Introduction

The Osorno and Calbuco volcanoes belong to the modern Southern Volcanic Zone (SVZ) of the Chilean Andes at 41,2ºS (Fig. 1). The SVZ arc is the result of the subduction of the oceanic Nazca plate under the continental South American plate. This volcanic arc extends from latitude 33°S to 46°S, being bounded by the intersection of the Juan Fernández ridge with the continental margin at ca. 32°S and the Chile Ridge triple junction at ca. 47°S. On the basis of petrographic, geochemical and tectonic considerations, the Quaternary front of the SVZ is currently divided into four main provinces (according to López-Escobar et al. 1995, and references therein): northern (NSVZ; 33 - 34.5°S), transitional (TSVZ; 34.5-37°S), central (CSVZ; 37-41.5°S) and southern (SSVZ; 41.5-46°S). In the CSVZ, where the thickness of the crust is ≤ 35 km, the volcanic products are predominantly basalts and basaltic andesites without hydrous minerals like amphibole and mica. This general correlation between the crustal thickness and the composition of the SVZ volcanic front is broken by the Calbuco volcano (41,4°S), which is andesitic, despite being located in a zone where the continental crust is relatively thin and most volcanic centres, including its neighbour Osorno volcano, are dominantly basaltic.

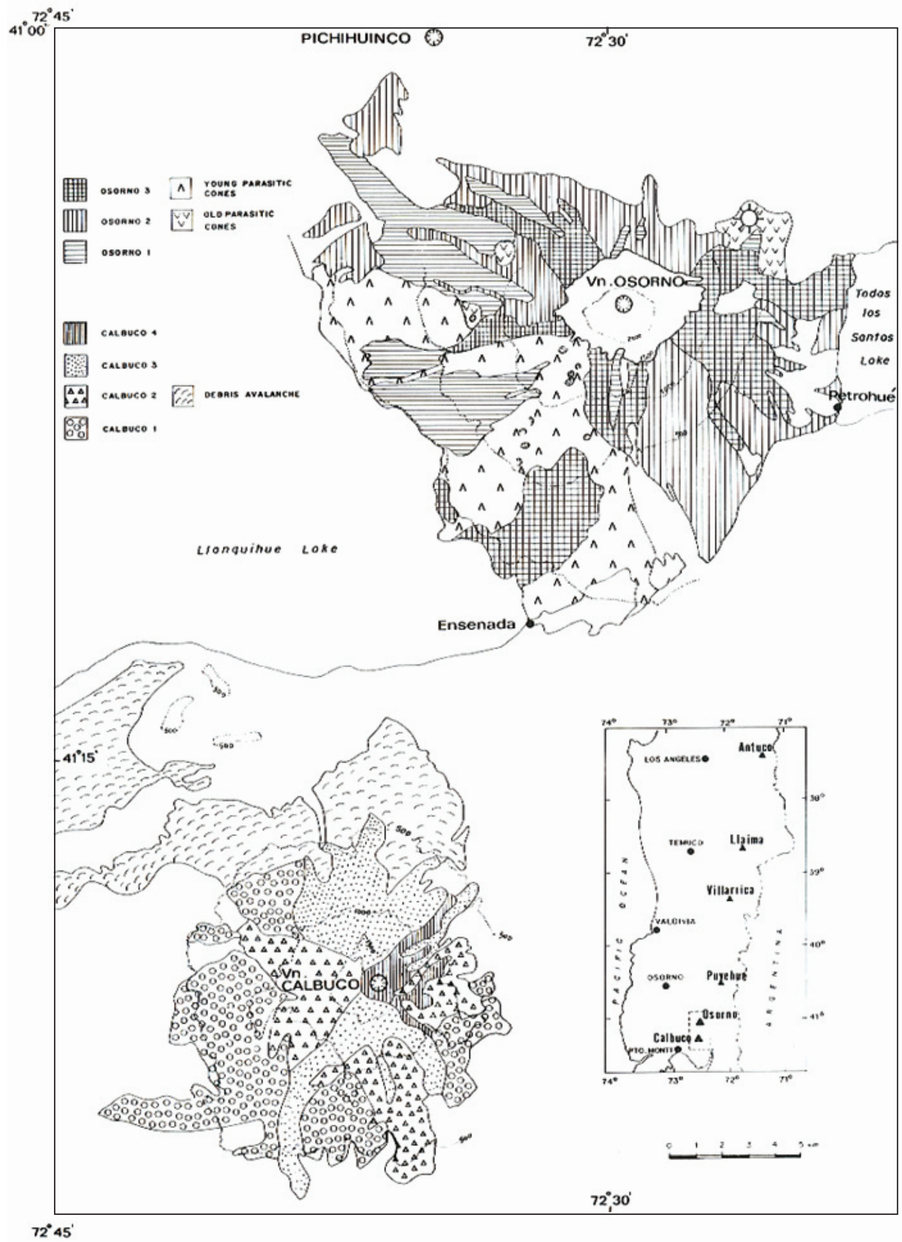

FIG. 1. Simplified geological sketch map of Osorno and Calbuco volcanoes, after Moreno *et al.* (1979); H. Moreno, J. Varela, L. López-Escobar, F. Munizaga and A. Lahsen[1]; A. Lahsen, H. Moreno, J. Varela, F. Munizaga and L. López-Escobar[2].

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Osorno volcano

General features and basement

The Middle?-Late Pleistocene to Historic Osorno composite stratovolcano is located toward the east of Llanquihue lake and forms a SW-NE volcanic chain together with the eastern Pleistocene to Holocene La Picada, Puntiagudo and Cordón Cenizos basaltic volcanoes. This chain is oblique to the recent volcanic arc and to the main structure located in the region, the Liquiñe-Ofqui Fault Zone (LOFZ; Fig.1; Hickey-Vargas et al, 1989; Cembrano, 1992; Cembrano and Herve, 1993; Cembrano and Moreno, 1994; López-Escobar et al, 1995; Lara et al., 1999). The oblique structure corresponds probably to a young tensional fracture in the crust, which allowed the extrusion of mainly mafic quaternary magmas (Moreno, 1976; Moreno and Parada, 1976; Moreno et al., 1979; López-Escobar et al., 1995; Lara and Moreno, 2000a, 2000b).

The composite Osorno stratovolcano and its products cover an area of more than 500 km^2, although the edifice base has a surface of about 320 km^2, with a volume of ca. 250 km^3 (Moreno, 1999). It has an almost perfect cone shape and consists mainly of lava flows interbedded with pyroclastic material, reaching an altitude of 2,652 m above sea level, and 2,600 m above its base. Its summit and main crater is covered by a 0,14 km^3 glacier. A very weak fumarole has melted and formed a small cavern under the ice on the eastern edge of the crater (Moreno et al., 1985).

The basement of Osorno volcano consists mainly of Tertiary volcanic and sedimentary rocks intruded by Miocene plutons (Moreno et al., 1979; 1985; López-Escobar et al., 1988; Munizaga et al., 1988; Moreno, 1999a). The Tertiary stratified folded sequences, comprise tuffs, breccias and lavas that are intruded by hypabyssal andesitic bodies, cropping out toward the north and NW of the volcano. The Miocene plutonic rocks are predominantly granitic to granodioritic in composition. Toward the east and NE the La Picada volcano sequence is covered by the Osorno products.

Several sedimentary deposits related to the quaternary glaciations in the region are also found in the area (Moreno et al., 1985). The young sedimentary deposits range in age from Middle Pleistocene to Holocene and consist of glacial, lacustrine and fluvial deposits, moderately to completely unconsolidated.

Geology outline

(Moreno et al., 1979, 1985; López-Escobar et al., 1988, 1992; Moreno, 1999a; Moreno et al., 2000; Naranjo et al., 2000)

According to morphostructural and stratigraphic criteria, the Osorno volcano edifice has been divided into three evolutive stages: an old composite stratovolcano (Osorno 1 unit, Middle? to Upper Pleistocene) was strongly eroded by glaciers. One of the oldest lava flows gave a poor K/Ar age of 250±100 BP. The continuous volcanic activity within the Upper Pleistocene (Intra and Postglacial) formed a new edifice (Osorno 2 unit), that covered almost all of the old sequence, leaving some remnants toward the west. During the Holocene and Historic times the building of the cone continued (Osorno 3 unit), reaching the current height of 2,652 m. Lava flows and pyroclasts have mainly a basaltic to basaltic andesite composition.

Within the Postglacial (last 14.000 years), Osorno volcano has generated pyroclastic density currents, with volumes ranging between 10^8 m^3 and 10^9 m^3, during explosive eruptions that covered an area of about 1,000 km^2, one of the last ones has about 600 BP. In addition, during the Holocene, only one dacitic plinian pumice fall has been found and it has ca. 1,500 BP.

On the SW and eastern flanks of this stratovolcano, there exist a number parasitic scoria cones, mostly controlled by the main SW to NE fracture (Fig.1). The SW Osorno 1 remnant has been almost completely covered by the major cluster of parasitic cones and their lava flows. A couple of older parasitic cones and related lava flows are also situated on the western flank, away from the main trend.

Along its whole evolution, the main composition of the eruptive products have been basalts to basaltic andesites (50,0 - 56,0% SiO_2). Besides, the medium andesites are scarce (56,0 – 58,0% SiO_2), the same as some silicic end members (62,0 – 65,0% SiO_2) and a gap has been found between 58,0 and 62,0% SiO_2.

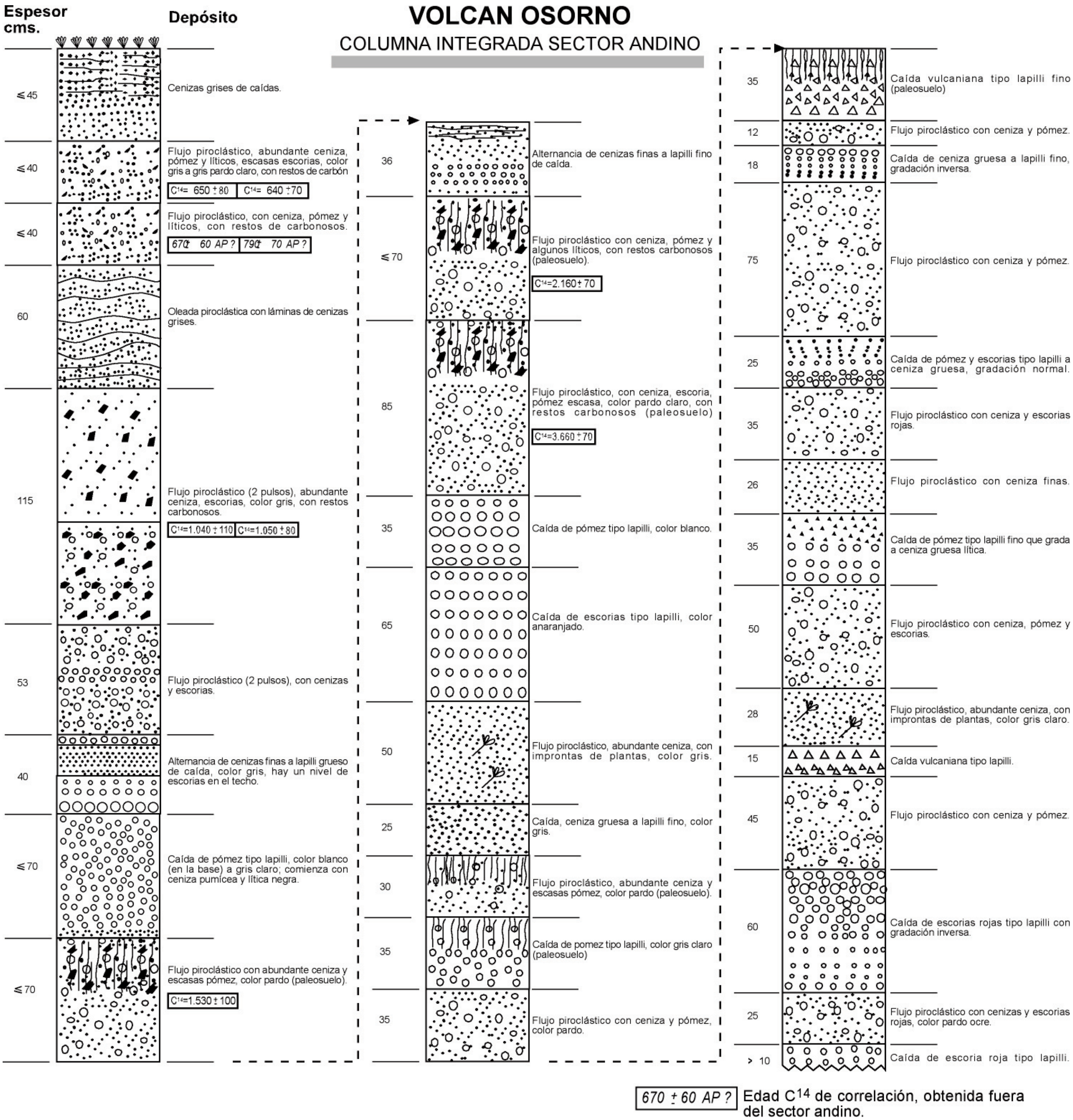
Volcanic materials are mostly aphyric to strongly porphyritic with plagioclase (the most abundant) followed by olivine and clinopyroxene phenochrysts, and they would have derived by crystal fractionation from more primitive magmas. Crystal clots of plagioclase and olivine plus anhedral crystals of clinopyroxene, that could be xenocrysts, has been observed in lavas from the Osorno 3 unit. The products of the parasitic cones are also olivine basalts and basaltic andesites. The silicic end members are hypersthene-bearing dacites.

During recent prehistoric and historic times, the activity of Osorno volcano has been concentrated on the main cone and on the youngest parasitic cones located on the SW and eastern flanks of the edifice (Fig.1), producing exclusively basaltic products. It has 12 well-documented eruptions during the XVIII and XIX centuries. Historical eruptive activity has been essentially effusive. The last large lava eruption of this centre occurred in 1835, mainly through several SW parasitic cones and the last ash eruption took place on 1869 (Petit-Breuilh, 1999).

Eruptive behaviour

The eruptive behaviour of Osorno volcano has commonly been considered to be dominantly effusive or slightly explosive, because of its historic record. However, recent detailed volcanologic and stratigraphic studies (Moreno, 1999a; Moreno et al., 2000; Moreno et al., In Ed.; Naranjo et al., 2000; Naranjo et al., 2001a; 2001b) show a previously unknown explosive postglacial history, which includes the generation of pyroclastic flows and surges, together with one plinian pumice eruption within the last 14,000 years.

The intensities and types of prehistoric eruptions have varied from Hawaiian (VEI = 0-1) to Plinian (VEI = 4?), although the historical ones (last 300 years), have been mainly Hawaiian and Strombolian (VEI = 0-2; Petit-Breuilh, 1999).


VOLCAN OSORNO
COLUMNA INTEGRADA SECTOR ANDINO
Espesor cms.
Depósito
≤45
Cenizas grises de caídas.
≤40
Flujo piroclástico, abundante ceniza, pómez y líticos, escasas escorias, color gris a gris pardo claro, con restos de carbón
C14= 650 ± 80
C14= 640 ± 70
≤40
Flujo piroclástico, con ceniza, pómez y líticos, con restos de carbonosos.
670 ± 60 AP ?
790 ± 70 AP ?
60
Oleada piroclástica con láminas de cenizas grises.
115
Flujo piroclástico (2 pulsos), abundante ceniza, escorias, color gris, con restos carbonosos.
C14=1.040 ± 110
C14=1.050 ± 80
53
Flujo piroclástico (2 pulsos), con cenizas y escorias.
40
Alternancia de cenizas finas a lapilli grueso de caída, color gris, hay un nivel de escorias en el techo.
≤70
Caída de pómez tipo lapilli, color blanco (en la base) a gris claro; comienza con ceniza pumícea y lítica negra.
≤70
Flujo piroclástico con abundante ceniza y escasas pómez, color pardo (paleosuelo).
C14=1.530 ± 100
36
Alternancia de cenizas finas a lapilli fino de caída.
≤70
Flujo piroclástico con ceniza, pómez y algunos líticos, con restos carbonosos (paleosuelo).
C14=2.160 ± 70
85
Flujo piroclástico, con ceniza, escoria, pómez escasa, color pardo claro, con restos carbonosos (paleosuelo)
C14=3.660 ± 70
35
Caída de pómez tipo lapilli, color blanco.
65
Caída de escorias tipo lapilli, color anaranjado.
50
Flujo piroclástico, abundante ceniza, con improntas de plantas, color gris.
25
Caída, ceniza gruesa a lapilli fino, color gris.
30
Flujo piroclástico, abundante ceniza y escasas pómez, color pardo (paleosuelo).
35
Caída de pomez tipo lapilli, color gris claro (paleosuelo)
35
Flujo piroclástico con ceniza y pómez, color pardo.
35
Caída vulcaniana tipo lapilli fino (paleosuelo)
12
Flujo piroclástico con ceniza y pómez.
18
Caída de ceniza gruesa a lapilli fino, gradación inversa.
75
Flujo piroclástico con ceniza y pómez.
25
Caída de pómez y escorias tipo lapilli a ceniza gruesa, gradación normal.
35
Flujo piroclástico con ceniza y escorias rojas.
26
Flujo piroclástico con ceniza finas.
35
Caída de pómez tipo lapilli fino que grada a ceniza gruesa lítica.
50
Flujo piroclástico con ceniza, pómez y escorias.
28
Flujo piroclástico, abundante ceniza, con improntas de plantas, color gris claro.
15
Caída vulcaniana tipo lapilli.
45
Flujo piroclástico con ceniza y pómez.
60
Caída de escorias rojas tipo lapilli con gradación inversa.
25
Flujo piroclástico con cenizas y escorias rojas, color pardo ocre.
> 10
Caída de escoria roja tipo lapilli.
670 ± 60 AP ?
Edad C14 de correlación, obtenida fuera del sector andino.

Volcanic hazards associated to Osorno volcano

(Moreno et al., 1985; Moreno, 1999a; Moreno et al., 2000; Moreno et al., In Ed.; Naranjo et al., 2000; Naranjo et al., 2001a; 2001b)

Although most of the historic eruptions have been mainly effusive, the permanent glacier that covers the volcano, together with the seasonal snow-cap, generates a very important volcanic hazard to its surroundings. Historical eruptions have produced lava flows, lahars and the ejection of pyroclastic material. Hence, the main hazards expected from future eruptions of Osorno volcano are those that derive directly from lava flows and tephra fallout, together with those induced by them, such as lahars and river flooding. The Chilean Geological Survey published the Volcano Hazards Map of Osorno volcano and its surrounding areas (Moreno, 1999). Here is briefly summarised the information given in that map.

Lava flows and Lahars (volcanic debris flows)

The areas that could be affected by these types of flows are located almost all around the volcano. The lava flows could be erupted from the central cone, as well as the parasitic scoria cones and can reach up to 12 km far from the vent. The flows, according to their transport, would travel down through the main valleys on the volcano slopes, and spread over wider areas when reaching lowlands, flat areas and especially close to the lake shores (Llanquihue and Todos los Santos). Along the Petrohué river, the lava flows could block up the valley causing dams. Lahars are the most important volcanic hazard associated to Osorno volcano, according to its recurrence and the location of urban areas (i.e. Las Cascadas, Ensenada and Petrohué villages).
The scenario for an eventual lahar generation varies according to the time of the year because of the seasonal snow covering thickness. Thus, in summer time the Petrohué valley could be affected by lahars that can reach about 80 x 10^6 m^3, although in winter the volume could increase to about 200 x $10^6 m^3$.

Tephra fallout

According to the prevailing high-altitude wind directions (from NW to SE) this type of hazard could affect areas located mainly on the eastern-southeastern side of the volcano. According to the hazard map, the Todos los Santos lake basin has a strong topographic control on the ash fall, because of the west-east winds. Although there are no important human settlements towards the East, if a highly explosive eruption occurs, the tephra fallout deposits could reach more populated areas further to the East, in Argentina.

Pyroclastic flows

Although this type of hazard is not the most common volcanic product in Osorno's recent eruptive history, their widespread distribution together with their highly destructive character, makes them an important hazard for the surroundings of the volcano. Moreover, it is important to say that there are no evidences that the explosive phase of Osorno volcano has finished yet.
Although admittedly the possibility of generation of a pyroclastic flow is very low, it does represent the most dangerous type of threat posed by Osorno volcano.

Calbuco volcano

General features and basement

The Middle?-Late Pleistocene to Historic Calbuco composite stratovolcano is located toward the SE of Llanquihue lake and its products cover an area of more than 400 km^2, although the edifice base has a surface of about 150 km^2, with a volume of ca. 100 km^3. It has a rough truncated-cone shape and consists mainly of blocky lava flows interbedded with abundant pyroclastic material, reaching an altitude of 2,003 m above sea level, and 1,800 m above its base. Its summit is covered by very small glaciers and has a sporadic fumarole on small main crater. The last one lasted from 1995 to 1999 (Moreno, 1999b).

The basement of Calbuco volcano consists mainly of Upper Paleozoic (?) metasedimentary rocks (Parada et al., 1987); Upper Tertiary (16 to 10 Ma) plutonic rocks (Parada et al., 1987; Munizaga et al., 1988) and Early Pleistocene volcanic and volcanoclastic sequences (Lahsen et al., 1985).

Calbuco edifice rests upon an uplifted block and the degree of uplifting and unroofing suggests an accelerating uplift during the last 12 Ma at an average rate of about 0.9 mm/y (Hickey-Vargas et al., 1995).

The plutonic rocks underlying Calbuco are part of an extensive Miocene plutonic belt of the Northern Patagonian Batholith, which extends northward to 39°S, and consist of granites, diorites and gabbros. The Early Pleistocene volcanic sequences are represented by the Hueñuhueñu sequence of more than 550m thick that extends east of the volcano and includes volcaniclastic materials.

Several sedimentary deposits related to the quaternary glaciations in the region are also found in the area (Moreno et al., 1985; Lahsen et al., 1985). The young sedimentary deposits range in age from Middle Pleistocene to Holocene and consist of glacial, lacustrine and fluvial deposits, moderately to completely unconsolidated.

Geology outline

(Moreno, 1976, 1979; Lahsen et al., 1985; López-Escobar et al., 1988, 1992; Hickey-Vargas et al., 1995; Moreno, 1998, 1999b; Moreno et al., 2000; Naranjo et al., 2000)

According to morphostructural and stratigraphic criteria, the Calbuco volcano edifice has been divided into four evolutive stages: an old composite stratovolcano (Calbuco 1 unit, Middle? to Upper Pleistocene) was deeply eroded by the last glaciation (Llanquihue) and one of the mid-sequence lava flows gave a K/Ar age of 113,000 BP. The continuous volcanic activity within the Upper Pleistocene (Intraglacial) formed a new edifice on top of the previous one (Calbuco 2 unit), leaving some remnants of the old unit toward the NW, west and south. At the beginning of the Postglacial a violent eruption produced the cone collapse and triggered a debris-avalanche with a volume of more than 3 km^3, that flowed down toward the NNW (Fig.1), leaving an avalanche crater of 2 km wide opened to the NE. In the bottom of this avalanche crater a dome started to grow and evolved to a new stratocone (Calbuco unit 3). This edifice also suffered another small collapse and a new dome started to grow in its bottom and currently has less than 50 metres height from the main crater rim that rises 2,003 m a.s.l. to the west (Calbuco unit 4).

Within the Postglacial (last 14.000 years), Calbuco volcano has generated pyroclastic density currents, with volumes ranging between 10^6 m^3 and 10^9 m^3, during explosive eruptions, the largest covered an area of about 1,500 km^2. The most recent ones recognized on the western foot of the volcano are 8 since 10,000 BP, although to the east, at least 20 pyroclastic flows were generated within the last 7,500 years and had a great movility overflowing several high ridges that have more than 1,000 m a.s.l. Thus, the average recurrence of such flows is less than 500 years. Besides, at least 10 subplinian pumice falls have been found, generated during violent eruptions within the Postglacial. In relation to parasitic vents, Calbuco has only one small parasitic dome on its northern flank.

Along its whole evolution, the main composition of the eruptive products have been medium andesites (56,0 - 61,0% SiO_2). Besides, the basaltic andesites are rare (52,0 – 56,0% SiO_2).

Volcanic materials are mostly porphyritic with plagioclase, clinopyroxene, orthopyroxene and very small amounts of olivine. Chrystal clots of amphibole with reaction rims have been found and most of them are xenochrysts.

A wide variety of xenoliths are abundant in Calbuco lavas. Xenolith lithologies include basalt and andesite, in addition to granulite, gabbronorite, pyroxenite and quartzite.

During recent prehistoric and historic times, the activity of Calbuco volcano has been essentially explosive and concentrated on the main central dome (Fig.1), producing exclusively andesitic products. It has 11 well-documented eruptions during the XVIII and XXth centuries. The last large eruption of this centre occurred in 1961.

Eruptive behaviour

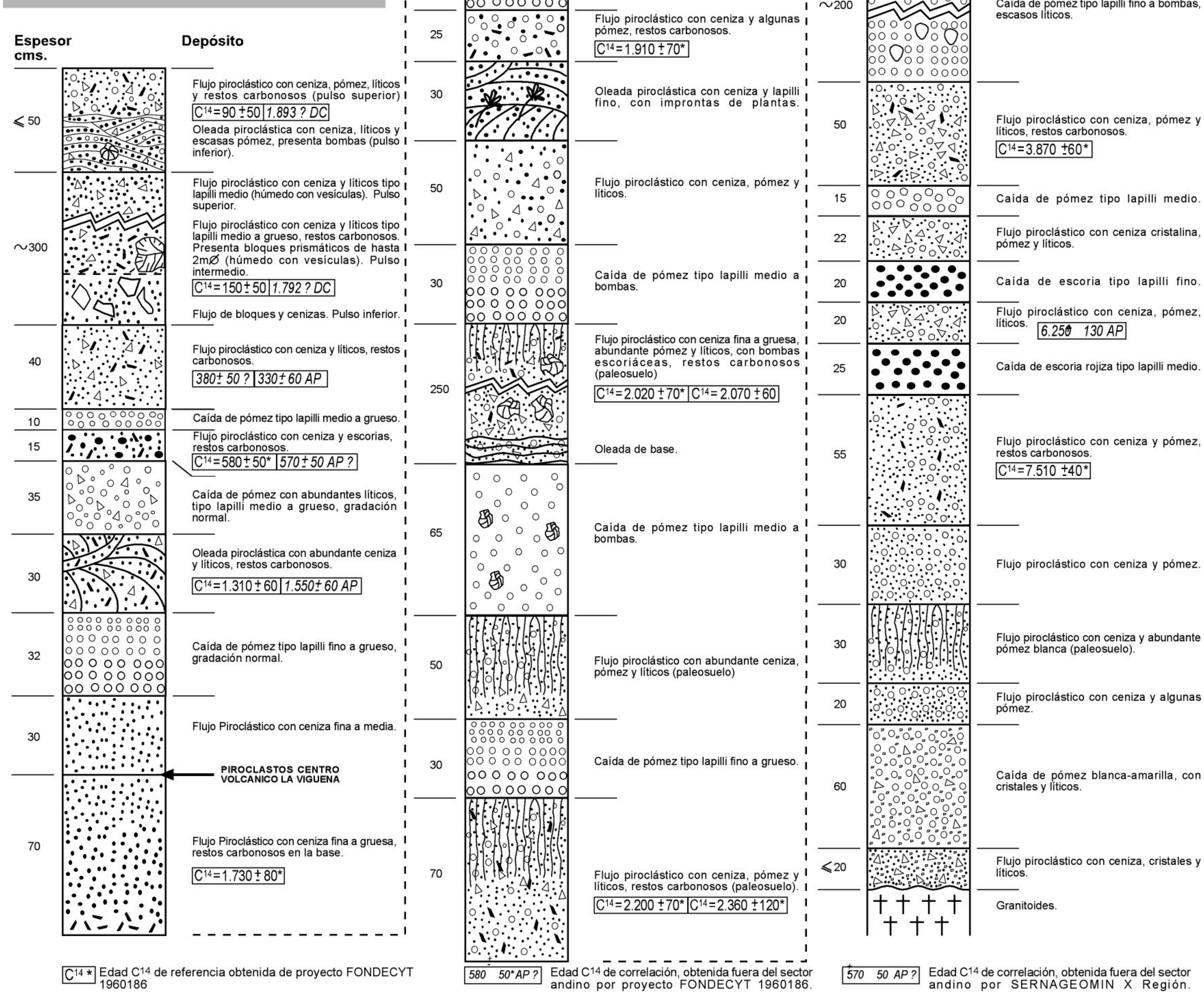
The eruptive behaviour of Calbuco volcano has been dominantly explosive along its Postglacial evolution, based on its geologic record, detailed volcanological studies and historic eruptions (*Petit-Breuilh, 1997, 1999 and references therein; Petit-Breuilh and Moreno, 1991*). The Postglacial explosive activity have include the generation of pyroclastic flows and surges (lateral blasts), block and ash flows caused by dome growth collapses, together with many subplinian pumice eruptions. However, the existence of past plinian eruptions are uncertain, due to the volume of the tephra-fall and the relatively small extent (*Moreno, 1999b; Moreno et al., 2000; Moreno et al., In Ed.; Naranjo et al., 2000; Naranjo et al., 2001a; 2001b*).

The building of the main central dome, nested within the avalanche caldera, together with the extrusion of thick blocky lavas (up to 60 metres high fronts along steep gully floors) have generated frequent block and ash flows during the historic eruptions, mainly toward the east and NE (Caliente-Hueñuhueñu river beds). This flows, mixed with the river waters yielded hot lahars characterized by a rich ash size particle matrix and monolithologic angular blocks (commonly PJB).

The intensities and types of Postglacial prehistoric and Historic eruptions have been mainly Subplinian (VEI = 2-4?; *Petit-Breuilh, 1999*) and the most catastrophic within historic times was the 1893-95 eruptive cycle (VEI=3).

VOLCAN CALBUCO

COLUMNA INTEGRADA SECTOR ANDINO



Volcanic hazards associated to Calbuco volcano

(Moreno, 1976; Lahsen et al., 1985; Moreno, 1999b; Moreno et al., 2000; Moreno et al., In Ed.; Naranjo et al., 2000; Naranjo et al., 2001a; 2001b)

Given that most of the historic eruptions have been explosive and that the volcano has an important seasonal snow-cap (the summit glaciers are very small) it implies a significant threaten to its surroundings. As the eruptions have produced big ash columns, dome growth, lateral blasts (surges), thick blocky lava flows, block and ash flows and hot lahars generation, the main hazards expected from future eruptions of Calbuco volcano are those that derive directly from these processes like heavy tephra fallout, pyroclastic flows and surges, block and ash flows and those induced by them such as hot lahars and river flooding. Although the lava flows are very viscous and they reach less than 10 km from the source, their high and unstable fronts produce fequent collapses and block and ash flows that can travel longer distances. The Chilean Geological Survey published the Volcano Hazards Map of Calbuco volcano and its surrounding areas (Moreno, 1999). Here is briefly summarised the information given in that map.

Lava flows and Lahars (volcanic debris flows)

The areas that could be affected by the blocky lava flows are located mainly toward the NE and SE of the volcano, although because of their high viscosity, they could also run over the crater's northern rim and flow down on that slope. The lava flows could be erupted from the central dome and can hardly reach up to 9 km far from the vent, although the block and ash flows run out could cover larger areas. If some lava flows travel to the east, they can block the Caliente river valley forming a dam and an unstable and hazardous lake, over which block and ash flows and/or lateral blasts could produce violent flooding downwards. The lahars could generate by two different ways: as a sudden melting caused by lavas or pyroclastic flows over the ice and seasonal snow or by mixing of block and ash flows with stream waters. In view of the fact that the eruptive historic record mentions the formation of "hot lahars" toward the NE, SE and south of the volcano, that rapidly indurate, it suggests that mixing of pyroclastic flows/surges and block and ash with river waters generates most of them.

Lahars have been the most dangerous and destructive processes when they have travelled down through the main valleys on the volcano slopes, and spread over wider areas when reaching lowlands, flat areas and especially close to the lake shores (Llanquihue and Chapo). Hence lahars are the most important volcanic hazard associated to Calbuco volcano, according to its recurrence and the location of urban areas (i.e. Ensenada, Correntoso and Chapo villages).

The scenario for an eventual lahar generation during an eruption, varies significantly according to the time of the year because of the seasonal snow covering thickness. As an example, in summer time the Blanco and Hueñuhueñu river valleys could be affected by lahars that can reach a volume of about 3 x 10^6 m^3, although in winter the volume could increase drastically to about 82 x $10^6 m^3$.

Tephra fallout

As Calbuco volcano is highly explosive, ballistic pyroclasts can reach long distances around the volcano. In fact, pumice bombs up to 10 cm in diameter have been found at 24 km far east from the volcano. During the 1893-95 eruptive cycle, bombs up to 30 cm in diameter were thrown out at 8 km from the vent, killed cattle and caused forest fires. Thus, human settlements close to the volcano like Ensenada, Colonia Río Sur, Chapo could be heavily battered by bombs and/or coarse lapilli fall. Moreover, the ash column and plumes, i.e. dispersal and tephra fall, according to the prevailing high-altitude wind directions (mainly from NW to SE) could affect areas located mostly on the east and southeastern side of the volcano. Consistent with the hazard map, the Chapo lake basin and the Reloncaví fjord will be the areas most exposed to this process. Therefore, localities toward the east and SE such as Ralún, Cochamó and Puelo villages, as well as the Canutillar Hydroelectric Power Plant located on the southeastern extreme of Chapo lake and the salmon industries along the Reloncaví fjord, would be heavily affected if a highly explosive eruption takes place. Besides, the tephra fallout deposits could reach more populated areas further to the East, such as El Bolsón, San Carlos de Bariloche and Villa La Angostura located in Argentina.

Pyroclastic flows

Although pyroclastic flows/surges and block and ash flows are a common volcanic product in Calbuco's recent eruptive history, their restricted distribution (because of the topography) and small volumes, makes them an important hazard only for the Blanco-Hueñuhueñu area (toward the NE). However, it is important to remember that the average recurrence of larger pyroclastic flows is less than 500 years, the current evolution of the volcano suggests that the main central dome is still growing and historic eruptions have been very explosive (like the 1893-95 period). For this reason, the future generation of a large pyroclastic flow (≥1 km^3) that could cover an area greater than 1,000 km^2, represents the most dangerous type of threat of Calbuco volcano.

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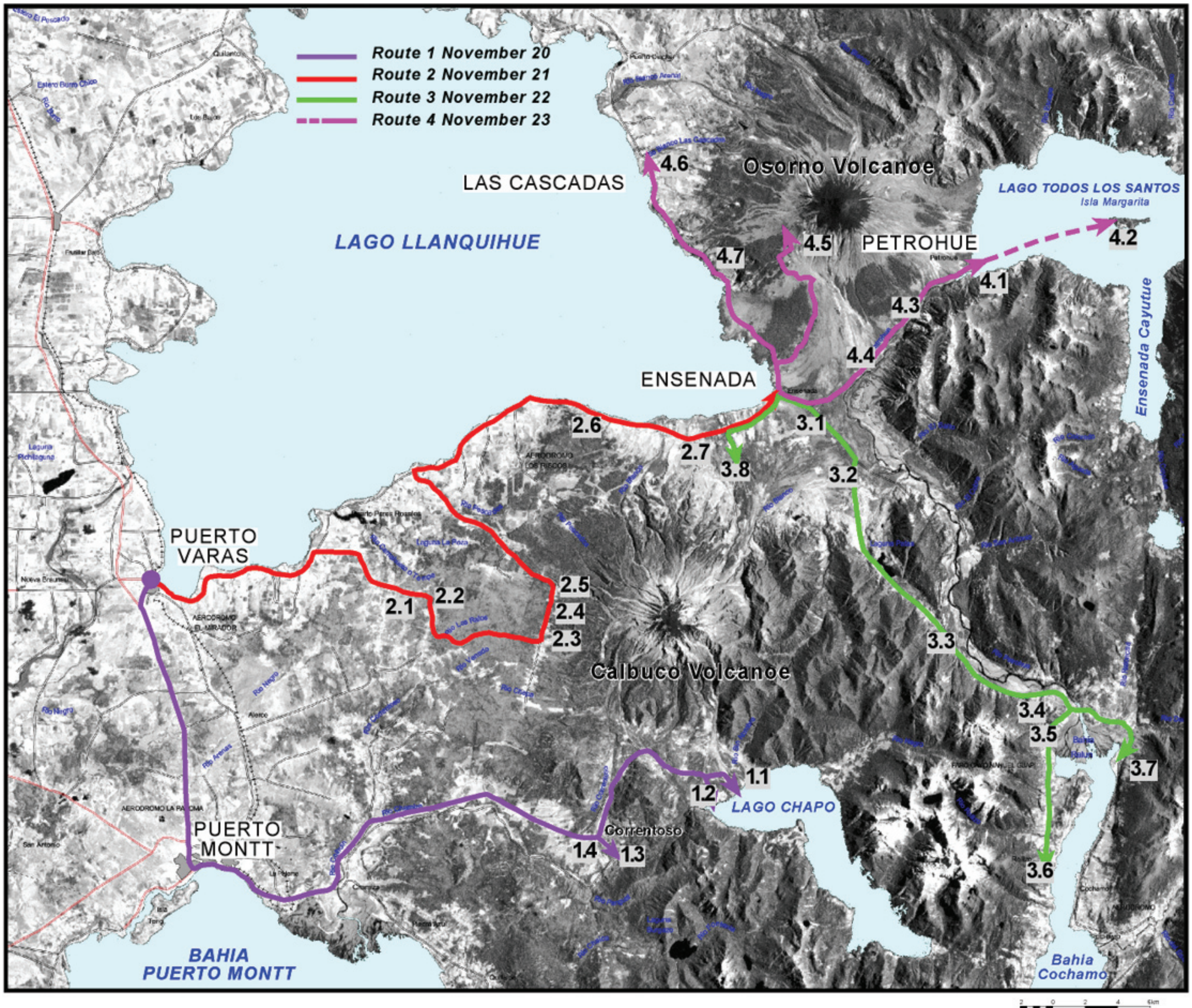
Brief description of stops



November 20th

09:30 Departure from Pucón to Puerto Varas.
13:30 Puerto Varas. Quick lunch.
15:30 Puerto Varas to Chapo lake, south of Calbuco volcano.

1. CHAPO AREA (South of Calbuco volcano) 703,00 / 5412,50 (300 m)

Calbuco seen from the SE. The road crosses an area over the 1961 eruption hot lahars that travelled toward Chapo lake. A small blocky lava flow came down along the Este river and the ice/snow melting together with the block and ash generation and water mixing caused the "hot lahars". Because of their muddy hot matrix they became indurated very soon (fine particle cohesion by hot water) and emitted vapour, however days later they lost their consistency (mainly by rains). Large blocks and boulders can be seen all over the place.

2. CHAPO LAKE (South of Calbuco volcano) 702,87 / 5410,68 (243 m)

Debris flows delta in the lake. Mid to distal facies of hot lahars and a natural submerged Alerce forest (> 1,100 years according to a ^{14}C dating). The area is dry now because of the Canutillar Hydroelectric Power Plant underground water drainage (located in the SE extreme of the lake). The amazing view of the forest and the lake's normal waterline table that preserved and kept the alerces like tree stumps. Their barks are charred, probably by pyroclastic flows that triggered forest fires. Large blocks and boulders can be seen everywhere, above the alerce forest.

3. CHAMIZA RIVER
(natural drainage of Chapo lake) 697,0 / 5407, 6 (120 m)

Deep gorge carved in granitic rocks with xenoliths, along fractures (joints) by water and debris flows erosion. The surface of the massive rock is polished, smooth and have striations. The place is a natural laharic passageway and lots of boulders can be seen downwards along the river. Across the bridge is the entrance to the "Alerce Andino National Park".

4. CORRENTOSO VILLAGE
(South of Calbuco volcano) 695,09 / 5408,64 (155 m)

The Correntoso village was settled on top of young hot debris flows. Along the road back to Puerto Montt, recent laharic deposits (no dates available) can be seen. They show pathways and small lateral levees. Most of them are indurated and exhibit a hard "crust". Blocks and boulders can be seen all over the place.

Back to Puerto Varas.

November 21st
Puerto Varas, Calbuco west foot and road to Ensenada.

1. ROAD TO COLONIA RIO SUR
(West of Calbuco) 683,258 / 5423,313 (186 m)

Road cut in a hummock of the early Postglacial Calbuco volcanic debris avalanche. The outcrop shows a rather massive structure with fractures and different degrees of crushed angular clasts of medium andesites. Some of them quite fresh and clast-supported. The matrix is fine grained to coarse sand size particles of grinding andesites. Greyish, orange and reddish patches of material can be observed, the later due to oxidation. The small hummock is covered by a pyroclastic flow deposit, completely weathered to clay minerals. Other hummocks can be seen nearby.

2. ROAD TO COLONIA RIO SUR
(West of Calbuco) 685,95 / 5423,24

Road Cut in another hummock of the early Postglacial Calbuco volcanic debris avalanche. The outcrop shows some stratified structures, lenses of crushed clasts, massive lenses and locally some lenses with internal lamination that consists in fine to coarse ash, fine lapilli and clasts. This laminated lenses suggest surge deposits within the debris avalanche, probably during its emplacement.

3. COLONIA RIO SUR
(West of Calbuco) 692,63 / 5421,20 (378 m)

Toward the volcano remnants of Calbuco 1 unit can be seen. This big remnant was surrounded by the ice of the last glaciation (Llanquihue). A sample from one lava that belongs to the mid part of the sequence gave 113,000 BP.
Cuesta Alta stream cut exposes a heavily weathered sequence with several paleosoil horizons, developed mainly on old pumiceous pyroclastic flows that belong to the Late Pleistocene, immediately prior to the Postglacial (last glacial advance). Some tree trunks (alerces) in an ancient swamp layer near the base of the sequence gave a ^{14}C age near 20.000 BP. Some white pumice layers have charred wood.

4. COLONIA RIO SUR
(West of Calbuco) 693,16 / 5423,31 (478 m)

A quarry outcrop which shows a succession of several volcaniclastic flows that probably relates to only one eruptive event (Photo 1). At least 5 layers can be distinguished and all of them are monolithologic. The sequence is quite monotonous and probably corresponds to distal facies of different block and ash deposits, that travelled down one after the other. In the lower layer some PJB blocks and bombs have been recognized. In this place the basaltic andesites (52 – 55% SiO_2) were found and are the most mafic rocks related to Calbuco volcano so far. The sequence underlies a pyroclastic flow and surge deposit with charcoal that gave a ^{14}C age of *ca.* 6,000 BP.

A quarry outcrop which shows a succession of monolithologic volcaniclastic flows (block and ash mainly), probably related to only one eruptive event.

5. COLONIA RIO SUR
(West of Calbuco) 693,41 / 5423,91 (478m) Luis Fidel Cardinale School

The school was settled on top of the prior block and ash sequence. The higher layer has plenty charcoal (waste pit) and it is covered by the surge deposit that outcrops around the area and spectacularly some hundredth metres far up the slope in a new road cut (the access is going to be evaluated). This surge deposit (that in other places is a flow deposit) has also lots of charred trees and branches and gave the ^{14}C age of *ca.* 6,000 BP.

6. ROAD TO ENSENADA
(LOS RISCOS, Llanquihue lake) 694,50 / 5434,05 (60 m)

The MIRADOR of Osorno volcano across the eastern part of the Llanquihue lake. The general morphology can be seen (if not cloudy) and on its SW flank (just in front of us), the cluster of young basaltic scoria cones and related lava flows of the February 1835 eruption that was described by the HMS Beagle Captain Robert Fitzroy, while travelling with Charles Darwin (he was in the Chiloe Island at that moment).

7. ROAD TO ENSENADA
(RIO BLANCO) 701,17 / 5432,92 (75 m)

In close proximity to Calbuco volcano, the general morphology can be observed (Photo 2). At the base of the volcano, in the foreground, several large hummocks (about 9) of the Postglacial debris avalanche can be distinguished. At the summit, the nested central dome top surpassed the 2 km wide avalanche caldera rim.

The Calbuco volcano general morphology can be observed. At the base of the volcano, in the foreground, large hummocks of the Postglacial debris avalanche can be distinguished.

Ensenada village.

November 22nd

[REMARKS*: if weather conditions are very good a this day, the field trip will be changed to Petrohué and Isla Margarita, planned for Nov. 23. If all the days are going to be good, then we have really a very good luck...*congratulations!]

Ensenada to Ralún, south of Osorno volcano and east of Calbuco volcano.

1. ROAD JUNCTION
(Petrohué and Ralún) 708,28 / 5434,82 (75 m)

Calbuco volcano seen from the NE. The whole edifice structure can be observed. Stands out mainly the 2 km diameter avalanche crater opened toward the NE and the central dome nested within the avalanche crater. The dome has grown enough to overflow and cover partly the southern crater rim, although still there are less than 150 m to reach the western rim height (2,003 m a.s.l.). On the other hand, the andesitic blocky lava flow from the 1961 eruption is outstanding.

2. HUEÑUHUEÑU BRIDGE
(road to Ralún) 711,45 / 5429,70 (40 m)

The Hueñuhueñu river birth takes place on the eastern slope of Calbuco volcano, but there it is called Rio Caliente. Then changes to Rio Blanco and finally Hueñuhueñu. This river valley is one of the main discharges of the volcano's drainages, thus it has been the pathway for debris flows. During the 1961 last big eruption, many hot lahars cut the pre-existing wooden bridge and millions of tons of volcanic debris filled the Petrohué river valley and were carried down toward the south, increasing the Reloncaví fjord delta extension.

3. CUESTA CABALLO
(road to Ralún) 716,35 / 5421,40 (180 m)

Road cut that shows a more than 6 m thick sequence of pyroclastic flows/surges and fallout deposits mainly from Calbuco volcano. The lower layer is a plinian pumice fall deposit more than 1,50 m thick, followed by more than 15 layers of pyroclastic flow, surge and fall deposits. The 6th layer from top to bottom is a pyroclastic flow deposit 0,30 m thick with ash, pumice, lithics and plenty charcoal that gave a ^{14}C age of *ca.* 1,500 BP.

4. LA VIGUERÍA
(road to Ralún) 722,40 / 5417,40 (20 m)

Quarry next to the road that exhibit a fluvial-lacustrine terrace of the Petrohué river valley, formed about 3,000 years ago by the river blockage caused by the monogenic volcano La Viguería and related basaltic lava flows, that was born in the valley bottom. A lake was formed upstream along the Petrohué river and was filled by volcanic debris (sand, gravel and some boulders) from Osorno and Calbuco volcanoes. The river erosion of the natural dam along the northeastern contact between the lava flows and the granitic basement rocks, carved a deep gorge and drained the lake. In this place a more than 50 m high wall shows large and thick vertical prismatic columns in the lava flow. The name "La Viguería" ("The Balks") comes from this structures. This small volcano is controlled by a NW – SE fault that intersect the N10°E LOFZ.

5. LA VIGUERÍA (Ralún) 723,70 / 5415,15 (20 m)

Road cut that exposes a more than 3 m sequence of a basaltic fallout deposit (vulcanian type) followed by a surge deposit related to La Viguería first subaerial activity. The sequence overlies a more than 3 m hardly indurated vesicular deposit that consists of pale brown ash, scoria and lithics. It suggests a pyroclastic flow erupted with high amounts of water, that would explain the vesicles and the concrete-like matrix. The whole sequence is followed by several layers (1 m thick) of Calbuco volcano pyroclastic flows and fall deposits. The penultimate layer us a thin (13 cm thick) pyroclastic flow layer with ash, pumice, lithics and charcoal that comes from Osorno volcano and gave a ^{14}C age of about 650 BP, consistent with other deposits all around Calbuco volcano.

6. PORTON ROJO (road from Ralún to Canutillar) 723,15 / 5408,10 (40 m)

Road cut that exposes a more than 5 m thick sequence of pyroclastic flows/surges and fallout deposits mainly from Calbuco volcano. Some of the flows have charcoal and a few ^{14}C ages have been obtained. From top to bottom a dark brown 70 cm thick weathered pyroclastic flow deposit with ash (clay), pumice, lithics and charcoal gave *ca.* 1,700 BP. It overlies a small pumice fallout deposit and underneath there is another weathered pale brown pyroclastic flow deposit with plenty ash (clay), few pumice and charcoal that gave about 2,000 BP. This deposit overlies a hard light grey crust layer that consists in a surge deposit with cross bedding and plant casts, which suggests a rather cold wet surge. It follows two pyroclastic flow deposits of about half a metre thick each, that lie over a pumice fall deposit. The lower brownish-light grey pyroclastic flow has a paleosoil with charred wood that gave more than 2,000 BP. Toward the base the succession is quite weathered and several paleosoils can be observed. If we remember the 1,500 BP pyroclastic flow deposit of Cuesta Caballo, it means that Calbuco volcano had a very explosive period that lasted about 500 years between 1,500 and 2000 years BP.

7. LOS TRES REYES (Ralún) 727,37-5413,4 (20 m)

Road cut that shows a thick superb sequence of pyroclastic flows/surges and fallout deposits mainly from Calbuco volcano, similar to the section at Portón Rojo, interbedded with the La Viguería basaltic monogenic volcano tephra fallouts.

8. CALBUCO RIO BLANCO (south of Ensenada) 703,82 / 5432,32 (92m)

A small quarry in the big NNE volcaniclastic fan from Calbuco volcano. The outcrop near the road show several pulses of Calbuco volcano debris flows deposits with logs and partly charred wood chunks (Photo 3). They have been interpreted as distal "hot lahar facies" derived from block and ash flows mixed with water. The light grey matrix is sandy with fine ash and very homogeneous, carrying mostly monolithologic angular juvenile grey clasts, although some of them are reddish by oxidation and others (larger in size) have typical PJB structures. This is a clear demonstration that their origin is a hot flow, in this case they derived from block and ash as seen on historic photographs (1929 and 1961 eruptions). Besides, the charred wooden remnants have been strongly shattered by the flow while travelling downwards, indicating a fast and chaotic transport. Also, the vapour emissions after they were emplaced, apparently left some very irregular and rough structures, mainly from the wooden remnants and from large PGBs.

Calbuco volcano debris flows deposits (hot lahars) with partly charred wood chunks.

- **Ensenada village.**

November 23rd

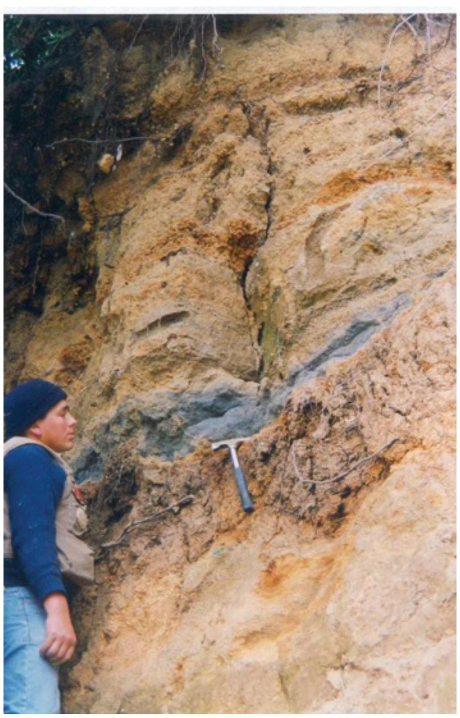
Ensenada to Petrohué, Isla Margarita, Ski Centre and Las Cascadas. Surrounding Osorno volcano.

1. PETROHUÉ WHARF
(Todos Los Santos lake) 718,50 / 5443,15 (190 m)

The Todos Los Santos lake was formed by the Osorno edifice building, that dammed the east-west glacial valley mostly with Postglacial basaltic lava flows.
Isla Margarita is a private island and has good outcrops with very good sections of pyroclastic deposits mostly from Osorno volcano.

2. ISLA MARGARITA
(Todos Los Santos lake) 727,00 / 5446,20 (190 m)

The sequence exposed on the island's western end shows an almost 13 metres thick sequence of pyroclastic flows/surges and fallout tephra deposits in about 40 layers. Among them, scoria and pumice fall deposits in layers up to 65 cm thick can be seen. Besides, several pumiceous pyroclastic flows/surges can also be observed and many paleosoil horizons may represent time break periods of low or none volcanic activity (Photo 4). Something amazing to notice is that almost all of the pryroclastic flow/surges travelled over the lake's waterline table and they only lost most of the lithics.
From top to base the pyroclastic flow deposits have plenty charcoal and they gave ^{14}C ages between 600 and 1,100 years BP. The first deep paleosoil located at 4,5 m from the top, developed from a 85 cm thick pyroclastic flow deposit and it has about 3,700 BP.
The eastern side of Osorno volcano can be completely observed, also some parasitic flank scoria cones and many "aa" basaltic lava flows.



Isla Margarita Osorno volcano pyroclastic deposits. Several pumiceous and scoriaceous pyroclastic flows/surges and fall deposits can be observed and the remarkable paleosoil horizon may represent a time break period of low or none volcanic activity.

3. PETROHUÉ RIVER FALLS
(Todos Los Santos lake natural drainage) 714,40 / 5439,65 (135 m)

The Petrohué river has eroded recent basaltic lava flows from Osorno volcano causing ravines, gorges and several extraordinary waterfalls (Photo 5). The eastern hills are basement granitic rocks and the Petrohué river valley is supposed to run along a NE – SW fault, a weak structure utilized by the Pleistocene glaciers to carve the rectilinear basin. The SE Osorno volcano geomorphology can be appreciated.

The Petrohué river action has eroded recent basaltic lava flows from Osorno volcano causing ravines, gorges and several extraordinary waterfalls. The whole volcano morphology can be observed from this site.

4. ROAD FROM ENSENADA TO PETROHUÉ
(near Petrohué river) 711,88 / 5436,93 (112m)

Debris flows from Osorno volcano slopes, caused by the winter snow melting or by heavy rainfalls frequently cut the road from Ensenada to Petrohué. Their composition, textures and structure are similar but in a very small scale, to eruption triggered lahars in the Southern Andes volcanoes.

5. OSORNO VOLCANO SKI CENTRE
(TESKY CLUB) 707,45 / 5444, 50 (1,180 m)

The road crosses old and recent (historic undetermined) basaltic lava flows erupted from the scoria cones cluster located on the SW slope of Osorno volcano (Photo 6). The older ones are covered by dense forest and tall trees, therefore, as vegetation is younger and smaller, the lava flows are younger. Higher along the road, the 1835 eruption scoria cones and related "aa" basaltic lava flows can be observed. Near the Ski Centre the Seismic Telemetric Station of Osorno volcano sends the signals to the Puerto Varas Sernageomin Technical Office. From this site, there is a magnificent view of the whole Calbuco volcano structure, geologic units and geomorphology.

The road toward the Ski Centre crosses old and recent (historic undetermined) basaltic lava flows erupted from the scoria cones cluster located on the SW slope of Osorno volcano (at the foreground).

6. LAS CASCADAS VILLAGE (road along the Llanquihue lake east coast) 698,50 / 5449, 70 (55 m)

The road crosses the 1835 basaltic lava flows erupted from the youngest scoria cones located on the SW slope of Osorno volcano. Once more, according to the vegetation coverage, the lava flows have different ages.

The Las Cascadas village was built on top of one of the laharic deposits triggered within the 1835 eruption. The debris flows form a fan delta into the Llanquihue lake and the settlement occupies the whole fan extension. The Las Cascadas village has mostly vacation cabins, but during the last 20 years has grown and now it has an important number of permanent inhabitants exposed to eventual future lahars. Large boulders and blocks can be seen all over the place. The local authorities are quite worried about this situation and lots of efforts have been done to prepare the population in case of future eruptions and emergency plans have been set up.

7. ROAD TO ENSENADA (OSORNO 1 UNIT) 702,35 / 5443, 40 (70 m)

A road cut shows an outcrop of prismatic basaltic columns disposed like a bouquet that belong to the pre-last glaciation Osorno 1 unit. The Osorno ancestral edifice dammed the Todos Los Santos valley some 200.000 years ago forming a primitive lake in the same place. The Pleistocene last glaciation (Llanquihue drift) eroded deeply the SE part of the stratovolcano and the huge glacier lobe filled the whole current Llanquihue lake basin until 14.000 years when the final ice retreat started.