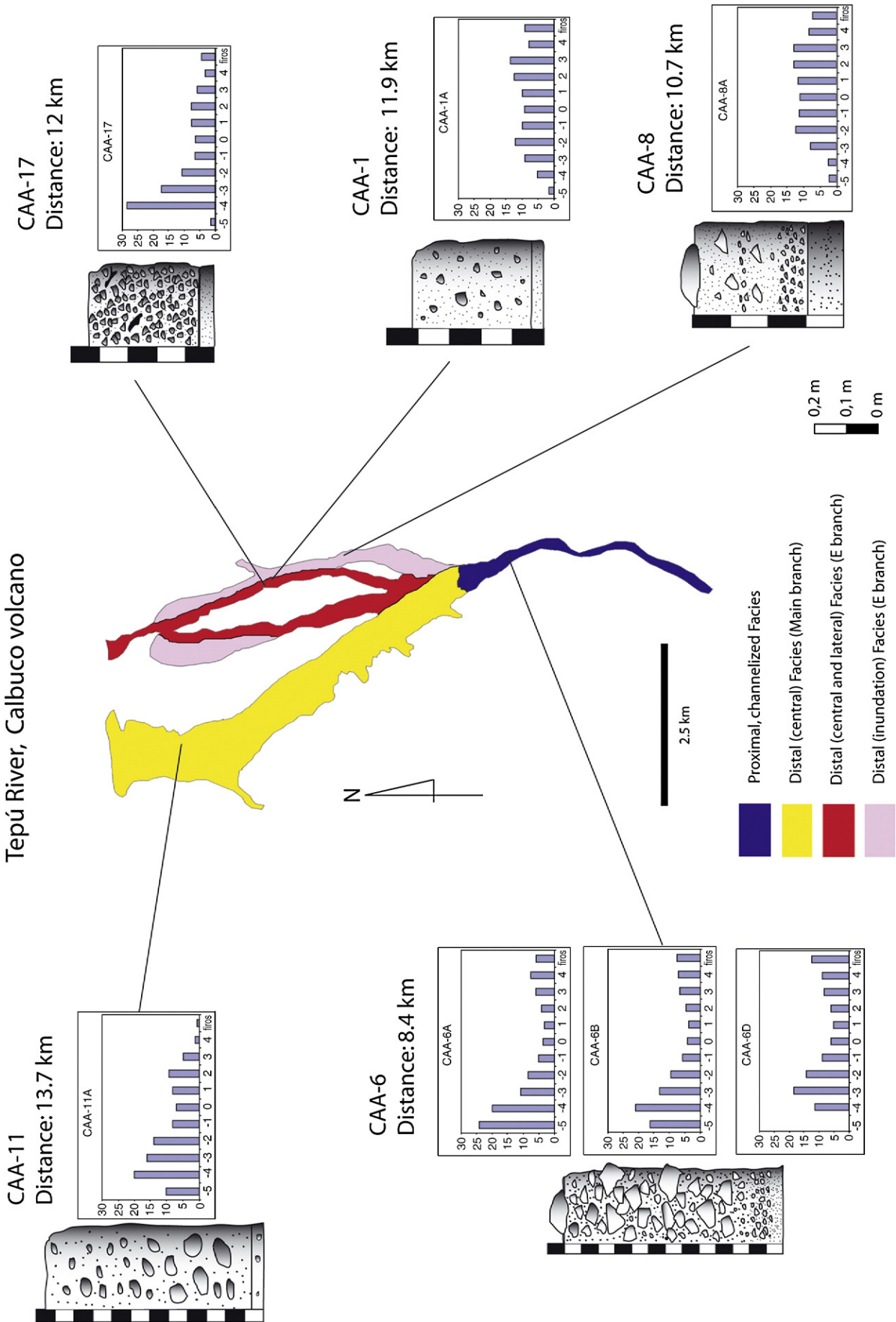
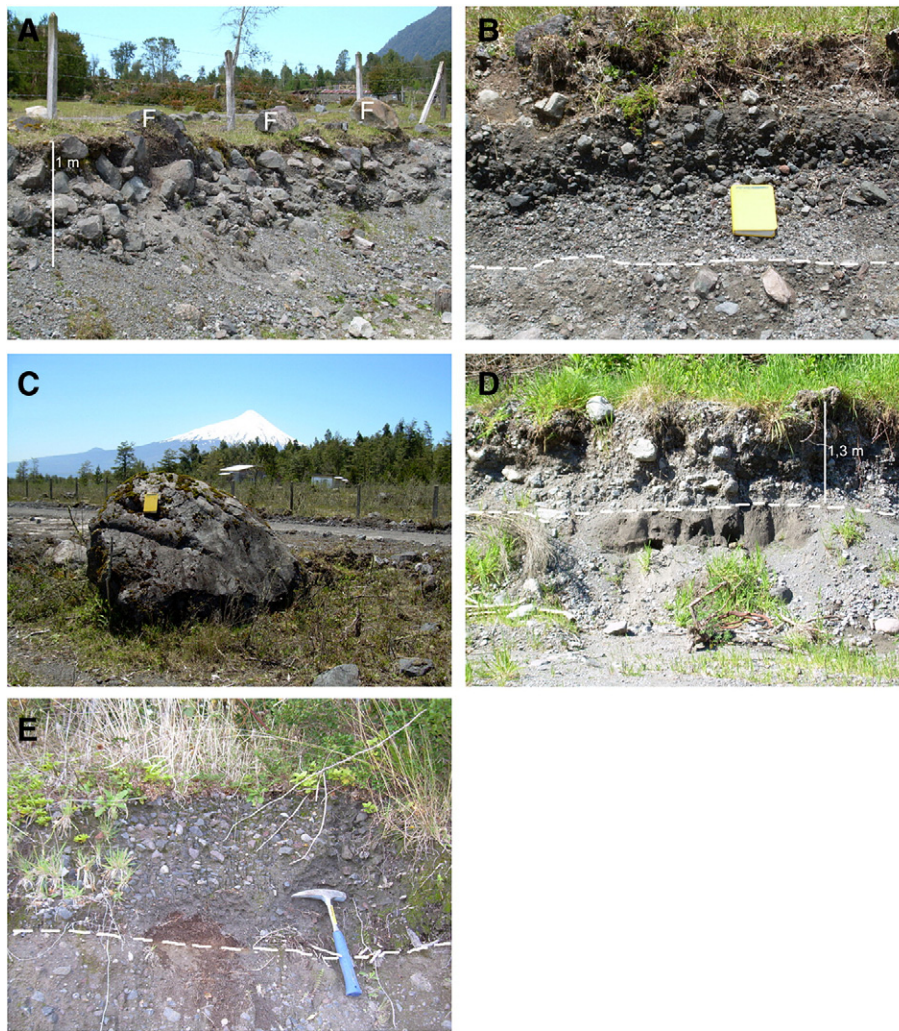


Fig. 9. Facies, granulometry and schematic columns of the Tepú River deposits.



**Fig. 10.** Laharic deposits at the Calbuco volcano (A) Site CAA-6. Massive deposit at the proximal facies with a high concentration of blocks bigger than 10 cm in diameter. (B) Site CAA-6b. Lateral deposit at the proximal facies showing reverse grading. (C) A large F type block on top of the deposits of the proximal facies. (D) Site CAA-11. Deposit at the distal central facies, massive with subrounded blocks up to 40 cm in diameter. (E) Site CAA-3. Deposit of the distal lateral facies, showing a clast supported texture with angular blocks of 4–5 cm in diameter.

## 5. Discussion

### 5.1. Origin, transport and deposition processes

The sedimentological, textural and granulometric characteristics of the laharic deposits at Villarrica and Calbuco volcanoes evidence differences of the dynamics on both lahars. The 1971 lahars at Villarrica volcano were caused by the sudden water release (Naranjo and Moreno, 2004) during the paroxysmal phase of the eruption on 29th–30th December (>400 m high lava fountain across a ~2 km-long fissure, González, 1995; Moreno, 1993). The granulometry on proximal facies often indicates bimodality with a node at about  $-2\phi$ . Vallance and Scott (1997) discussed that alluvium composed of gravel and sand typically lacks this size class and the incorporation of this material can explain the node. Lahar deposits of the 1997 lahar at Popocatepetl volcano where the flows were formed after the bulking of a sudden release of water, also show some places with bimodality with the same node (Capra et al., 2004). Naranjo and Moreno (2004) showed that in the upper flanks of the Villarrica volcano there are abundant moraine material that can act as source of the lahars. Field, microscope and SEM observations reveal that all particles are basalt-andesites, but with different roundness, shapes, vesicularities and crystalinities, thus supporting the diverse origin of the bulked material. The bulked material of the upper flanks transformed the

water floods in flows with characteristics between hyperconcentrated and debris flows, as inferred from the textural and granulometry of the deposits on the proximal facies.

The lahar that descended in the Tepú River was originated at 5 AM, February 1, 1961. The samples from proximal facies are similar in granulometry to Block and Ash Flow (BAF) deposits from the volcano. SEM analysis also shows a similarity of the shape, roundness and composition of the clasts, suggesting that the BAFs acted as the parent flows of the lahars, in accordance with Moreno et al. (2006) who pointed out that the lahars were generated when block and ash pyroclastic flows originated by the collapse of the active dome or the flow front of the lava flow and mixed with water mainly from rivers and possibly with melted ice and snow, as pointed out by Klohn (1963).

The presence of several flow units at both volcanoes suggests that the laharic flows moved in a number of individual conservative waves, each with its own head, body and tail. Iverson (1997) explains that these surges may occur spontaneously, without a perturbation in the flow or an episodic sediment supply and that major pulses tend to overtake and incorporate the smaller ones. These surges had been recognized in other gravitational flows, like block-and-ash flows and other types of pyroclastic flows (Schwarzkopf et al., 2005).

Once the confinement of the lahars is lost and the terrain slope is less than  $5^\circ$ , the character of the flows changed from mainly erosive to

**Table 1**

Apparent bulking and debulking factors calculated for selected size fraction of the matrix of the Tepú river deposits.

Sample	Distance (km)	Facies	Size fraction % ( $\phi$ )			ADFt	ABFt	ABF [2–3]	ADF [–5 to –4]	ABF [–5 to –4]
			Fine	[2–3]	[–5 to –4]					
CAA-6A	8.3	Proximal	5.95	10.4	44.3					
CAA-8	10.7	Distal (inundation)	7.18	25.6	4.6	0.17	N/A	0.51	0.91	N/A
CAA-3	12	Distal (central)	6.27	16.7	19	0.05	N/A	0.34	0.59	N/A
CAA-1	12	Distal (lateral)	9.1	26	6.1	0.35	N/A	0.39	0.91	N/A
CAA-10	14.1	Distal (central)	8.29	29.7	0	0.28	N/A	0.51	1.00	N/A
CAA-11	13.6	Distal (main branch)	0.58	14.2	30.3	N/A	0.90	0.93	N/A	0.86

mainly depositional. Evidence supporting this interpretation includes the occurrence of the largest sizes of F type blocks at the beginning of the medial facies, as well as a bigger concentration of them, suggesting a decrease of energy and consequently a loss in carrying capacity. Another evidence is the lack of any erosion contact at the base of the deposits and the preservation of soft sediment beneath it.

Vallance and Scott (1997) introduced the concept of apparent bulking and debulking factors as a way to estimate relative erosion or deposition of a selected size fraction. Assuming that fine content (clay + silt) is bulked at proximal facies and not downstream, it can be used as a reference size to calculate apparent bulking (ABF) or debulking (ADF) factors:

$$ABF = 1 - (R_f / R_i)(S_i / S_f) \quad (1)$$

Where  $R$  is the proportion of the size class not affected by bulking and  $S$  is any other class,  $i$  indicates initial value and  $f$  downstream values (Vallance and Scott, 1997; Vallance, 2000). If the values are negative, there is a selective deposition and a debulking factor can be calculated:

$$ADF = 1 - (R_i / R_f)(S_f / S_i) \quad (2)$$

To calculate the ABF total,  $S_f$  and  $S_i$  are 1 (Vallance, 2000):

$$ABFt = 1 - R_f / R_i \quad (3)$$

In Tables 1 and 2 some apparent bulking and debulking factors at selected sizes are calculated for the Tepú (Calbuco) and Voipir (Villarrica) rivers. At Calbuco volcano (Table 1), the total ADF are low (0.05–0.35) and increase downstream, from 0.05 (CAA-3) to 0.28 (CAA-10). Laterally there is also an increase of the values (CAA-1 and CAA-8). The debulked material is mainly in the pebble range [–5 to –4  $\phi$ ]. At the main branch (CAA-11) there is a positive ABFt suggesting a bulking of material. At this point, the Tepu river has a huge increment of the caudal and there are abundant alluvium that was incorporated in the lahars as can be seen in Fig. 10d where the deposits show a high proportion of rounded material >6.4 cm.

At Villarrica volcano (Table 2), the total ADFs are higher (0.59–0.92) with high values at the beginning of the Medial facies (VMA-45,

VMA-49), suggesting a rapid debulking at the start of the medial facies, with subsequent irregular values, probably due to some incorporation of material. The debulked material is mainly in the size range [–5 to –4  $\phi$ ]. There are also lateral variations (VMA-38–VMA38B) with an increase of debulked material away from the centre.

Despite the character mainly depositional of the flows in medial and distal facies there is also evidence of some erosion. At Voipir River there is an increase in the diversity of material downstream. SEM and microscopic analysis reveals the appearance of scarce clay aggregates (<1%) at distal facies, probably from soil layers and old pyroclastic sequences (Gaytán et al., 2005) and also a greater diversity in the roundness, shape and lithology of the components. At Chaillupen system, after the impact of the flow with the Lican hill (Granitic composition) some rounded granitic F blocks and very scarce (<1%) granitic clasts in the sand size appear, suggesting that the lahars were able to incorporate loose blocks but with little erosion of the bedrock.

All this evidence suggests that the flows lost energy and carrying capacity at the medial and distal facies, changing to a mainly depositional character, with debulking occurring more easily in the more diluted flows at Villarrica volcano. Erosion can also occur, especially if the flows finds active rivers and loose alluvium (main branch of the Tepú river).

A Villarrica volcano, a common feature of the deposits is the reverse-normal grading from base to top, with a greater concentration of big clasts (>6.4 cm) at the middle of the deposits. This feature has been commonly described before in clay-poor lahar deposits (e.g. Quinteros, 1991; Scott, 1988; Cronin et al., 2000). Vallance (2000) discussed that this is the consequence of aggradational deposition of transition flows, where the flows comprise a head, body and tail. The head is the first to sediment and it is very diluted with a low sediment concentration. The body has a debris flow character carrying most of the sediment load and big clasts. The tail, again is more diluted with less carrying capacity (Fig. 11). Cronin et al. (1999) defined 4 stages for lahars generated after the release of water from a crater lake, where the head is divided in 2 zones: the first one correspond mainly to displaced water of the river that is pushed forward by the lahar and the second is a mixing zone that increases in length downstream. Another widely present feature at both volcanoes is the presence of a thin (~10 cm) layer at the base of the deposits with absence of large particles. This feature has also been described in Block and Ash Flows

**Table 2**

Apparent bulking and debulking factors calculated for selected size fraction of the matrix of the Voipir river deposits.

Sample	Distance (km)	Facies	Size fraction % ( $\phi$ )			ADFt	ADF [0–1]	ADF [–5 to –4]
			Fine	[0–1]	[–5 to –4]			
VMA-41	12.8	Proximal	0.84	24	28			
VMA-44	15.1	Medial (central)	2.94	35.5	4.2	0.71	0.58	0.96
VMA-49	15.1	Medial (overflow)	10.23	28.3	2.24	0.92	0.90	0.99
VMA-30	17.3	Medial (lateral)	2.04	57	0	0.59	0.02	1.00
VMA-38	17.8	Medial (central)	2.82	27.5	10.4	0.70	0.66	0.89
VMA-38f	17.8	Medial (lateral)	2.63	40	4.45	0.68	0.47	0.95
VMA-38b	17.8	Medial (lateral)	3.39	9.1	0	0.75	0.91	1.00
VMA-46	24	Distal	3.21	5	0	0.74	0.95	1.00



## A. Schematic diagram of a 1971 lahar flow

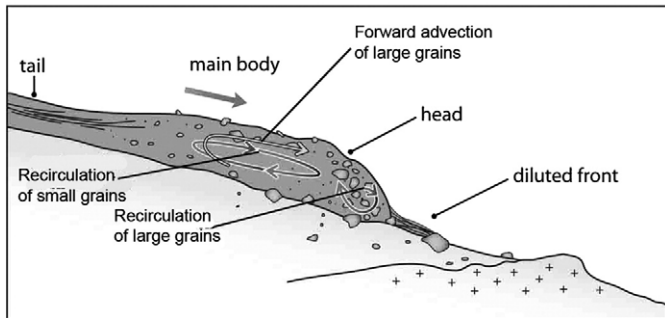


Fig. 11. Schematic of the main parts of the flow and clasts trajectories inside the flow (based in Iverson, 2005).

(e.g. Schwarzkopf et al., 2005), but in the present case, the layer is more restricted to the very bottom of the deposit. Schwarzkopf et al. (2005) discussed that the cause of this basal layer is the high grain dispersive pressures due to the high velocity in steep slopes, together with the kinetic sieving of the particles, that segregates the bigger particles away from the base.

Calbuco deposits are mainly massive with appearance of few structures only laterally. This may indicate a more bulked flow, less watery than Villarrica lahars and more uniform in water content and sediment concentration longitudinally. Klohn (1963) reported that only 48 h after the emplacement of the flows, the deposits were consolidated and supported the weight of motor vehicles, opposed to more watery flows (e.g. Ruhapehu lahars) where the deposits do not support body weight, even after a week (Cronin et al., 1999). Dilution of the flows appears to be more important at Villarrica volcano, especially at Voipir river, where the caudal of the river can be of the order of  $40 \text{ m}^3/\text{s}$  and there is a decrease of the modal size and sorting downstream. Cronin et al. (2000) discussing lahars generated at Ruapehu volcano pointed up that dilution occurs not only due to mixing with water but also due to a loss of competence when the flows reach broad areas and rapidly thinned and slowed (also described on the Nevado del Ruiz lahars, Pierson et al., 1990) and the coarser boulder and cobbles are deposited. This second explanation for dilution also appears to be the case for Villarrica lahars. For example at Chaillupen stream, that commonly is without water at the period of the year of the eruption, sedimentary structures and characteristics of hyperconcentrated flows start to be prominent at the broader and more plain areas, after the emplacement of the bigger F-type blocks.

At Villarrica volcano, reported velocities at the Chaillupen lahars were around  $10 \text{ m/s}$  near the shoreline of the Calafquen lake. Estimated maximum discharges were about  $14,000 \text{ m}^3/\text{s}$  (Naranjo and Moreno, 2004), comparable to the lahars generated at North Fork Toutle river, Mount St Helens, 1980 (Pierson and Scott, 1985) or some of the lahars generated during the eruption of Nevado del Ruiz, 1985 (Pierson et al., 1990). At Calbuco volcano, reported velocities were about  $5 \text{ m/s}$  (Klohn, 1963) with discharges about  $3000 \text{ m}^3/\text{s}$ , suggesting a smaller event in accordance with the estimated volumes at both volcanoes.

Lahar deposits on both volcanoes indicate an accretional deposition. Some ubiquitous characteristics such as alignment of clasts, sedimentary structures (lamination, bedding, and lenses), and higher marks of peak flows than the deposits clearly correspond to an incremental accretion (Vallance and Scott, 1997; Vallance, 2000). Massive deposits also are the result of accretional deposition. Some experiments with small-volume debris flows (Major, 1997; Major, 2000) have shown that a poorly-sorted massive deposit, can be the result of incremental deposition of several different surges, and Vallance and Scott (1997) also concluded an incremental deposition for the massive deposits of the Osceola mudflow, a cohesive lahar with a high proportion of clay material.

The different stages in which the lahar flows develop can be summarized as follows:

- Initially, huge amounts of water were released at Villarrica volcano, which quickly bulked up in the upper flanks and formed transitional flows. At Calbuco volcano, block and ash flows incorporated water mainly from rivers and became debris flows. The flows were composed of several kinematic waves in which the largest clasts travelled at the top of the wave. The flows moved in a confined channel with high energy and little or no deposition occurred. The resulting deposits are massive, poorly-sorted and typically thin ( $<1.5 \text{ m}$  thick).
- When the lahars reached an unconfined zone with slopes  $<5^\circ$ , the flows slowed and thinned, losing carrying capacity, and the largest particles stopped their motion. This loss of sediment load caused a dilution of the flow that could be helped by the mixing with river water. At Villarrica volcano, the longitudinal profile of the flows, with a dilute head, a more bulked body, and again a diluted tail, together with an incremental deposition generated deposits that typically have an inverse-normal grading. At Calbuco volcano, the flows contained less water and were more uniform in sediment concentration and more massive deposits were generated. In this zone the deposits reached the largest thickness, particle size and F-type concentration.
- The accretional deposition of the flows continued downstream, with decreasing energy, forming thin ( $<1 \text{ m}$  thick) deposits, with smaller clasts (less than  $10 \text{ cm}$  in diameter), until the lahar became a flow with more fluvial characteristics, like at the Voipir River or until the flow entered into a lake, as it happened at the Chaillupen stream and Tepú river.

### 5.2. F-type blocks origin

Typically, the volume of F-type blocks is larger than the volume of I-type blocks at any given distance at both volcanoes. Although the presence of large blocks at the surface of lahar deposits has been described before (e.g. Pierson and Scott, 1985; Quinteros, 1991), its origin is still not well understood. Vallance (2000), Iverson (2005) and Vallance (2005) have suggested some processes which can govern grain size segregation in debris flows. Largest particles tend to move upwards and then forward in the flow direction as shown in Fig. 11. This is due mainly to 2 factors: i) kinetic sieving, and, ii) the vertical velocity profile. Kinetic sieving is a process in which the smallest particles migrate downwards into open spaces beneath them in vibrating or shearing mixtures (Vallance, 2005). The velocity profile in a debris flow shows an increment from the bottom to the top, because of the higher friction at the base of the flow (Vallance, 2005; Iverson, 2005), leading the largest particles to move forward when they reach the top of the flow, because the flow moves faster in this zone. These combined processes can also account for the origin of the reverse grading that is especially common in the 1971 lahar deposits of the Villarrica volcano at their bases, as well as for the migration of large blocks to the top of the flows (F-type blocks) and the accretion of large particles at flow perimeters. The latter, not observed in the studied deposits, have been reported to occur in the Pedregoso River (Naranjo and Moreno, 2004), in lahar deposits associated with the same eruption.

### 5.3. Effects of the impact with a topographic barrier

At the Chaillupen valley, the lahars impacted against the Licán hill ( $743 \text{ masl}$ ) in a secondary stream (Estero Seco) at almost  $90^\circ$  (Fig. 12A). The deposits in this area differ notably from the other facies, with modes and sorting very different from the other deposits (Fig. 7) and erosional bases not found on other sites. The lahar flow behaviour when hitting an obstacle can be of great importance in

## Schematic diagram

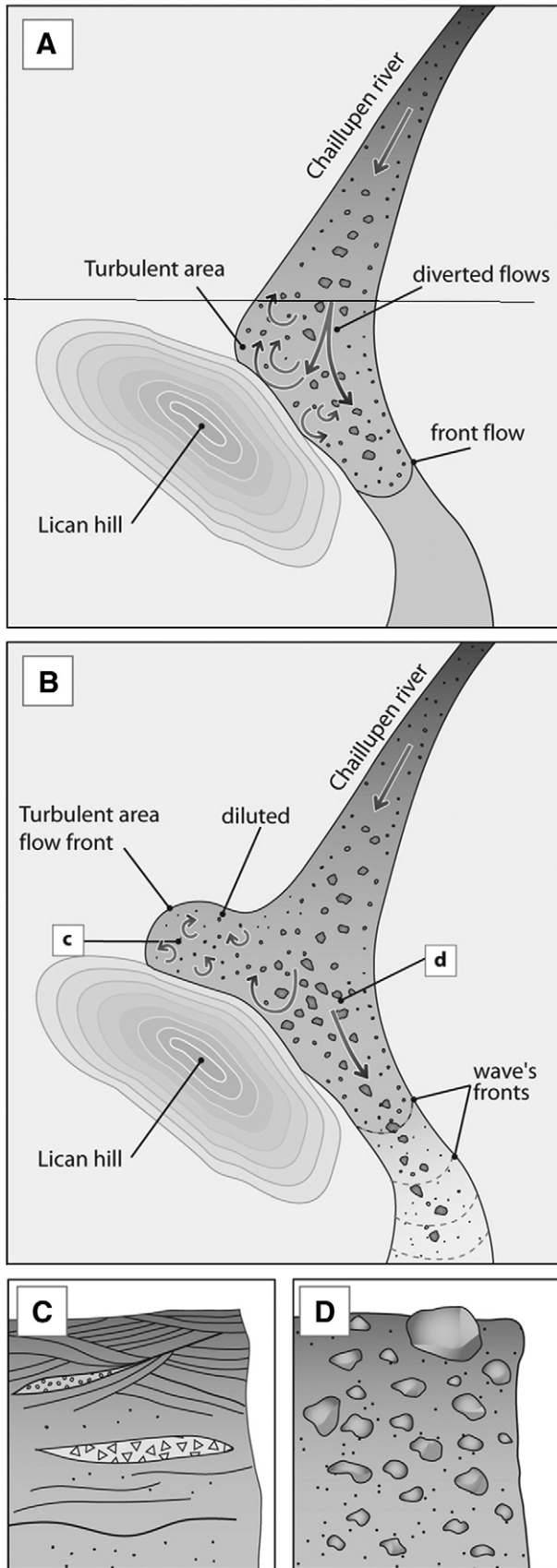


Fig. 12. Schematic diagram showing the effects of the hit of the flow against a topographic obstacle and the resulting deposits.

terms of hazard assessment, as the flow would be able to inundate completely different areas. Iverson et al. (1994) carried out experiments on the effects of debris flows hitting obstacles. These experiments show that the impact can produce waves and lateral spray in the flow, associated to a higher energy (Fig. 12B).

As pointed out before, Cronin et al. (2000) discussed that dilute lahar flows can be vertically segregated with a high concentrated lower part and a more dilute and finer grained upper part. Also, higher flow energy may itself enhance vertical segregation, leading to a denser and coarser basal layer, in a similar way as a secondary pyroclastic flow may be generated by suspended-load fallout from a parent pyroclastic surge (Druitt et al., 2002).

Due to the highly watery nature, the lack of fines in the matrix and the increased energy due to the impact, the segregation was extremely efficient, leaving a massive, thin and very coarse deposit on the site of the direct impact against the hill, where the energy was higher (Fig. 12D). The upper, more dilute and finer-grained part of the flow, sprays around with less energy just upstream, generating fine grained, well-laminated deposits (Fig. 12C).

The run-up deposits are about 5–6 m in height above the main channel. Using the simple formula  $v = (gh)^{1/2}$  a minimum velocity of 8 m/s can be estimated, in agreement with the reported values of 10 m/s given by Naranjo and Moreno (2004) at the Chaillupen stream, just before the lahars entered the Calafquen lake.

An important consequence of these processes is the possibility of build artificial barriers (with a tested and controlled location) that could reduce the risk associated in some specific locations (Montserrat, 2005).

#### 5.4. Lateral variations

The lahar deposits at both volcanoes, show lateral variations with a decrease in clast size, better sorting and more sedimentary structures away from the channel. Lateral variations are typical of clay-poor lahars caused by the sudden release of water (e.g. Cronin et al., 2000; Capra et al., 2004) where marginal flows are less energetic carrying fewer coarse particles (Fig. 13A). Cronin et al. (2000) argued that lahars at Ruapehu volcano can be segregated vertically, with a basal coarse layer, restricted to the channel and an upper more diluted and fine grained part, with a hyperconcentrated flow character. In this way at upper terrain, away from the channel bed, only the fine part of the flows is deposited. This can explain some of the lateral variations of the deposits at Villarrica volcano where the overflow facies are at higher terrain and are very fine with hyperconcentrated flow characteristics.

However, one of the striking features observed in the Voipir River system is the sudden lateral change of the deposits, in only a couple of meters, and without changes in the bed elevation, from a massive, coarse deposit to a very fine grained deposit, rich in structures.

A possible explanation for this lateral variation is that there is a local mixing of the lahar with existing secondary channels, generating a local dilution of the flow (Fig. 13B). At the Voipir River, the medial facies deposits covered an area with a width of almost 1 km, where many secondary streams run close to the main river, before join it.

## 6. Conclusions

The 1971 lahars that originated the deposits on the western flank of Villarrica volcano (Voipir and Chaillupén) began as watery flows that bulked and became flows with characteristics between debris and hyperconcentrated flows that moved downstream in a channelized way, with little or none deposition occurring at the proximal areas. At this stage, due to the velocity profile and flow agitation, particle segregation processes occurred within the flow, generating that the largest blocks tend to migrate to the top and head of the flow. Once the flow reached unconfined zones, the flow energy decreased and rapid deposition of the largest clasts took place. The remaining

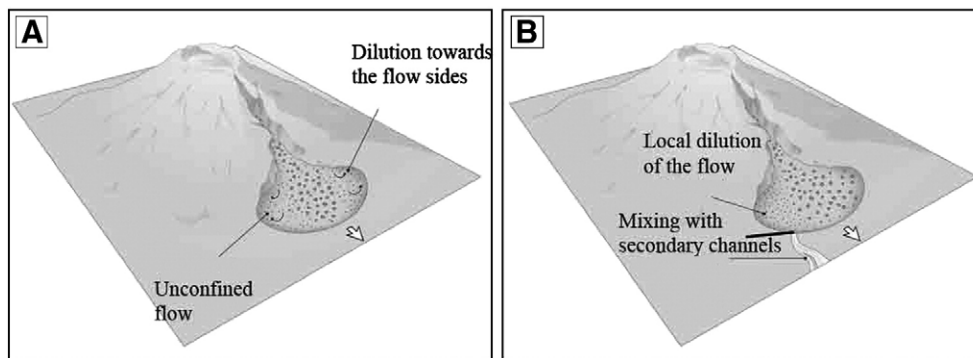


Fig. 13. Possible causes for the sharp lateral variations observed in the medial facies in the Voipir River.

flow had a lower sediment concentration becoming more diluted. When these flows encountered active streams, they transformed into hyperconcentrated flows, due to their continuing decreasing concentration, as observed in the Voipir River. At this stage the flow dilution was higher and numerous internal structures formed within the resulting deposits, like planar and cross lamination, clasts imbrication, and normal and reverse grading.

The 1961 lahars at Calbuco volcano began as pyroclastic flows generated by the collapse of the active dome and/or the lava flow front that melted the snow or ice or entered the Rivers to become debris flows, with a higher concentration of sediments, compared to the Villarrica lahars. In these flows there is also a clast segregation with the biggest blocks found on top of the deposits, but less abundant and smaller in volume, probably because of the smaller volume and energy of these flows. The deposits of the flows are more massive than the Villarrica lahars due to a more homogeneous flow with a lesser proportion of water, and a greater proportion of fines.

Collision of the flow against a topographic obstacle at the Chaillupén River generated a higher internal energy, which separated the main flow into 2 parts. The deposition at the site of the direct impact formed a massive deposit with very coarse clasts, while on the upstream side the resulting well-laminated deposit is composed only by very fine sand.

Strong lateral variations in flow regime and therefore in the characteristics of the resulting deposits within a few meters occurred. These were due probably to the strong lateral segregation of dilute flows and/or due to local mixing with water in active streams, which decreased the flow sediment concentration. The study of the 1961 and 1971 lahars deposits at the Calbuco and Villarrica volcanoes has revealed the importance of understanding the dynamics of the transport and emplacement of these flows, in order to improve the risk assessment and possible mitigation strategies regarding this type of flows from active volcanoes in southern Chile.

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### References

Capra, L., Poblete, M.A., Alvarado, R., 2004. The 1997 and 2001 lahars of Popocatepetl volcano (Central Mexico): textural and sedimentological constraints on their origin and hazards. *Journal of Volcanology and Geothermal Research* 131, 351–369.

Clavero, J., Moreno, H., 2004. Evolution of Villarrica volcano. In: Lara, L., Clavero, J. (Eds.), *Villarrica Volcano (39.5°S) Southern Andes, Chile: Servicio Nacional de Geología y Minería. Boletín n°61*, pp. 17–27.

Clavero, J., Godoy, E., Arancibia, G., Rojas, C., Moreno, H., 2008. Multiple Holocene sector collapses at Calbuco volcano, Southern Andes. Abstracts, Poster Session III, IAVCEI General Assembly, Reykjavik, Iceland, p. 41.

Cronin, S.J., Neall, V.E., Lecoindre, J.A., Palmer, A.S., 1999. Dynamic interactions between lahars and stream flow: a case study from Ruapehu volcano, New Zealand. *Geological Society of America Bulletin* 111, 28–38.

Cronin, S.J., Lecoindre, J.A., Palmer, A.S., Neall, V.E., 2000. Transformation, internal stratification, and deposition of a channelised, multi-peaked lahar flow. *NZ Journal of Geology and Geophysics* 43, 117–128.

Druitt, T., Calder, E.S., Cole, P.D., Hoblitt, R.P., Loughlin, S.C., Norton, G.E., Ritchie, L.J., Sparks, R.S.J., Voight, B., 2002. Small-volume, highly mobile pyroclastic flows formed by rapid sedimentation from pyroclastic surges at Soufriere Hills volcano, Montserrat: an important volcanic hazard. In: Druitt, T., Kokelaar, B.P. (editors) *The eruption of Soufriere Hills Volcano, Montserrat, from 1995 to 1999*. The Geological Society, London, Memoir 21, pp. 263–279.

Gaytán, D., Clavero, J., Rivera, A., 2005. Actividad eruptiva explosiva del Volcán Villarrica, Andes del Sur (39.5°S), durante la glaciación Llanquihue. *Congreso Geológico Argentino*, No. 16. La Plata, Argentina, (CD-ROM).

González, O., 1995. *Volcanes de Chile*. Instituto Geográfico Militar, Santiago, 640pp.

Iverson, R.M., 1997. The physics of debris flows. *Reviews of Geophysics* 35 (3), 245–296.

Iverson, R.M., 2005. Debris-flow mechanics. In: Jakob, M., Hungr, O. (Eds.), *Debris-flow hazards and related phenomena*. Springer, Berlin, pp. 105–134.

Iverson, R.M., LaHusen, R.G., Major, J.J., Zimmerman, C.L., 1994. Debris flow against obstacles and bends: dynamics and deposits. *EOS. Transactions of the American Geophysical Union* 75, 274.

Klohn, E., 1963. The February 1961, eruption of Calbuco Volcano. *Seismological Society of America Bulletin* 53, 1435–1436.

Lahsen, A., Moreno, H., Varela, J., Munizaga, F. y López, L. 1985. Geología y riesgo volcánico del Volcán Calbuco y centros eruptivos menores. Central Canutillar. (unpublished report) Depto. de Geología-ENDESA. Santiago, Chile. 215pp.

Major, J., 1997. Depositional processes in large-scale debris-flow experiments. *Journal of Geology* 105, 345–366.

Major, J., 2000. Gravity-driven consolidation of granular slurries: implications for debris-flow deposition and deposit characteristics. *Journal of Sedimentary Research* 70, 64–83.

Monserrat, S., 2005. Estudio experimental de obras contra aluviones. (Unpublished Master thesis), Universidad de Chile. Santiago, Chile, 267pp.

Moreno, H., 1993. Volcán Villarrica, Geología y evaluación del riesgo volcánico, Regiones IX y X, 39° 25'S. Final report (unpublished) FONDECYT project 1247. Santiago, Chile, 112pp.

Moreno, H., 1999. Mapa de peligros del volcán Calbuco. Región de los Lagos. Servicio Nacional de Geología y Minería, Documento de trabajo, No. 12, 1 mapa escala 1: 75 000. Santiago, Chile.

Moreno, H., Naranjo, J., Clavero, J., 2006. Generación de lahares calientes en el volcán Calbuco, Andes del Sur de Chile (41,3°S). XI Congreso Geológico Chileno. Antofagasta, Chile, (CD).

Moreno, H., Clavero, J., 2006. Geología del área del volcán Villarrica, Regiones de la Araucanía y de los Lagos. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Carta Geológica de Chile, No. 98, 1 mapa escala 1:50 000. Santiago, Chile.

Naranjo, J.A., Moreno, H., 2004. Laharic debris-flows from Villarrica Volcano. In: Lara, L., Clavero, J. (Eds.), *Villarrica Volcano (39.5°S) Southern Andes, Chile: Servicio Nacional de Geología y Minería. Boletín n°61*, pp. 28–38.

Petit-Breuilh, M.E., Lobato, J., 1994. Análisis comparativo de la cronología eruptiva histórica de los volcanes Llaima y Villarrica. *Congreso Geológico Chileno*, N° 7, Actas, Vol. 1. Concepción, Chile, pp. 366–370.

Petit-Breuilh, M., 1999. Cronología Eruptiva Histórica de los volcanes Osorno y Calbuco, Andes del Sur (41°–41°30S). *Servicio Nacional de Geología y Minería, Boletín*, No. 53, p. 46.

Pierson, T.C., Scott, K., 1985. Downstream dilution of a lahar: transition from debris flow to hyperconcentrated streamflow. *Water Resources Research* 21 (10), 1511–1524.

Pierson, T.C., Janda, R., Thouret, J., Borrero, C., 1990. Perturbation and melting of snow and ice by the 13 November 1985 eruption of Nevado del Ruiz, Colombia, and consequent mobilization, flow and deposition of lahars. *Journal of Volcanology and Geothermal Research* 41, 17–66.

Quinteros, C., 1991. Estudio de los lahares del volcán Llaima-IX° Región de la Araucanía. (Unpublished thesis), Universidad de Chile. Santiago, Chile 103pp.



- Rivera, A., Bown, F., Mella, R., Wendt, J., Casassa, G., Acuña, C., Rignot, E., Clavero, J., 2006. Ice volumetric changes on active volcanoes in Southern Chile. *Annals of Glaciology* 43 (1), 111–122.
- Schwarzkopf, L., Schmincke, H., Cronin, S., 2005. A conceptual model for block and ash flow basal avalanche transport and deposition, based on deposit architecture of 1998 and 1994 Merapi flows. *Journal of Volcanology and Geothermal Research* 139 (1–2), 117–134.
- Scott, K., 1988. Origins, behavior, and sedimentology of lahars and lahar-runout flows in the Toutle-Cowlitz River system: U.S. Geological Survey Professional Paper 1447-A, 76 pp.
- Vallance, J., 2000. Lahars. In: Sigurdsson, H. (Ed.), *Encyclopedia of Volcanoes*. Academic Press, San Diego, pp. 601–616.
- Vallance, J., 2005. Volcanic debris flows. In: Jakob, M., Hungr, O. (Eds.), *Debris-flow hazards and related phenomena*. Springer, Berlin, pp. 105–134.
- Vallance, J., Scott, K., 1997. The Osceola Mudflow from Mount Rainier: sedimentology and hazards implications of a huge clay-rich lahar. *Geological Society of America Bulletin* 109, 143–163.