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Nature, origin, transport and deposition of andosol parent material in south-central Chile (36–42°S)

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Abstract

The andosols of south-central Chile (36–42°S) are developed on yellow-brown loams that cover the region with a thickness of several meters. In the literature, several hypotheses concerning the nature, origin, mode of transport and deposition of the andosol parent material have been advanced but no general agreement has been found. In this paper, we test these hypotheses by analyzing new representative outcrops located around Icalma (38°50′S) and Puyehue (40°40′S) lakes by a pluri-methodological approach. Our data demonstrate that the andosol parent material has the typical mineralogical and geochemical signature of the regional volcanism and that these deposits are post-glacial in age. The grain size of the deposits and the morphology of the coarse grains evidence that most of these particles haven't been re-transported by wind but are direct volcanic ash falls deposited throughout the Late Glacial and Holocene. Because of the prevailing westerly winds, most of these volcanic ashes have been transported to the East. Following the deposition of the volcanic particles, weathering and pedogenetic processes have transformed part of the volcanic glasses and plagioclases into allophane and have wiped out the original layering. This work demonstrates that most of the andosols that occur in the Andes and in the eastern part of the Intermediate Depression of south-central Chile are developed on volcanic ashes directly deposited by successive volcanic eruptions throughout the Late Glacial and Holocene.

Keywords: Andosol; Volcanic ashes; Volcanic glasses; Allophane; Chile

1. Introduction

Volcanic soils cover over 50% of south-central Chile (36–42°S). Although regional variations exist, these soils are mainly developed on yellow-brown soft deposits covering the area with a thickness of several meters (Laugenie, 1982). These deposits cover the Andes and the eastern part of the Intermediate Depression and constitute a nearly continuous formation between 36° and 47°S (Besoain, 1985). This distribution is imposed by the location of the regional active volcanoes at the western side of the southern Andes, which is part of the Southern Volcanic Zone of Chile (SVZ, 33–46°S, Gerlach et al., 1988). The soils developed on these soft deposits are locally called Trumaos, *i.e.* the Araucanian name for andosols signifying "dust accumulation" (Langhor, 1971).

The nature, origin and mode of transport and deposition of the Trumaos parent material have often been discussed in the literature but up to today no agreement has been reached (for a review, see Besoain, 1985; Moreno and Valera, 1985; Veit, 1994). It seems that each author finds his own explanation depending on the study location. For south-central Chile, three main hypotheses have been proposed: (1) direct volcanic ash falls (Wright, 1965 In: Besoain, 1985); (2) loess-like deposits (Laugenie et al., 1975) or (3) glacial transport with ablation moraine-like deposition (Langhor, 1974). Authors sometimes propose a mixed depositional pattern (Besoain, 1985). Locally, pyroclastic flows, lahar deposits and fluvial sediments might have participated to the accumulation of particles on which the andosols further developed (Wright, 1965 In: Besoain, 1985). The main objective of this paper is to analyze new representative outcrops located around Icalma and Puyehue

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lakes by a pluri-methodological approach, in order to test the diverse hypotheses about the nature, origin, transport and deposition of the andosol parent material in south-central Chile.

2. Geological setting

Icalma lake (71°20′W, 38°50′S) is small water body (11.65 km^2) located in the Andes at an elevation of 1140 m (Fig. 1). Its watershed covers 147 km^2 and is flanked westward by three active volcanoes: Lonquimay, Llaima and Sollipulli. On the other hand, Puyehue lake (72°20′W, 40°40′S) is a larger lake located at the foothill of the Andes. Its watershed reaches 1267 km^2 and is characterized by the occurrence of Antillanca and Puyehue–Cordón de Caulle volcanic complexes eastward, with the Osorno volcano being nearby to the south (~50 km). The whole region is dominated by westerly winds coming from the Pacific Ocean. Combined to the rough topography of the Andes, these winds are responsible for high precipitation in the area, with an annual rainfall reaching 2000–3000 mm/year around Icalma (Mardones et al., 1993) and 2000–5000 mm/year at Puyehue (Muñoz Schick, 1980). Occasionally, a Foehn type easterly wind locally called "Puelche" blows down from the Andes (Aravena et al., 1993).

The watersheds of both lakes are covered by unconsolidated and weakly stratified yellow-brown loams, several meters thick. As in many locations of the Intermediate Depression and the Andes in south-central Chile, andosols – *i.e.* soils developed on volcanic ashes – are developed on these deposits (Fig. 2). In many locations and particularly at Icalma and Puyehue, these deposits sit on top of glacial or fluvio-glacial sediments.

In the Icalma region, the andosol parent material reaches a maximum thickness of 6 m and bury all the underlying Pleistocene deposits, whether they are glacial, fluvial or lacustrine (Mardones et al., 1993). In addition, the deposits contain two distinct pumice layers that have been attributed to the Holocene explosive eruptions of Sollipulli (Naranjo et al., 1993) and Llaima (Naranjo and Moreno, 1991) volcanoes, respectively dated at 2900 yr BP (Naranjo et al., 1993; De Vleeschouwer et al., 2005) and 9000 yr BP (9030 yr BP, De Vleeschouwer et al., 2005 or 8830 yr BP, Naranjo and Moreno, 1991). Westward, *i.e.* closer from Llaima and Sollipulli

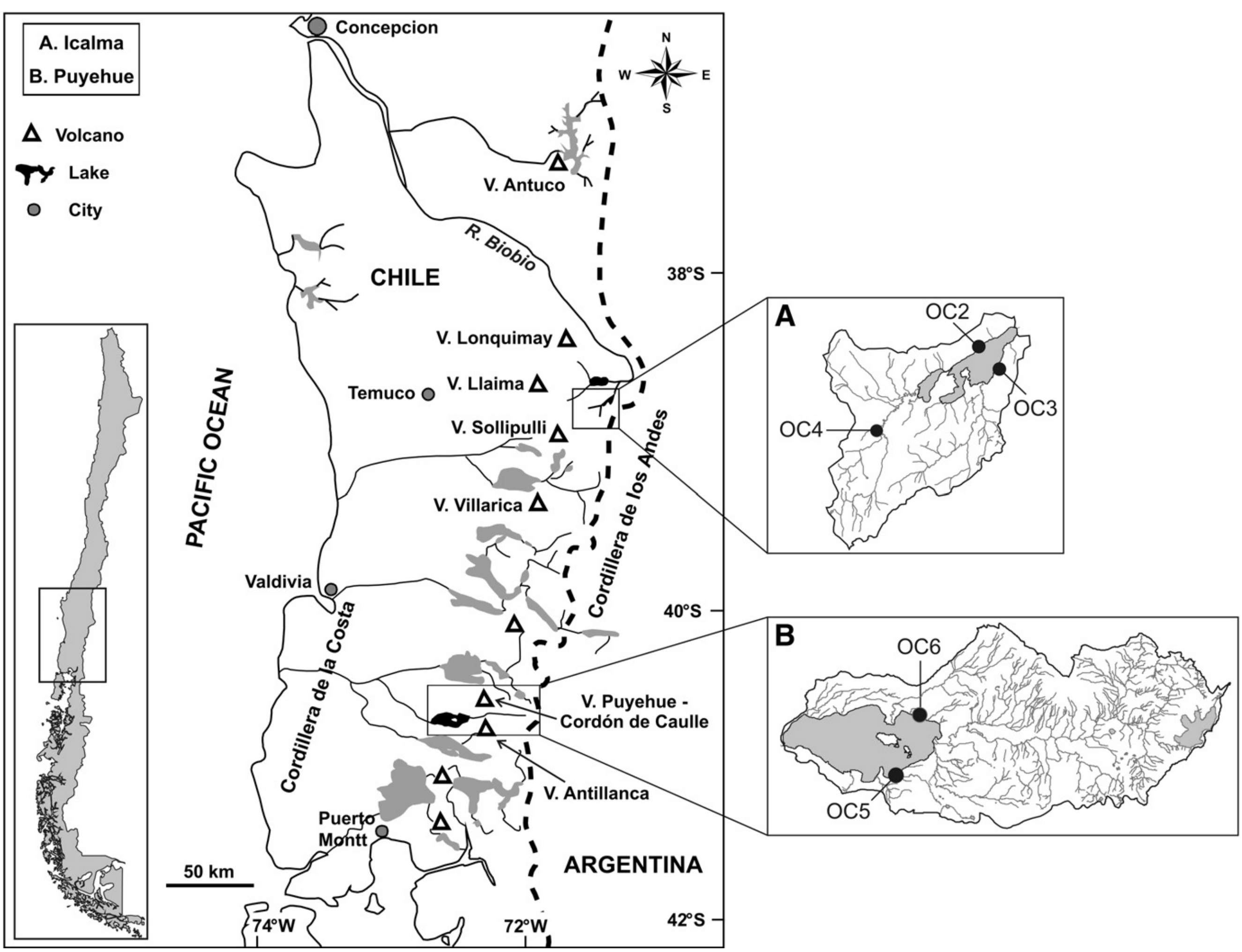

Fig. 1. Study area and sampling sites.

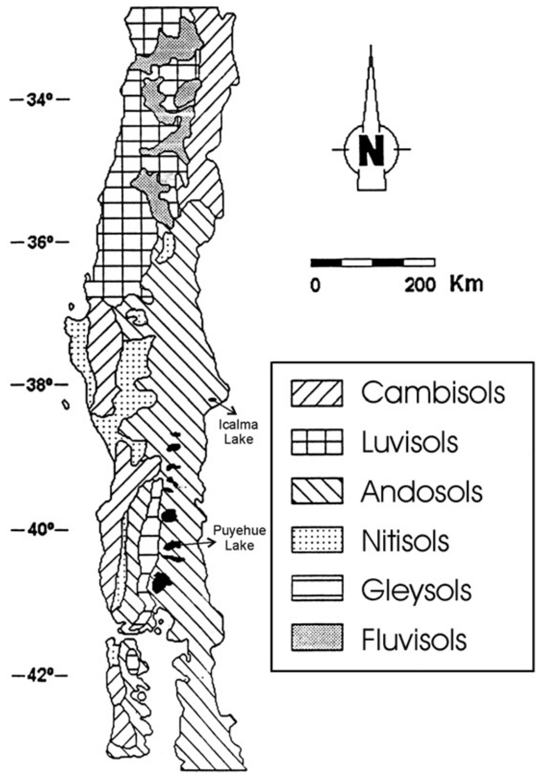

Fig. 2. Simplified pedological map of south-central Chile (FAO–UNESCO, 1971 in: Aravena et al., 1993).

volcanoes, additional intercalated and well distinct tephra layers occur.

Around Puyehue lake, the yellow-brown soft deposits are thinner (maximum 4 m) with no intercalated distinct tephra layer. They overlay fluvio-glacial and glacial deposits. Further to the East the loam deposits are progressively replaced by coarse scoriae particles and volcanic rocks, which is due to the proximity of the Puyehue–Cordón de Caulle and Antillanca volcanic complexes. On the Argentinan side of the Andes, the yellow-brown soft deposits re-appear, with the number of distinct tephra layers decreasing eastward.

3. Materials and methods

3.1. Sampling

The soft deposits covering the catchments of Icalma and Puyehue lakes have been studied in detail during two fieldwork campaigns in summer 2001–2002 and in December 2003. As a result of a preliminary geological investigation of the area, three representative sections were selected for sampling around Icalma and two around Puyehue (Table 1, Fig. 1). After sedimentological description and color characterization with a Munsell color chart, the sections were sampled for mineralogical, geochemical and grain-size analysis. Moreover, OC2 outcrop has been continuously sampled and impregnated for observation in thin section following Boës and Fagel (2005). In this paper, two representative sections are described in detail: OC2 and OC5.

3.2. Grain size

Grain-size measurements were performed on organic matter-free samples using a laser diffraction particle analyzer Malvern Mastersizer 2000. Organic matter was removed using H_2O_2 10%. The samples were introduced into a 100 ml deionized water tank free of additive dispersant, split with a 2000 rpm stirrer and crumbled with ultrasonic waves. The sample quantity was adjusted in order to obtain a laser beam obscuration between 10 and 20%. The grain-size parameters are averaged over 10,000 scans. Although the grain-size analyzer is theoretically capable of measuring particles within a 0.02–2000 µm size range, samples containing particles coarser than 420 µm were systematically analyzed by a combination of laser diffraction and sieving methods. The distribution parameters have been calculated following Folk and Ward (1957). In order to assess the size of the coarsest grains, the D99 parameter, *i.e.* the equivalent diameter for which the distribution sum has the value of 99%, has been calculated.

3.3. Mineralogy

Bulk and clay mineralogy were achieved by X-ray diffraction (XRD) on a Bruker D8-Advance diffractometer with CuKα radiations. Bulk samples were powdered to 100 µm using an agate mortar. An aliquot was separated and mounted as unoriented powder by the back-side method (Brindley and Brown, 1980). The powder was submitted to XRD between 2° and 45° 2θ and the data were analyzed in a semi-quantitative way following Cook et al. (1975).

Grain-size separation of the clay fraction (<2 µm) was performed by sedimentation in glass vials according to the Stokes law (Moore and Reynolds, 1989). Because the clay fraction obtained after 50 min of sedimentation (<2 µm) did not contain enough material for X-ray diffraction, the clay mineralogy was analyzed on the fraction obtained after 20 min of sedimentation (<4 µm). Oriented mounts of the clay-size fraction were realized by the "glass-slide method" (Moore and Reynolds, 1989) and subsequently scanned on the diffractometer. Slides revealing the presence of crystallized clays after air drying (*N*) were scanned after two additional treatments: ethylene-glycol solvation during 24 h (EG) and heating at 500 °C during 4 h (500). As the mineralogy of the clay-size fraction is dominated by amorphous particles, only a qualitative estimation of the amount of crystallized clay minerals is given. It is based on the intensity of the highest clay diffraction peak on the natural (*N*) diffractogram.

3.4. Geochemistry

The major elements of bulk samples from OC3 (5.00 m), OC5 (0.00, 0.75, 1.50 and 2.25 m) and OC6 (−2.00, 1.00 and 3.00 m) sections were determined by X-ray fluorescence (XRF) on fused Li-borate glass beads. Analyses were performed on a ARL 9400 spectrometer. The trace elements of the OC5 (1.50 m) sample were analyzed by ICP-MS. In addition, the chemical composition of individual grains was

Table 1
Location, size and sampling intervals of the 5 investigated outcrops

	Outcrop no.	Latitude	Longitude	Thickness (m)	Sampling step (cm)	Number of samples
Icalma	OC2	S38°47.07″	W71°17.06″	4.90	50–10	10–50
	OC3	S38°47.95″	W71°16.01″	6.15	50	10
	OC4	S38°50.23″	W71°22.37″	4.60	50	8
Puyehue	OC5	S40°42.97″	W72°24.31″	2.70	25–10	11–28
	OC6	S40°38.11″	W72°22.39″	4.30	50	9

See Fig. 1 for map location. The geographic coordinates are referenced to the WGS84 datum. The thickness of the andosol parent material does not take into account the underlying glacial or fluvio-glacial sediments. For OC2 and OC5 outcrops, the two sampling steps represent samples collected for mineralogical and grain-size analysis, respectively.

determined using a Cameca Camebax SX 50 microprobe at Louvain-La-Neuve University, Belgium (Table 2). Finally, the chemical test of Fieldes and Perrot (1966) was applied to a series of samples. This classical test for andosols is based on the propriety of allophanes to produce an alkaline reaction with sodium fluorure (Quantin, 1972). It consists in controlling the variation of pH after mixing 1 g of sediment with 50 ml of NaF 1 N solution. In the presence of a high allophane content, the solution reaches a basic pH (10–11) after 1 h.

3.5. Infrared spectrometry

Infrared spectra of the clay-size fraction of OC3 (5.00 m) and OC5 (1.50 m) samples were recorded with a Nicolet Nexus spectrometer in the 400–4000 cm^{-1} range. Two milligrams of sediment were mixed with KBr in order to obtain a 150 mg pellet for analysis.

4. Results

4.1. Description

4.1.1. Icalma

At Icalma OC2 site, the andosol parent material sits on top of a coarse unit (−2 to 0 m, Fig. 3A) containing pebbles and sand grains similar in nature to the regional bedrock. The pebbles are composed of granite (Galletue Plutonic Group) and blue-green sedimentary rocks (Icalma Member of Biobio Formation *sensu* Suárez and Emparan, 1997). Between 0 and 1.30 m, gravel, sand and silt occur with a fining-upward texture. Above 1.30 m, the deposits are composed of organic matter-rich yellow-brown loams with two intercalated pumice layers: the Llaima pumice dated at 9000 yr BP (1.60 to 1.95 m) and the Alpehue pumice emitted by the Sollipuli volcano in 2900 yr BP (3.65 to 4.00 m) (De Vleeschouwer et al., 2005).

Table 2
Microprobe analyses of plagioclases separated from the sediments of OC3 (5.00 m) and OC5 (1.50 m) samples

SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Total	An	Ab	Or
Plagioclases OC3 5.00 m											
46.6	0.00	32.0	0.67	0.11	17.9	1.77	0.00	99.13	84.8	15.2	0.0
45.1	0.00	33.0	0.52	0.11	19.3	1.27	0.05	99.31	89.1	10.6	0.3
49.0	0.07	30.5	0.63	0.10	16.2	2.86	0.00	99.34	75.8	24.2	0.0
55.3	0.00	26.5	0.56	0.09	10.8	5.64	0.12	98.92	50.9	48.4	0.7
46.1	0.00	32.8	0.48	0.10	18.5	1.57	0.00	99.48	86.7	13.3	0.0
55.7	0.00	26.6	0.38	0.06	10.6	5.70	0.12	99.19	50.3	49.0	0.7
47.9	0.00	31.6	0.65	0.13	17.4	2.23	0.04	99.93	81.0	18.8	0.2
51.2	0.09	29.1	0.55	0.17	14.4	3.69	0.08	99.33	68.1	31.4	0.5
49.4	0.00	30.2	0.71	0.08	16.0	3.05	0.06	99.50	74.1	25.6	0.3
45.9	0.00	32.9	0.51	0.08	18.9	1.34	0.00	99.59	88.6	11.4	0.0
45.1	0.00	33.5	0.48	0.06	19.7	1.05	0.00	99.88	91.2	8.8	0.0
47.6	0.00	31.2	0.68	0.13	17.1	2.28	0.00	99.04	80.6	19.4	0.0
44.9	0.00	33.2	0.48	0.08	19.2	1.22	0.00	99.14	89.7	10.3	0.0
Plagioclases OC5 1.50 m											
56.0	0.00	26.5	0.33	0.03	10.6	5.71	0.20	99.35	49.9	49.0	1.1
59.9	0.20	21.7	1.91	0.30	7.86	5.40	0.86	98.03	42.1	52.4	5.5
52.4	0.00	28.7	0.53	0.18	13.7	4.09	0.19	99.73	64.2	34.7	1.1
56.0	0.00	26.8	0.19	0.03	10.6	5.80	0.10	99.52	49.8	49.6	0.6
46.6	0.00	32.4	0.55	0.08	18.2	1.81	0.00	99.64	84.8	15.2	0.0
52.7	0.08	28.3	0.71	0.21	13.9	3.95	0.15	99.97	65.4	33.8	0.8
51.6	0.06	28.9	0.89	0.16	14.1	3.76	0.16	99.66	66.9	32.2	0.9
55.5	0.00	27.0	0.32	0.00	11.1	5.51	0.16	99.58	52.3	46.8	0.9
55.6	0.00	27.3	0.25	0.00	10.9	5.49	0.16	99.68	52.0	47.1	0.9

An, Ab and Or represent the Anorthite, Albite and Orthose content of each sample, respectively.

Under both pumice layers, outcrops show brunified buried soils. Apart from the pumice layers and the three brunified horizons (Fig. 3A), no stratification was observed. Microscopical inspection of thin sections revealed no lamination (Fig. 4). However, we observed a high porosity, a very poor sorting of particles and we noticed the abundance of highly coated grains. This clayey coating has a post-depositional pedogenetic origin and is probably due to the high lixiviation of chemical elements (chitonic structure, *sensu* Stoops and Jongerius, 1975). It is responsible for the yellow-brown color of the grains. Moreover, the observation of thin sections revealed a succession of 5–10 cm thick organic-rich horizons. This indicates that the physical processes controlling the deposition and reworking of particles were not constantly active, therefore allowing enough time for a vegetal cover to develop.

4.1.2. Puyehue

From −10 to 0 m, the Puyehue OC5 outcrop shows fluvio-glacial deposits composed of coarse granitic and volcanic particles with a grain size ranging from boulder (max 40 cm) to sand (Figs. 3 and 5). The andosol-bearing loams occur between 0 and 2.70 m and overlay the fluvio-glacial deposits by a relatively sharp contact (Figs. 3 and 5). No stratification was observed and the deposits contain no distinct tephra layer. Pedogenetic processes are responsible for the brunification of the upper part of the outcrop (30 cm).

4.2. Grain size

In volcanic soils, the original grain-size distributions can be altered by weathering and illuviation processes, transforming weatherable minerals into very fine-grained amorphous silicates (Buurman et al., 2004). Moreover, the deposits contain 15–20% of organic matter, which has a significant effect on the bulk grain-size distribution of the samples. To better assess the original grain size of the deposits, the organic matter was dissolved and the results are considered as a minimum of the original grain size.

4.2.1. Icalma

The grain-size data of OC2 section show four distinct units (Fig. 3): a) a fining-upward unit at the base of the outcrop, b) the two coarse pumice layers and c) a constant grain size for the andosol parent material (loam to silt loam). Due to the presence of coarse non-weathered particles, the upper two samples are coarser. The frequency curves characterizing the yellow-brown loams are bimodal (modes at 15–30 μm and 300–450 μm; Fig. 3). Above the pumice layers, the yellow loam deposits contain a few pumice fragments and are therefore coarser. The D99 values of the andosol parent material without pumice fragments vary between 506 and 860 μm.

4.2.2. Puyehue

The grain size of OC5 samples does not significantly vary with depth and is typical for silt loams (Fig. 3B). The base and the top of the outcrop are coarser, which is due to the presence of coarse fluvio-glacial deposits and coarse non-weathered volcanic particles, respectively. The grain-size distribution curves are bimodal, with the coarse fraction always being less abundant (<15% in volume). The D99 values vary between 87 and 783 μm.

4.3. Mineralogy

4.3.1. Icalma

The bulk mineralogical composition of the coarse unit at the base of OC2 outcrop (0–1.3 m) clearly differs from the overlying deposits (Fig. 3). It is principally composed of plagioclase, pyroxene, amphibole, chlorite and quartz, mainly originating from the bedrock. The samples do not contain amorphous particles. Above 1.3 m, the typical yellow loam deposits are characterized by a constant mineralogical composition, largely dominated by plagioclase and amorphous particles (volcanic glasses, organic matter and non-crystalline clay minerals). Pyroxene and quartz are secondary minerals. Smear slides reveal that the amorphous particles are mainly composed of allophane, which is identified by its typical microscopical characteristics: yellow-brown in color and isotropic and amorphous under polarizing microscope. In smear slides, the coarse grains (>200 μm) of OC2 samples have been identified as typical volcanic particles: scoriae (>60%), pumices, plagioclase and traces of pyroxene and olivine.

4.3.2. Puyehue

The yellow-brown loam deposits of OC5 outcrop are mineralogically similar to OC2 outcrop. They are dominated by amorphous particles, plagioclase and pyroxene. The coarser than 200 μm fraction is composed of typical volcanic particles: scoriae, plagioclase, volcanic glasses, pyroxene, olivine and amphibole. The sample collected at 0.00 m, *i.e.* at the limit with the underlying fluvio-glacial deposits, is relatively poor in amorphous particles.

4.3.3. Clay minerals

The andosol parent material of both sections does not contain crystalline clay minerals. The only samples where non-amorphous clay minerals have been detected are samples from the base of Icalma OC2 outcrop (low amounts of kaolinite, illite, chlorite or vermiculite have been identified). The clay-size particles of the other samples are only composed of allophane. The allophanic nature of the amorphous clay minerals is confirmed by the infrared (IR) spectrometry analyses. The IR spectra display two broad absorption bands at 3450 and 1000 cm^{-1} and a weaker band at 1630 cm^{-1}, which is typical for allophane (Snetsinger, 1967; Henmi et al., 1981; Wilson, 1994; Gustafsson et al., 1999). The broad band near 1000 cm^{-1} (and its harmonic at 550 cm^{-1}) is due to Al–O and Si–O stretching (Snetsinger, 1967; Gustafsson et al., 1999), while the two others are due to absorbed molecular water (Snetsinger, 1967; Kawano and Tomita, 1992; Wilson, 1994). In addition, the low amount of <2 μm particles is a typical characteristic for andosols. It is due to the colloidal behaviour of allophanes (Quantin, 1972).

4.4. Geochemistry

4.4.1. Icalma

The bulk chemical analysis of OC3 (5.00 m) sample reveals a basaltic composition (SiO_2: 51.8%, TAS: 3.5%).

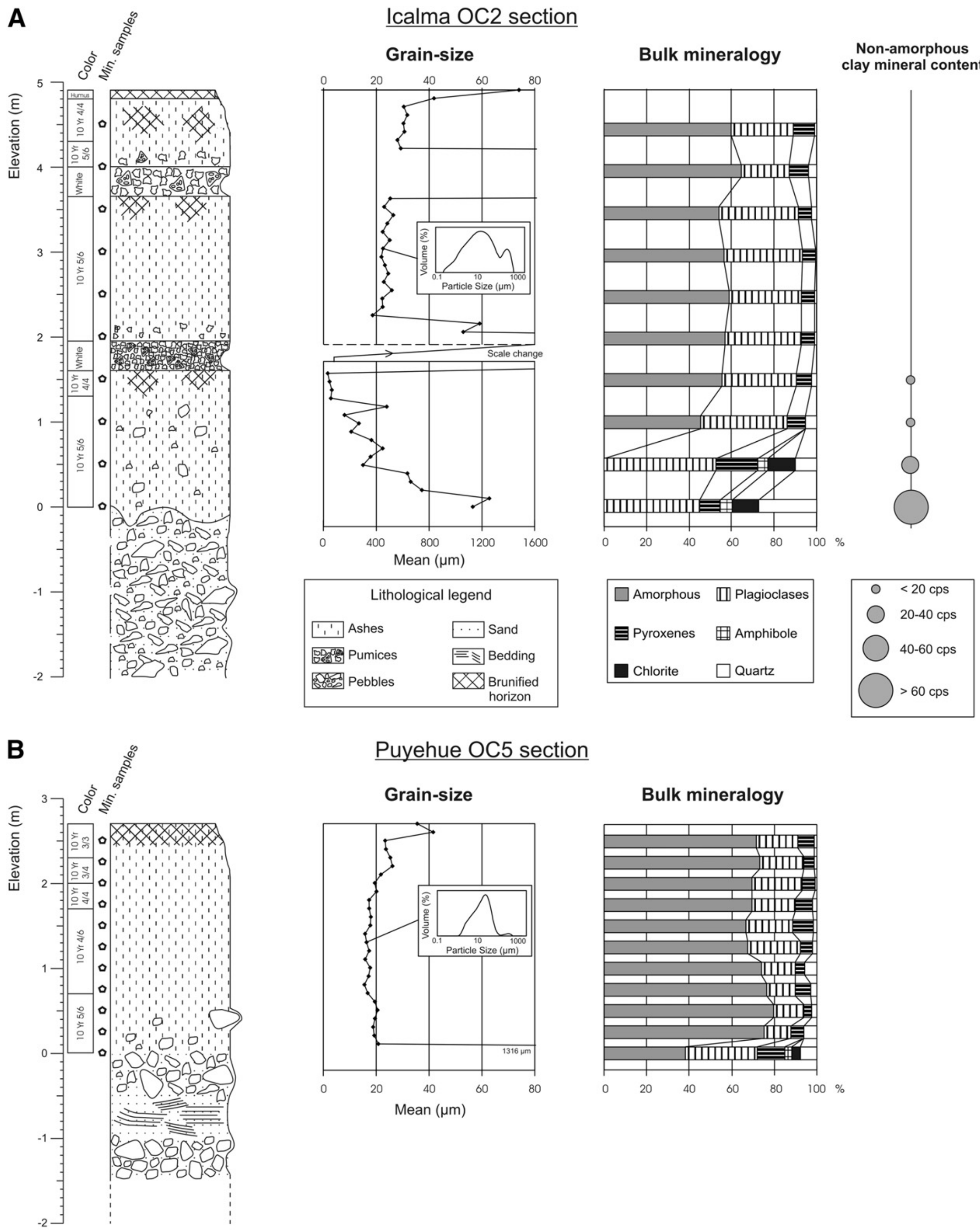

Fig. 3. Mineralogical composition and grain size of samples collected in OC2 and OC5 outcrops (see Fig. 1 for location). The grain-size distribution has been measured on organic matter-free samples and the mean grain size has been calculated following Folk and Ward (1957). The minerals detected in the bulk samples by X-ray diffraction were semi-quantified using the intensity of the principal diffraction peak of each mineral corrected by a multiplication factor from Cook et al. (1975) (pyroxene: 5; chlorite: 4.95; plagioclase: 2.8, amphibole: 2.5 and quartz: 1). For the amorphous material, we used a correction factor of 75, which has been calculated from diffraction results on mixtures of known quantities of amorphous material and quartz. It applies to the maximum of the broad diffraction band at 3.7 Å.

4.4.2. Puyehue

The bulk chemical composition of the samples from OC5 and OC6 outcrops is in the range of basalts to andesites (SiO_2: 49.2–63.5%, TAS: 1.1–3.1%), with the upper samples being always more silicic.

Due to their abundance and to the petrogenetic significance of their geochemical composition, the plagioclases have been extracted from the host sediment and analyzed by microprobe for major elements (Table 2). Their composition varies from anorthite (An 90–100) to andesine (An 30–50) (Fig. 6). The grains from Icalma OC3 outcrop (An 50–91, Or 0–1) tend to be enriched in anorthite (An) compared to grains from OC5 outcrop (An 42–85, Or 0–6). Analysis of plagioclases from the Llaima and Alpehue (Sollipulli) pumice layers show typical andesine plagioclases: An 28–40, Or 0–1 and An 32–47, Or 1–3 respectively (De Vleeschouwer, 2002; De Vleeschouwer et al., 2005) (Fig. 6).

For the OC5 (1.50 m) sample, some volcanic glasses (SiO_2 75–73%, TAS: 4.5–5.9%) and olivine (Fo 75–83) were also analyzed.

The trace elements of the OC5 (1.50 m) sample are represented in a chrondrite-normalized spidergram (Fig. 7).

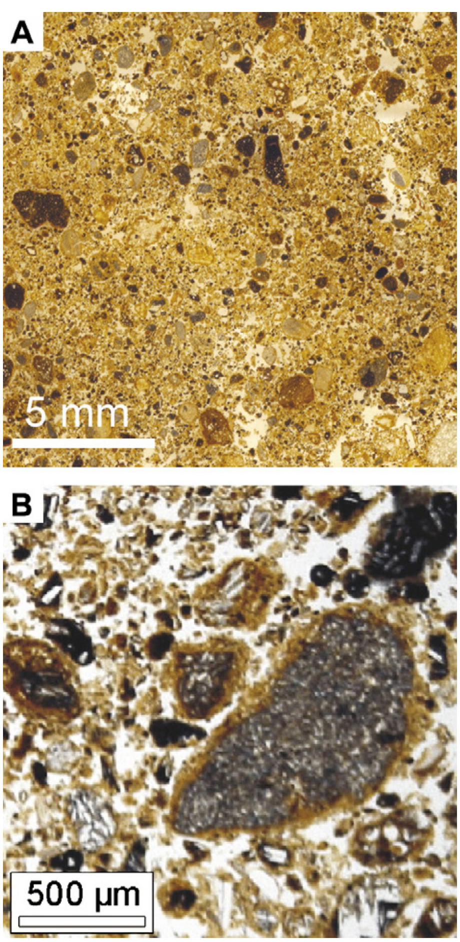

Fig. 4. Microscope images of some thin sections of OC2 outcrop sediments. Both images show coated and very poorly sorted grains. A) Bulk sediment (OC2 3.20 m); B) detail of the grain coating (OC2 3.05 m). (For color figures the reader is referred to the web version of this article.)

Fig. 5. Picture of OC5 outcrop located in the watershed of Puyehue lake. The picture shows the andosol parent material overlying fluvio-glacial sediments. The volcanic deposits are 2.70 m thick. (For color figures the reader is referred to the web version of this article.)

For comparison, the trace elementary composition of volcanic rocks of the Southern Volcanic Zone (SVZ) and of the Puyehue–Cordon de Caulle volcanic complex has also been plotted. Except for Ba, K and Sr, the composition of the OC5 (1.50 m) sample is in perfect agreement with the typical volcanic signature of the SVZ (33–46°S).

The test of Fieldes and Perrot (1966) shows a pH rising to 10.5 after 30 min and reaching 11.5 after 2 h (samples OC3 5.00 m and OC5 1.50 m). This confirms the high allophane content of the samples.

In addition, we also analyzed the density and the pH of the same samples. The pH values are between 6.4 and 6.5 and the bulk density of the samples is 0.85, which are both typical for andosols (Quantin, 1972; Besoain, 1985).

4.5. Scanning electron microscope

Scanning electron microscope (SEM) observations were performed on different grain-size fractions of samples from OC3 and OC5 outcrops (from bulk sediment to the clay-size fraction). The observations reveal that most of the grains are composed of cohesive agglomerates of particles (Fig. 8). Grains are neither rounded nor dull (Fig. 8A,B) and the samples contain fresh volcanic glass shards (Fig. 8C).

5. Discussion

5.1. Age of the andosol parent material

Around Icalma and Puyehue, the yellow-brown loam deposits on which the andosols developed overlay glacial and fluvio-glacial deposits. These deposits occurring at the base of the outcrops are believed to date from the last glacial period (Llanquihue phase *sensu* Mercer, 1976; Porter, 1981) and the last deglaciation (Laugenie, 1982; Mardones et al., 1993). Therefore, the unconsolidated deposits on which the andosols developed are post-glacial in age.

Near Icalma, the andosol parent material does not directly overlay the glacial sediments. Both units are separated by an

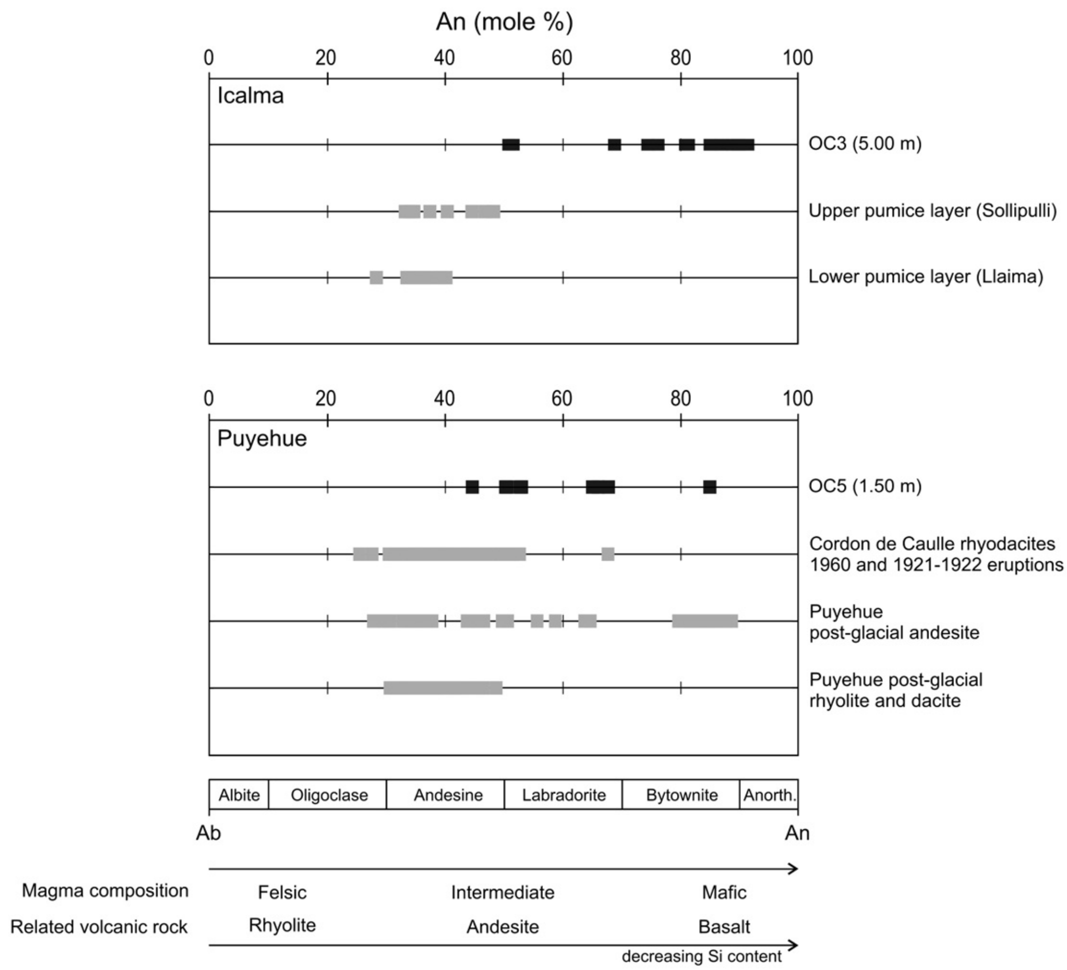

Fig. 6. Plagioclase composition of samples from Icalma (OC3 5.00 m) and Puyehue (OC5 1.50 m) outcrops plotted in an Ab–An binary diagram. The An content is calculated as An/(An+Ab). For comparison, results obtained on plagioclases from the Llaima and Sollipulli pumice layers are presented (De Vleeschouwer, 2002). The data from the Puyehue–Cordon de Caulle volcanic complex are from Gerlach et al. (1988).

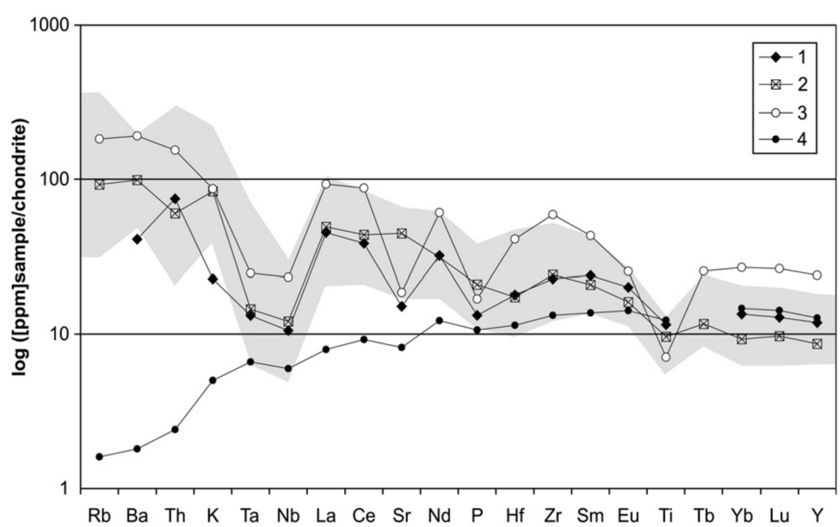

Fig. 7. Trace elements of the OC5 (1.50 m) sample plotted in a chondrite-normalized spidergram. 1) OC5 (1.50 m) sample; 2) mean of the Southern Volcanic Zone between 33 and 46°S (Georoc website); 3) mean of the post-glacial volcanic rocks from the Puyehue–Cordón de Caulle volcano (Gerlach et al., 1988); 4) N-Morb (Sun and McDonough, 1989). The gray shaded area corresponds to 90% of the reported values for the Southern Volcanic Zone between 33 and 46°S (from the Georoc website: http://georoc.mpch-mainz.gwdg.de/georoc/). Data corresponding to xenolithic rocks were removed from the database.

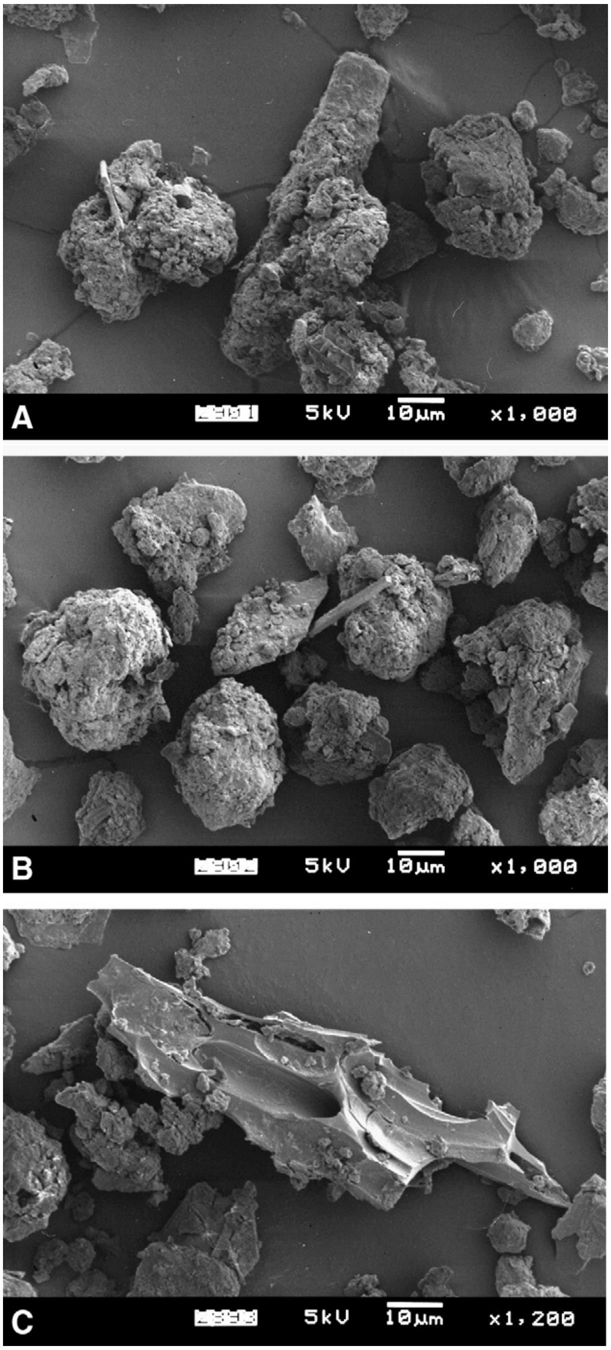

Fig. 8. Scanning electron microscope (SEM) images of particles from OC3 (5.00 m) sample. (A, B) Coarse grains with a typical rough morphology; (C) glass shard.

intermediate fining-upward deposit, composed by a mixture of yellowish loam particles and rock fragments similar in nature to the geological bedrock (*e.g.*, OC2 outcrop 0.00–1.30 m). Because of the non-volcanic nature of the rock fragments this deposit cannot be confused with the Curacautin ignimbrite, which is composed of ashes and basaltic scoriae (Naranjo and Moreno, 1991). This layer probably originates from solifluction movements, which are frequent in periglacial environments. Therefore, it probably dates from the last deglaciation.

Veit (1994) assumes that the andosol parent material accumulated during the Late Glacial and Early Holocene, which would have left enough time for soils to develop during the rest of the Holocene. However, around Icalma, the two pumice layers intercalated in the yellowish soft deposits, and especially the upper pumice layer dated at 2900 BP (Naranjo et al., 1993; De Vleeschouwer et al., 2005), indicate that these sediments accumulated during most of the Holocene.

5.2. Allophane formation

The investigated soils bear all the typical characteristics for andosols (amorphous bulk and clay minerals, slightly acid pH, low density…) (Quantin, 1972; Besoain, 1985). As evidenced by microscopic observations (SEM and smear slides), the amorphous particles detected in the bulk samples are mainly non-crystalline clay minerals and volcanic glasses. Similarly, the clay-size fraction is dominated by non-crystalline minerals and traces of plagioclase. The IR spectrometry analyses have proved that these non-crystalline clay-size particles are allophane, a typical secondary product of volcanic ashes under humid, temperate or tropical climatic conditions (Quantin, 1972; Righi and Meunier, 1995). Although allophane can also derive from the weathering of plagioclase (Aomine and Wada, 1962; Besoain, 1963; Snetsinger, 1967), it is mainly produced by hydrolysis of volcanic glasses (Henmi and Wada, 1976; Laugenie, 1982). In the investigated samples, halloysite and imogolite, which are clay minerals frequently observed in association to allophane in andosols, have never been detected. However, it is known that halloysite forms by neoformation of allophane (Laugenie, 1982; Besoain et al., 1992a) in a minimum time range of 8000 to 9000 years (Aomine and Miyauchi, 1963) and that imogolite is a frequent intermediate product appearing during the crystallization of allophane into halloysite (Besoain, 1968). However, due to the humid Mediterranean climate conditions of south-central Chile, allophane can regionally remain stable for up to 18,000 to 22,000 years (Besoain, 1985). Because the transformation of allophane into halloysite requires 18,000 to 22,000 years, its absence in our samples indicates that the investigated deposits are younger than the Last Glacial Maximum, which is in agreement with the stratigraphic evidence. This argument is supported by the detection of halloysite and imogolite in older andosol samples from south-central Chile (Besoain, 1968; Laugenie et al., 1975).

5.3. Volcanic origin

Due to their relative young age, the investigated andosols still contain a lot of primary minerals and non-altered volcanic glasses. Their mineralogical and geochemical composition clearly evidences the volcanic origin of their parent material:

(1) The bulk mineralogy of the outcrops is dominated by plagioclase, amorphous particles (original volcanic glasses and secondary allophane products) and pyroxene (Fig. 3). These minerals are typical for the regional volcanism (Laugenie, 1982). Similar conclusions were obtained by Laugenie et al. (1975) when studying the heavy minerals of regional andosols.

(2) The trace elemental composition of the representative OC5 (1.50 m) sample shows a typical SVZ signature (Fig. 7). The only elements deviating from the SVZ signature are Ba, K and Sr. This depletion is due to the high mobility of Ba, K and Sr during weathering processes (Martínez Cortizas et al., 2003).
(3) The nature of the plagioclases in OC3 and OC5 outcrops is characteristic for plagioclases associated to basaltic and andesitic magma, which are typical for the regional volcanoes of the SVZ (Fig. 6).

However, the nature of the plagioclases from Icalma OC3 outcrop (An 50–91) differs from the plagioclases associated to the Llaima and Sollipulli pumice layers (An 28–40 and An 32–47 respectively; De Vleeschouwer, 2002) (Fig. 6). This difference is due to the relation between the plagioclase composition and the magma chemistry, itself characteristic for the type of eruption (Fig. 6). Because of the dacitic (Si-rich) composition of the magma at the origin of the Llaima and Sollipulli pumice layers (De Vleeschouwer et al., 2005), the plagioclases associated to these pumices are enriched in Ab (andesine–oligoclase). However, the magma generally emitted by Llaima, Sollipulli and Lonquimay volcanoes has a basaltic to andesitic composition (Naranjo and Moreno, 1991; Besoain et al., 1992b; Suárez and Emparan, 1997), which means that most of the plagioclases emitted by these volcanoes are An-rich, as they occur in the andosol parent material of OC3 outcrop.

The plagioclases occurring in the OC5 (1.50 m) sample show an An content ranging from 42 to 85%. This composition is roughly similar to the plagioclases associated with the post-glacial andesitic rocks emitted by the Puyehue volcano (Fig. 6). As a general rule for the Puyehue–Cordon de Caulle volcanic complex, the An content of the plagioclases decreases with an enrichment of the magma in silica (Gerlach et al., 1988; Fig. 6). The best example is the Ab-rich plagioclases associated to the exceptional rhyodacitic eruption of 1960. However, the Puyehue–Cordon de Caulle is not the only volcano at the origin of the volcanic particles deposited around Puyehue lake. A large part of the particles may originate from Antillanca and Osorno volcanoes which are typical for the SVZ and basaltic or andesitic in composition (Gerlach et al., 1988). Although there is no data available for Antillanca and Osorno in the literature, the relation between the plagioclase composition and magma chemistry evidence that the volcanic products emitted by the volcanoes located around Puyehue lake mainly contain An-rich plagioclases, as they occur in the OC5 outcrop.

In agreement with the results of Laugenie (1982), these new data demonstrate that the particles composing the andosol parent material in south-central Chile have the same geochemical and mineralogical characteristics than the regional volcanic products. They can therefore be considered as volcanic ashes.

5.4. Mode of transport and deposition

The previous arguments have demonstrated that the andosol parent material is composed of volcanic ashes that bear the mineralogical and geochemical signature of the SVZ volcanoes. Our field observations demonstrate that these deposits cover the region whatever the elevation, with a relatively uniform thickness draping all but the steepest topography. This argument is incompatible with the glacial (Langhor, 1974) and pyroclastic flow (Wright 1965 In: Besoain 1985) origins that would have concentrated the volcanic particles in valleys and local depressions. On the contrary, the above-cited characteristics appear to be typical for pyroclastic fall (Orton, 1996) or loess-like (Laugenie et al., 1975) deposits.

5.4.1. Relation between the grain size and thickness of the deposits and their location to volcanoes

The grain size and the thickness of the andosol parent material in Icalma and Puyehue outcrops are significantly different. Around Icalma, the deposits are thick (4 to 7 m), they contain coarse intercalated pumice layers and they are characterized by an average mean grain size of 25 μm (Fig. 3). Near Puyehue lake, the deposits are typically less than 3 m thick and the average mean grain size is 18 μm (Fig. 3). These differences are due to the relative position of the outcrops compared to the regional volcanoes. Because of the dominant westerly winds, the volcanic particles are mainly transported from the volcanoes to the East. Therefore, the Icalma outcrops, which are located east of Llaima, Lonquimay and Sollipulli volcanoes (Fig. 1), receive more and coarser particles than the outcrops selected around Puyehue, which are located west of Puyehue and Antillanca volcanoes.

Within individual watersheds, a clear relation between the grain size and the thickness of the deposits and their relative position to volcanoes has been noticed. In Icalma watershed the sediments of OC4 outcrop contain 6 distinct tephra layers and are significantly coarser than in OC2 and OC3 outcrops, which are located east of OC4 and therefore further away from the local volcanoes (De Vleeschouwer, 2002). In the watershed of Puyehue lake, a significant fining and thinning westward was deduced from the analysis of 7 outcrops located at various distances from the Puyehue and Antillanca volcanoes (Bertrand, 2005). Laugenie (1982) made similar observations around Villarica volcano.

These data evidence that since the end of the last glaciation the westerly winds are responsible for the spatial distribution of the volcanic ashes and that they strongly influence the grain size and thickness of the andosol parent material. These results are confirmed by the observations made during historical eruptions, which show that most of the emitted particles have been transported eastward, as far as Argentina (Wright and Mella, 1963; Moreno and Valera, 1985; González-Ferrán et al., 1989; Naranjo and Moreno, 1991; Naranjo et al., 1993; González-Ferrán, 1994). Similar conditions probably prevailed during most of the Quaternary period (Moreno and Valera, 1985).

5.4.2. Grains morphology

In order to characterize the type of aeolian transport which is responsible for the delivery of volcanic ashes in south-central Chile (pyroclastic fall *vs* loess-like deposition), we compared the size (using the D99 factor) and the morphology of the coarsest volcanic particles to typical loess and pyroclastic deposits.

The occurrence of high D99 values, *i.e.* very coarse particles, in both outcrops is a new argument for rejecting the sole loess-like origin of the andosol parent material. Indeed, the D99 values of the andosol parent material range between 91 and 860 μm (506–860 μm for OC2 and 91–783 μm for OC5), which is much higher than the typical D99 values for loess deposits (typically lower than 100 μm; Manil and Delecour, 1957; Sun et al., 2000). Grains coarser than ~100 μm cannot travel on large distances by wind only.

The morphology of the volcanic ash soil particles is in agreement with a very limited transport of the particles by wind. Indeed, the MEB observations display grains with a rough, not rounded morphology (Fig. 8). The rough morphology is due to the agglomeration of smaller volcanic particles during volcanic eruptions, which leads to the formation of strongly cohesive agglomerates. These observations evidence that the particles composing the andosol parent material have been directly deposited after volcanic eruptions. Because of their coarse grain size and rough, non-abraded morphology, we can argue that these particles have virtually never been reworked by wind.

5.5. Unique event or successive eruptions?

The previous arguments demonstrate that most of the andosol parent material is composed of volcanic ashes originating from eruptions of regional volcanoes and directly deposited by gravity. However, whether these particles accumulated rapidly during the Late Glacial and early Holocene (Veit, 1994) or continuously since the last glaciation remained unclear. The only macroscopical chronological markers occurring in the investigated outcrops are the two intercalated pumice layers described in Icalma outcrops, which indicate that the andosol parent material around Icalma accumulated during several volcanic eruptions throughout the Holocene. Several additional arguments evidence that these particles accumulated during successive volcanic eruptions: (1) the heavy minerals study of Laugenie (1982) shows that the mineral sources of the andosol parent material were frequently renewed by successive magmatic eruptions; (2) the tephra record of Puyehue lake sediments attest that at least 78 tephras reached the region since the Last Glacial Maximum (Bertrand et al., in press-b); (3) the Icalma lake and peat deposits contain a large number of Holocene tephra layers, representing 40% of the lake sedimentary infill at certain locations (De Vleeschouwer, 2002; Bertrand et al., in press-a); (4) the high resolution geochemical analyses realized by McCurdy (2003) on andosols from Calafquen (39°S) and Ensenada (41°S) evidence that those outcrops are composed of several superimposed paleosoils. Therefore, we argue that most of the particles composing the andosol parent material are typical fall-out ashes deposited by successive volcanic eruptions throughout the Late glacial and Holocene.

5.6. Layering and pedogenesis

If the andosol parent material has been deposited during successive volcanic eruptions, one can expect for it to be stratified. Our field observations have demonstrated that the only macroscopically visible layering is caused by the Sollipulli and Llaima pumice layers in outcrops around Icalma and by several distinct tephra layers in outcrops located at the vicinity of regional volcanoes. In thin section, the OC2 deposits appear structurally homogeneous (Fig. 4A). The absence of stratification seems to be the result of intense weathering processes during the soil formation, as they typically occur under the very humid climate of south-central Chile (Laugenie et al., 1975). Moreover, previous studies have demonstrated that the biological activity is able to generate a deep pedoturbation in the andosols of south-central Chile, especially by roots and worms (Langhor, 1971). Therefore, we argue that the andosol parent material was initially layered, but weathering and pedogenetic processes have rapidly wiped out the internal structures. Because the development of andosols can only be interrupted by the deposition of thick volcanic sediments (Buurman et al., 2004), only the two pluridecimetric Sollipulli and Llaima pumice layers have interrupted the soil formation and buried older soils. All the thinner tephra layers have been incorporated into previously deposited particles, although some of them have probably affected the soil development during short periods of time, as evidenced by the occurrence of successive organic-rich layers (5–10 cm) in thin sections.

6. Conclusion

The andosols of south-central Chile are developed on plurimetric yellow-brown loams mainly composed of plagioclase and (bulk and clay-) amorphous particles. The mineralogy and geochemistry of these particles is typical for the regional volcanism, except for allophane which originates from the post-depositional weathering of volcanic glasses and plagioclase. The stratigraphy of the andosol parent material and the tephra record of regional lake and peat deposits demonstrate that the andosol parent material accumulated during successive volcanic eruptions throughout the Late glacial and Holocene. Moreover, the presence of very coarse particles and the rough morphology of the coarse grains evidence that these deposits haven't been re-transported by wind. Therefore, even if a small fraction of the fine particles may have been re-transported by wind, these deposits cannot be considered as typical loess sediments. Our results evidence their direct volcanic ash fall origin. Because of the prevailing westerly winds, most of the particles have been transported to the East. Very locally, andosols might have developed on volcanic ashes re-transported by glaciers, lahars or rivers.

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