# Changes in diatom, pollen, and chironomid assemblages in response to a recent volcanic event in Lake Galletué (Chilean Andes)

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## Abstract

Several lakes in Chile are near important volcanic areas where eruption impacts can limit the quality of lacustrine sediments for reconstructing past environmental changes. In this study, we report changes in diatoms, pollen, and chironomids assemblages after a tephra deposition in Lake Galletué (Chilean Andes). A sediment core obtained from Lake Galletué (40 m water depth) was sliced in 1 cm intervals and subsamples were taken to analyze each proxy. $^{210}$Pb and $^{137}$Cs activities were measured to obtain the geochronology and mineralogical analyses were performed to determine the mineral composition of the tephra. Diatom species composition and productivity were modified when the lake received the tephra; *Aulacoseira granulata* decreased and was later replaced by *Cyclotella* af. *glomerata*. After the tephra input, *Aulacoseira granulata* abundance increased to pre-disturbance levels and *Cyclotella* af. *glomerata* decreased. These changes seem to suggest a momentary increase in lake nutrient levels after the tephra deposition. Chironomid assemblages also decreased in head capsules just after the tephra deposition, but the most important change was the replacement of *Ablabesmyia* by *Parakiefferiella*, probably due to the sedimentological changes produced by the input of coarse tephra grains. Furthermore, unlike other studies, chironomid assemblages in Lake Galletué did not show a decrease drastically in diversity within the tephra layer. The pollen analysis indicated that, prior to the volcanic event, the vegetal community was dominated by *Nothofagus* sp., *Araucaria araucaria*, and *Blechnum* sp.-type. After the tephra deposition, the same taxa are dominant, indicating that the volcanic event seems not produce changes in the vegetation. Nevertheless, within the tephra layer it is possible to see an increase in Poaceae, which represent - due to the percolation process - the effect of eruption on the vegetation. According to our results, diatoms were the most sensitive proxy for describing the changes produced by tephra deposition into the aquatic ecosystem and, despite the noticeable changes in its sedimentological properties; the lake seems to have a high resilience capacity, allowing it to return to pre-tephra input conditions.

**Keywords:** biological proxies ; tephra impacts ; lake sediment ; Chilean Andes

## INTRODUCTION

Information about the effect of tephra falls on aquatic ecosystems is limited in southern South America, although tephra layers have commonly been used as chronostratigraphical markers in studies of past environmental changes (Newnham & Lowe 1999; Newton & Metcalfe 1999). However, our limited understanding of tephra effects does not allow discriminating these from other natural or anthropogenic impacts (Telford, Barker, Metcalfe, & Newton 2004).

Some studies in the Northern Hemisphere have indicated that volcanic eruptions and associated processes can significantly impact human and natural ecosystems (Eastwood, Tibby, Roberts, Birks, & Lamb 2002). Volcanic events could impact aquatic ecosystems through increased nutrient input due to chemical weathering of tephra and changes in physical conditions such as short-term diminished light penetration, the sealing of the sediment-water interface, or the burial of macrophytes in littoral zones. Other effects might include changes in pH, organic matter input, mineral concentrations, and lake water salinity (Barker et al. 2000; Birks & Lotter 1994; Eastwood et al. 2002; Heinrichs, Walker, Mathewes, & Hebda 1999). Tephra can be directly discharged into a lake or dragged in through the catchment, in which case the weathered tephra will be an important source of silica (Abella 1988; Telford et al. 2004). Such changes in the lacustrine system can, in turn, produce important changes in the lake's algal communities and benthic fauna.

Birks and Lotter (1994) reported changes in diatoms assemblages after a tephra deposition near Laacher See Volcano, Germany. They found that diversity and accumulation rates of some taxa (both terrestrial vegetation and diatoms) near the volcano were affected after tephra deposition. Hickman and Reasoner (1994), also

working on diatoms in British Columbia, found that tephra deposition affected diatom production but not diversity. Telford et al. (2004) described lacustrine responses to tephra falls, mainly represented in diatoms assemblages.

Although Chile is a mountainous country with a lot of active volcanoes, no information is available about the consequences of volcanic activity on aquatic ecosystems and their watersheds. Considering that, the aim of this research is to determine the changes provoked by a volcanic sediment deposition on diatom, chironomid, and pollen assemblages in the sediment column of Lake Galletué (Chilean Andes).

**Study area**

Lake Galletué (Fig. 1) is located at 38°41'S and 71°17'W and is 1150m a.s.l. It is approximately 26km away from the nearest city, Lonquimay. The water body has a surface of 12.5 km$^2$ and the maximum depth is 45 m. According to its nutrient levels, the lake is classified as oligotrophic and according to its water column temperature regime, it is a monomictic temperate lake with summer stratification (Parra et al. 1993). The lake's watershed presents a steep seasonal gradient in air temperature with extremes of -6.0 °C in winter and 28.9 °C in summer. Annual average precipitation is 1900 mm with a maximum of 3018 mm and a minimum of 1180 mm (Parra et al. 1993).

Mardones, Ugarte, Rondanelli, Rodríguez, and Barrientos (1993) found different vegetational associations in the Lake Galletué watershed. Typical temperate rainforests in the north and northeast are composed mostly of *Nothofagus pumilio* (Poepp. et Endl.) Krasser, *Nothofagus dombeyi* (Mirb.) Oerst., and *Araucaria araucaria* (Mol.) K. Koch. The upper canopy of this forest reach 35-50 m high and the mid-levels are composed mainly of young individuals of the above species. The understorey, however, is dominated by *Berberis* spp. (michay), *Drimys winteri* J.R. et G. Forster var. andina Reiche, and the Chilean bamboo *Chusquea* sp. (quila). High prairie grasslands, called "coironal", are found in the east and south east parts of the watershed and cover important tracts of land next to the lake, where they grow in a cushion form called "champas". The "coironal" composition is predominantly *Festuca scabriuscula* (Phil.), *Acaena sericea* (Jacq.fil.), *Baccharis magellanica* (Radín), and *Rumex acetosella* (Linnaeus). This low vegetational community can also be mixed with *Nothofagus antarctica* (G. Forster, Oerst.) and *Araucaria araucaria* forests. In the wetland zones near the lake, species of Juncaceae and Ciperaceae occur together with the herbaceous genera *Trifolium, Melilothus,* and *Caltha* (Mardones et al. 1993). This community indicates that the lake has relatively pristine vegetation in its watershed.

**Fig. 1.** *Study site map indicating the location of Lake Galletué.*
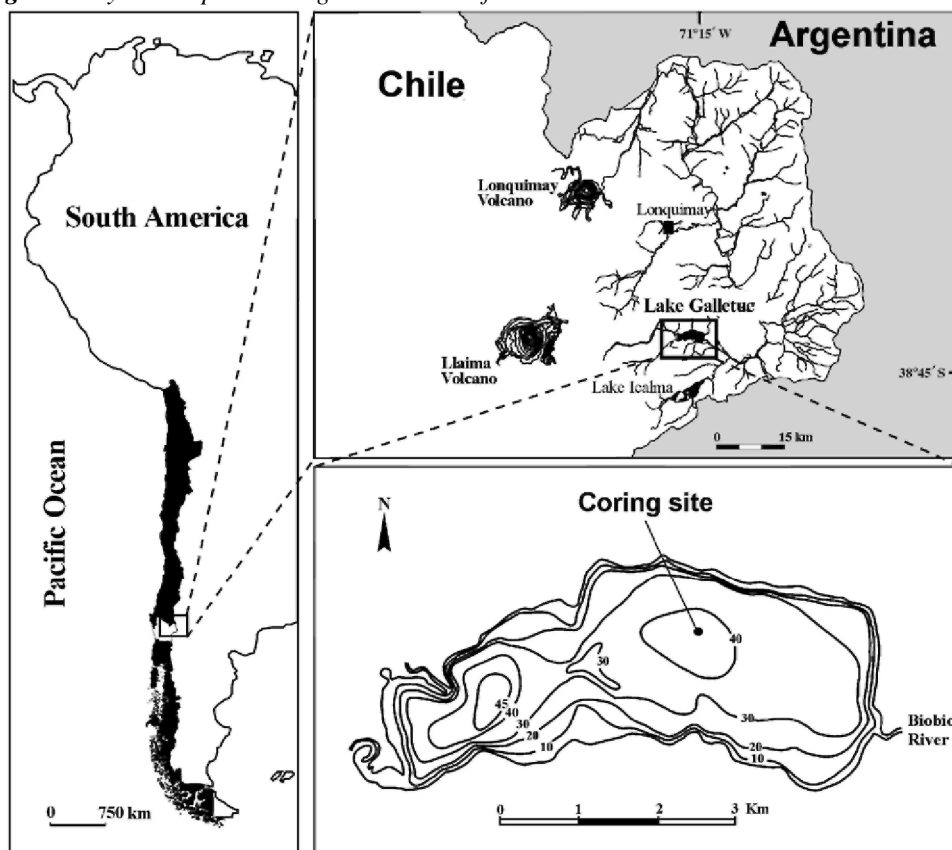
## MATERIALS AND METHODS

### Sampling and physical analysis

A Lowrance X-16 echo sound profiler was used to find the maximum depth of the lake and to evaluate the adequacy of the bottom sediment for coring. A 17 cm sediment core was retrieved from the deepest part of the lake using an Uwitec gravity corer with a plexiglass tube (6 cm in diameter). After the X-ray inspection, the core was sliced vertically at 1 cm intervals and the samples were stored in plastic bags.

Lithology was assessed with X-rays (taken at 50 kV and 26-30mAs$^{-1}$) of the core, following the method outlined by Axelsson (1983). The X-rays clearly identified a highly reflective sediment layer, which was sub-sampled for mineralogical analyses. The chemical composition (major elements) of this sediment layer was determined using an electron microprobe (Cameca SX50) at the Centre d'Analyse par Microsonde pour les Sciences de la Terre, Louvain-la-Neuve University, Belgium (CAMST). The accelerating voltage was 15 kV and the beam current was 20 nA. Counting times were 20 s for all elements.

For grain size analysis, samples were sieved at 4.0 and 1.0 φ units and separated into fine (mud) and coarse (sand) fractions. Grain size was analyzed using a Elzone 282 PC Coulter Counter particle analyzer. The organic content in each layer was estimated by the loss on ignition (LOI) technique, following the method described by Boyle (2002).

### Geochronology

The core's age was determined through $^{210}$Pb activity. Gammaspectrometrical measurements were done using an HPGe detector with a 0.5 mm beryllium window and an energy resolution of 570 eV at the level of 122 eV. The detector and the measuring geometry were calibrated with certified reference material (RGU-1, RGth-1, and RGK-1) from the International Atomic Energy Agency (IAEA). Once the activity of each sample was obtained, constant initial concentration (CIC) and constant rate supply (CRS) age models (Appleby & Oldfield 1978) were evaluated in terms of an age-depth profile, and coherency with peak $^{137}$Cs activity. The CIC model was the most adequate. The peak in $^{137}$Cs activity was used to validate the age estimate since the maximum activity represents approximately 1963, when nuclear weapon tests released large amounts of this isotope into the atmosphere (Guevara & Arribere 2002; Longmore, O'Leary, & Rose 1983).

### Diatom analysis

Diatom analyses were done according to Battarbee (1986). To eliminate organic matter and facilitate the observation of diatom valve structures, 0.1 g of dry sediment was oxidized with $H_2O_2$. Subsequently, for the taxonomic identification and quantification of diatom assemblages, permanent slices were mounted with Hyrax resin (I.R. = 1.7). The diatom concentration was estimated by adding a microsphere solution to the samples (Battarbee & Kneen 1982). About 500 and 600 diatom valves were counted and identified for each sample. The identification was carried out following specialized literature (Krammer & Lange-Bertalot 1991, 2000; Rivera 1970, 1974; Rivera, Parra, & González 1973; Rivera, Parra, González, Dellarossa, & Orellana 1982).

### Pollen

The pollen analysis was performed following Erdtman (1960). The sediment samples were processed using concentrated HF and acetolysis. Permanent samples were mounted in gelatine-glicerine and 350 pollen grains were counted for each centimeter; pollen was identified following Marticorena (1968) and Heusser (1971). The results are shown in percentage diagrams; the terrestrial pollen estimate considered arboreal and non-arboreal taxa, excluding fern spores.

### Chironomids

Chironomid analysis consisted of deflocculating 4 ml of wet sediment in KOH 10% for 15 min at 70 °C and passing it through a 90 µm sieve. The remains were then transferred to a Bogorov counting tray where head capsules were picked out with entomological forceps. Each head capsule was dehydrated in 80% and 100% ethanol and then mounted in Euparal, ventral side up. Chironomids were identified using a Zeiss microscope at magnifications of 25, 40, or 100 × and the keys of Hofmann (1971), Rieradevall and Brooks (2001), Wiederholm (1983), Epler (2001), and Paggi (2001).

### Statistical methods

To distinguish different associations along the profile, a stratigraphically constrained sum-of-squares cluster analysis (CONISS) was applied to the percentages values of the different proxies using Tilia and Tilia Graph (Grimm 1987) programs. Diagrams were also constructed using Tilia and Tilia Graph (Grimm 1991).

**Fig. 2.** *Physical parameters of the Lake Galletué sediment core: (a) radiograph, (b) organic matter, (c) grain size, (d) $^{210}Pb$ activity, (e) $^{137}Cs$ activity, (f) age vs. depth profile, and (g) bulk mineralogy.*
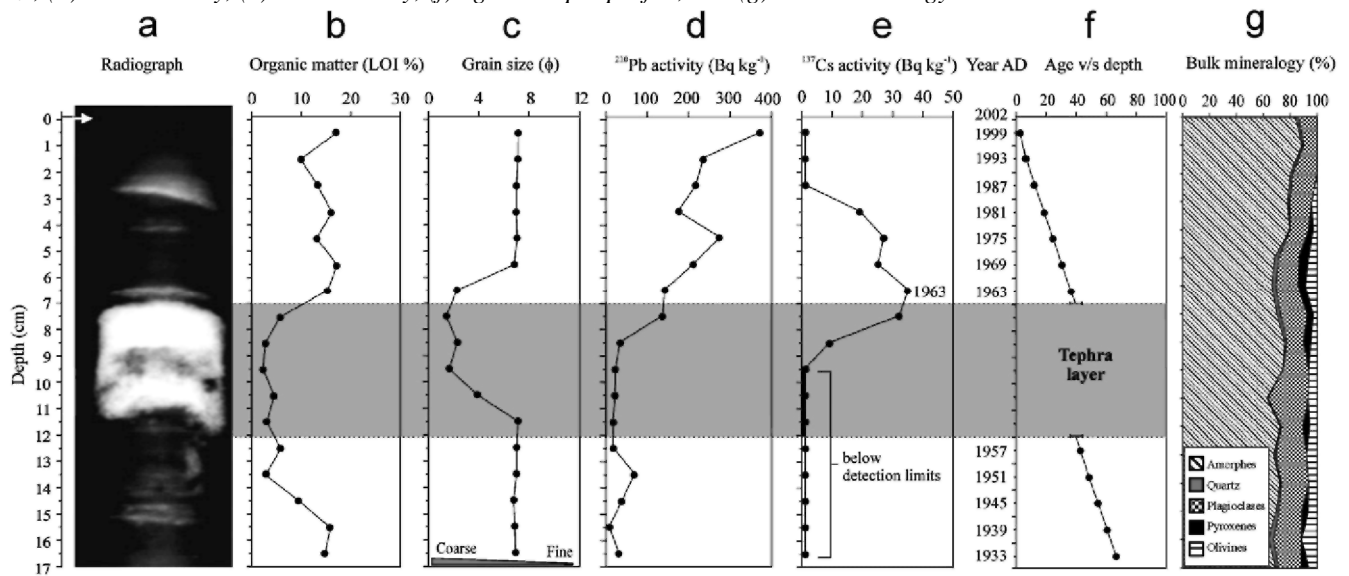


## RESULTS

### Geochronology and physical parameters

The radiograph of the sediment column from Lake Galletué is depicted in Fig. 2(a). The clear layer of high reflectivity (white area) between 7 and 12 cm indicated higher density than the rest of the sediment. A preliminary visual inspection revealed coarse, dark, irregular, and very sharp particles likely to be a tephra layer. According to the microprobe analysis, the chemical composition of this tephra corresponds to basaltic andesite (Le Bas, Maitre, Streckeinsen, & Zanetin 1986) with 54.29% $SiO_2$ and 4.32% $Na_2O + K_2O$ (Fig. 3). The bulk mineralogy (%) in turn, indicated a predominance of amorphes (Fig. 2(g).

The organic content (LOI) trend is influenced by the tephra layer (Fig. 2(b)), decreasing noticeably in the section of core where the tephra layer is evident (7-12 cm). Organic content was highest (17.2%) at 6 cm and lowest (2.3%) at 10cm, within the volcanic layer. The lower organic content in the volcanic layer is obviously due to the tephra's inorganic nature.

The grain size analysis (Fig. 2(c)) showed an increase in particle sizes in the tephra layer, passing texturally from silt to sand (mean size 6.83 φ = 8.8 μm to 2.16 φ = 223 μm). The sediment below the tephra layer was composed mainly of silt (Fig. 2(c)). A more detailed diagram of grain size is depicted in Fig. 4 were the sedimentological changes due to tephra deposition are showed.

$^{210}Pb$ and $^{137}Cs$ activities are presented in Fig. 2(d) and 2(e), respectively. In general, $^{210}Pb$ activity tended to decrease toward the deepest part of the core. $^{210}Pb$ activity peaked (375 Bq kg$^{-1}$) in the first cm and was lowest at 16 cm (8.0 Bq kg$^{-1}$). The total $^{210}Pb$ inventory in the core reached 2351 Bq kg$^{-1}$ that is a total $^{210}Pb$ flux to the sediments of 73.2 Bqm$^{-2}$ yr$^{-1}$. $^{137}Cs$ activity (Fig. 2(e)) was detectable from 4 cm (19.0 Bq kg$^{-1}$), peaking at 7 cm (35.0 Bq kg$^{-1}$); no activity was detectable from 10 to 17 cm. According to Longmore et al. (1983) and Guevara and Arribere (2002), $^{137}Cs$ activity probably peaked in 1963, when this radioisotope was released in large quantities due to nuclear weapon tests. There is good agreement between the $^{137}Cs$ profile and $^{210}Pb$ dating (Fig. 2(f)), with 1963 coinciding with the $^{137}Cs$ peak.

**Fig. 3.** *Geochemical results obtained by microprobe analyses on glass shards from tephra layer. Basaltic andesite composition is indicated in the TAS classification (Le Bas et al. 1986).*
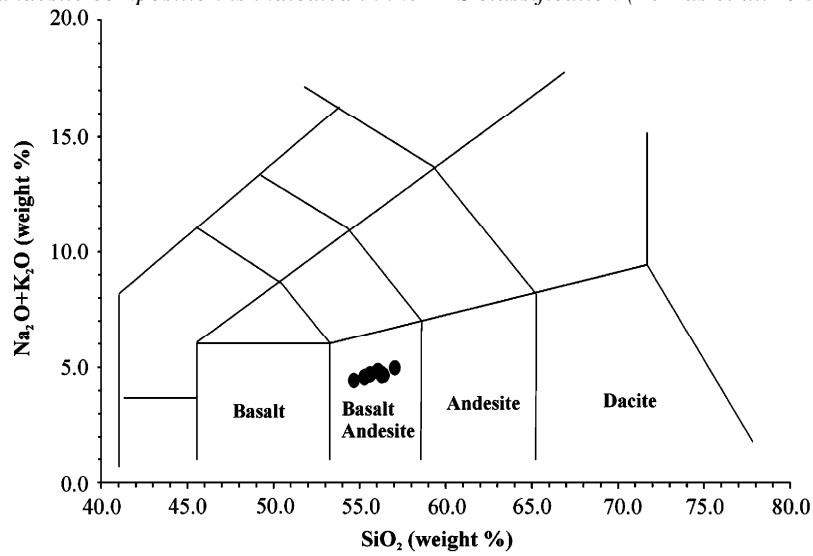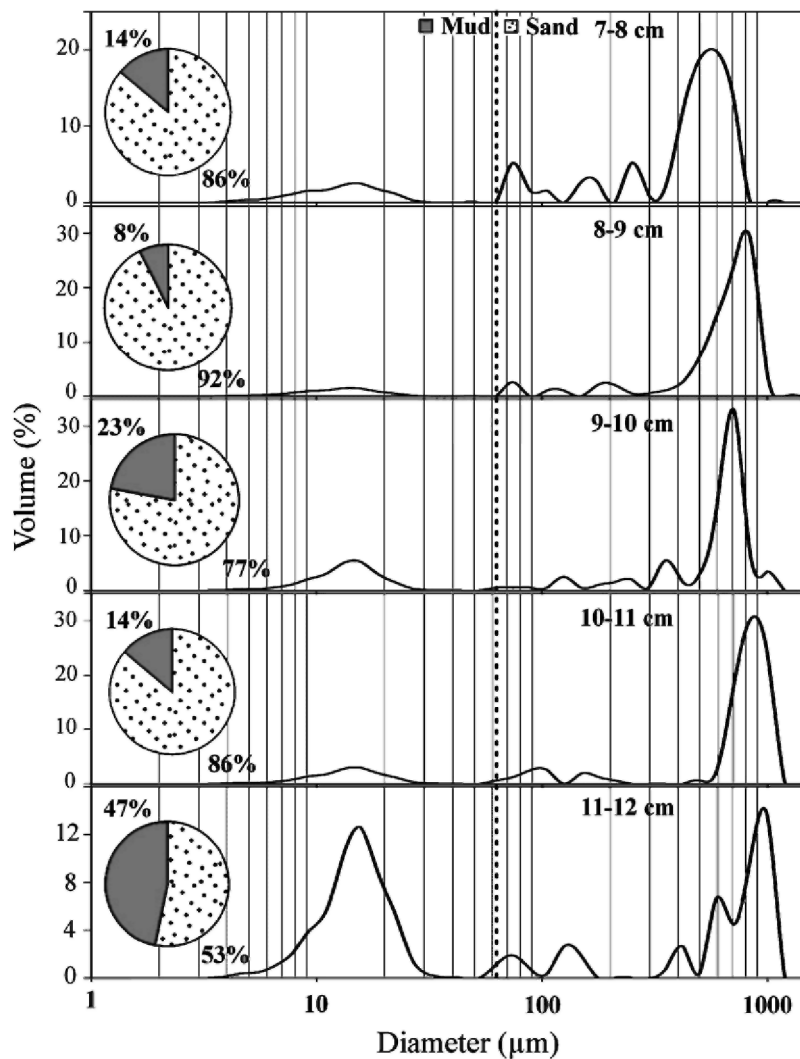


**Fig. 4.** *Grain-size distribution of the 5 cm where tephra layer is evident, pie diagrams (inset) indicate sand-mud proportion. The lower sample (11 cm) has the highest proportion of mud, reflecting the arriving of tephra particles (coarse) with the host sediment (fine).*

**Diatoms**

All sedimentary samples analyzed from Lake Galletué showed a good preservation of diatom valves, allowing the identification of the total taxa registered. Fig. 5 summarizes the most abundant species. The principal biostratigraphical changes occurred between 13 and 7 cm of the profile, corresponding to the deposition of tephra materials into the lake. Both layers showed the most important changes in the diatom assemblage composition, with changes in the dominant species.

The diatom stratigraphy was grouped using a cluster analysis, thereby evidencing three zones that can be distinguished throughout the profile (Fig. 5).

Zone Diat-I (pre-volcanic event period). This zone was dominated by the species *Aulacoseira granulata* (Ehr.) Simons., *Cyclotella stelligera* Cleve and Grunow, *Cyclotella* af. *glomerata*, *Fragilaria construens* (Ehr.) Grunow, and *Fragilaria pinnata* Ehrenberg; *Aulacoseira granulata* was the most abundant (52-64%). Planktonic diatoms dominated the system in this zone, and benthic diatoms, largely represented by *Fragilaria pinnata,* were scarce.

Zone Diat-II (the volcanic event period). Diatom structure assemblages evidenced a change in which *Aulacoseira granulata* was replaced as the most abundant species by *Cyclotella* af. *glomerata,* which peaked at 51% (11cm). *Aulacoseira distans* (Ehr.) Simons and *Asterionella formosa* Hassall also increased during this period. Diatom concentrations were lower, but started to increase at the end of the zone II (Fig. 5).

Zone Diat-III (post-volcanic event period). This zone indicated a return to initial conditions, with *Aulacoseira granulata* reaching the abundance levels found prior to the volcanic material input; *Cyclotella* af. *glomerata* decreased drastically until almost disappearing from the assemblages. *Urosolenia eriensis* (H. L. Smith) Round, Crawford, and Mann and *C. meneghiniana* Kützing, however, appeared in the sedimentary record; they were most abundant in the upper layers of the profile. *Asterionella formosa* abundance increased during this period, peaking at 33% (5cm). On the other hand, diatom productivity changed during this period, with higher diatom concentrations than those observed prior to the volcanic event (Fig. 5).

*Fig. 5. Sedimentary diatom assemblages from Lake Galletué: diatom concentration, influx, and principal zones.*
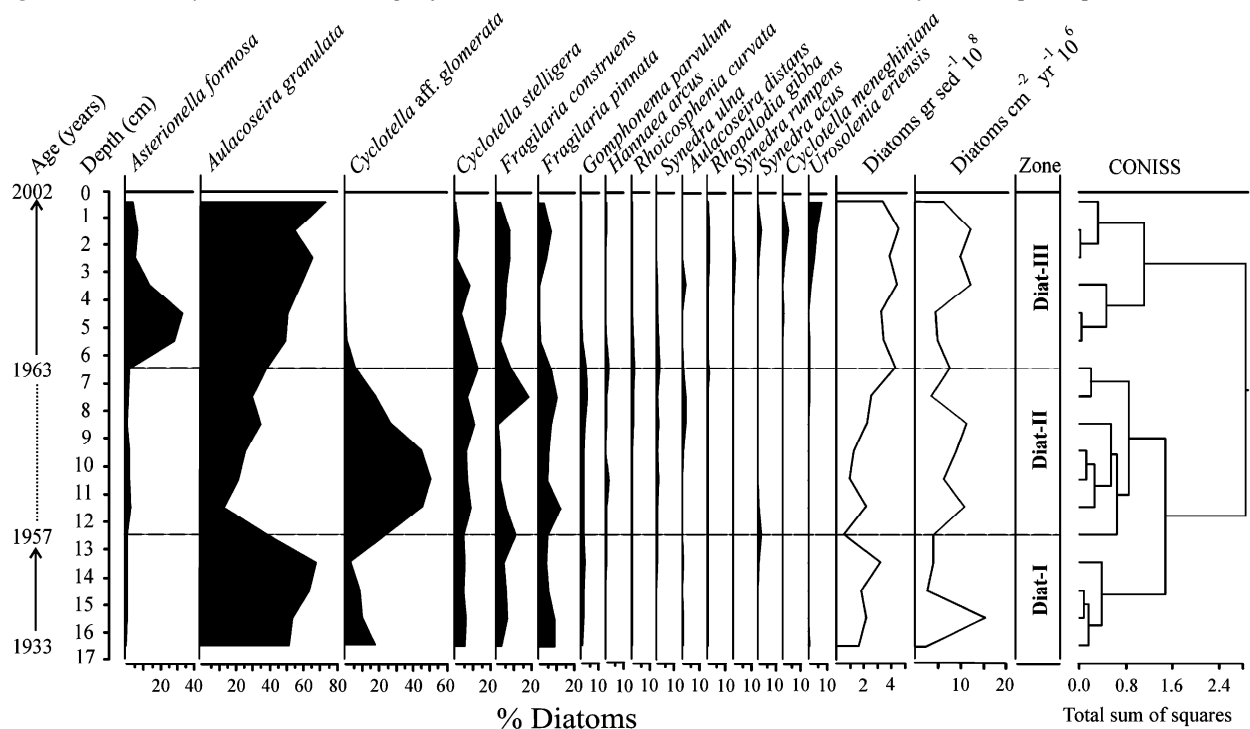


**Pollen**

Fig. 6 shows the relative abundance of pollen taxa during the last ~70 years at Lake Galletué. According to the CONISS analysis and some marked fluctuations in key taxa, the pollen profile was divided into four zones: Poll-1 (before the volcanic event) and Poll-2, Poll-3, Poll-4 (after the volcanic event).

*Zone Poll-1* (17-12 cm): In this segment, the vegetational community was dominated by *Blechnum*-type (average = 37%) and *Nothofagus*-type (average = 28%) pollen. Of the arboreal pollen, *Araucaria araucana* (average = 17%) was important. *Pinus radiata* appeared in the upper part of this zone. The Poaceae family reached an abundance of 8.7%.

*Zone Poll-2* (12-6 cm): This zone represent - due to percolation of pollen grains within tephra particles – the changes provoked on the vegetation immediately after the volcanic eruption. The zone was dominated by *Blechnum*-type (average = 27.4%) and *Nothofagus*-type (average = 23%) pollen, which decreased in comparison to the previous zone. The Poaceae family underwent an important increase in this zone, reaching an average of 20% abundance. *Plantago lanceolata* appears at the beginning and disappeared in the upper part of this zone.

*Zone Poll-3/Poll-4* (6-1 cm): Poll-3 was dominated by *Nothofagus*-type (average = 32%), which increased noticeably from the previous zone, whereas *Blechnum*-type decreased to an average of 22%. *Araucaria araucaria* (average = 8.8%) also dropped in comparison with zone Poll-2 and showed a decreasing trend toward the upper part of this zone. *Pinus radiata* had the highest abundance of the entire profile. The drastic decrease of Poaceae compared with the previous zone should be noted. *Plantago lanceolata* disappeared from the record in zone Poll-4, as did Chenopodiaceae; *Acacia*-type, on the other hand, appeared.

*Fig. 6. Pollen percentage diagram for main vegetational taxa in the sediment core from Lake Galletué.*
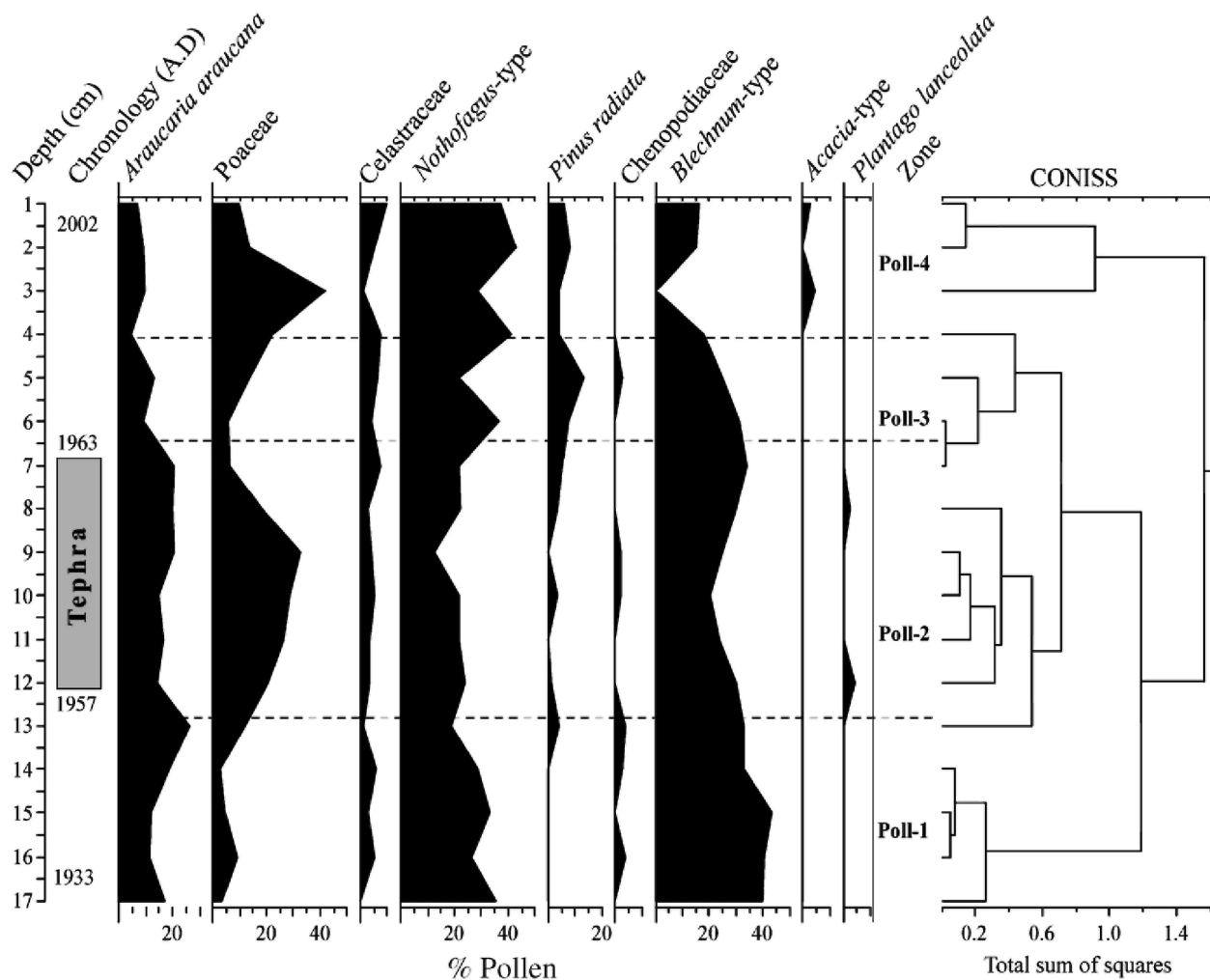


## Chironomids

A total of 23 chironomid taxa were identified in the sediment column of Lake Galletué representing the subfamilies Chironominae, Tanypodinae, Orthocladiinae, and Podonominae. The most important sub-family in terms of abundance was Chironominae, which reached 37.1% of the total and was composed of the tribes Tanytarsini (25.7%) and Chironomini (11.4%). The second sub-family in importance was Tanypodinae (29.1%) followed by Orthocladiinae (27.1%). The sub-family Podonominae had very low abundance (0.3%).

Unidentified remains composed 6.3% of the total. Two different groups of Tanytarsini - types A and B - were distinguished based mainly on differences in the shape of the antennal pedestal. CONISS analysis was used to distinguish three zones in the chironomid assemblages (Fig. 7). Zone Chir-I (17-12 cm) before the tephra layer impact, Zone Chir-II (12-6 cm) during the impact, and Zone Chir-III (6-1 cm) after the impact.

*Zone Chir-I* (17-12 cm, pre-impact): *Ablabesmyia* (Johannsen, 1905) was relatively abundant in this zone, decreasing at 16 and 13 cm. *Macropelopia* (Thienemann, 1916) showed some of its highest abundances here and other abundant taxa in this zone were *Parakiefferiella* (Thienemann, 1936), Tanytarsini type A, unidentified remains of Orthocladiinae, and *Pseudochironomus* (Malloch, 1915). The latter only occurred in this zone and with very low abundances. The number of head capsules found in this zone was relatively high compared with the other zones, reaching around 15 heads per ml of wet sediment at some levels.

*Zone Chir-II* (12-6 cm, during the impact): In this zone, *Ablabesmyia* abundance decreased after 11 cm, reaching its lowest value at 8 cm and beginning to increase gradually above 7 cm. *Macropelopia* abundance was lower in this zone than in the previous zone. Tanytarsini Type A decreased at the beginning of the zone, then increased later on. Tanytarsini Type B was absent in the first part of the zone, appearing at 11 cm, decreasing at 8 cm, and increasing at 7 cm. *Cricotopus/ Orthocladius* (Wulp, 1874) also showed a gradual decrease in abundance during this period. However, the greatest change in this zone was the increase in *Parakiefferiella,* which reached considerably higher abundances than in the pre-impact zone. The total number of head capsules was most abundant before the tephra deposition, dropped noticeably immediately after the event (13-10 cm), and increased at 9 cm.

*Zone Chir-III* (6-1 cm, post-impact): After the tephra deposition, some taxa rapidly started to increase in abundance. *Ablabesmyia* increased after 5 cm, reaching a maximum at 3 cm. Following the impact, both *Macropelopia* and *Parachironomus* (Lenz, 1921) also increased. Other taxa that increased in abundance are unidentified Tanytarsini and Tanypodi-nae. However, one of the most noticeable changes after the volcanic event was the diminishing abundance of *Parakiefferiella,* which was most abundant within the tephra layer. The number of head capsules increased at 4-5 cm and decreased toward the surface sediments.

The diversity estimated by the Shannon index (Pielou 1966) did not show a noticeable change along the profile, suggesting that the impact of the tephra did not reduce chironomid diversity.

**Fig. 7.** *Chironomid abundance (%) diagrams, showing assemblage structure in the sediment of Lake Galletué. Stratigraphical divisions were made following CONISS analysis.*
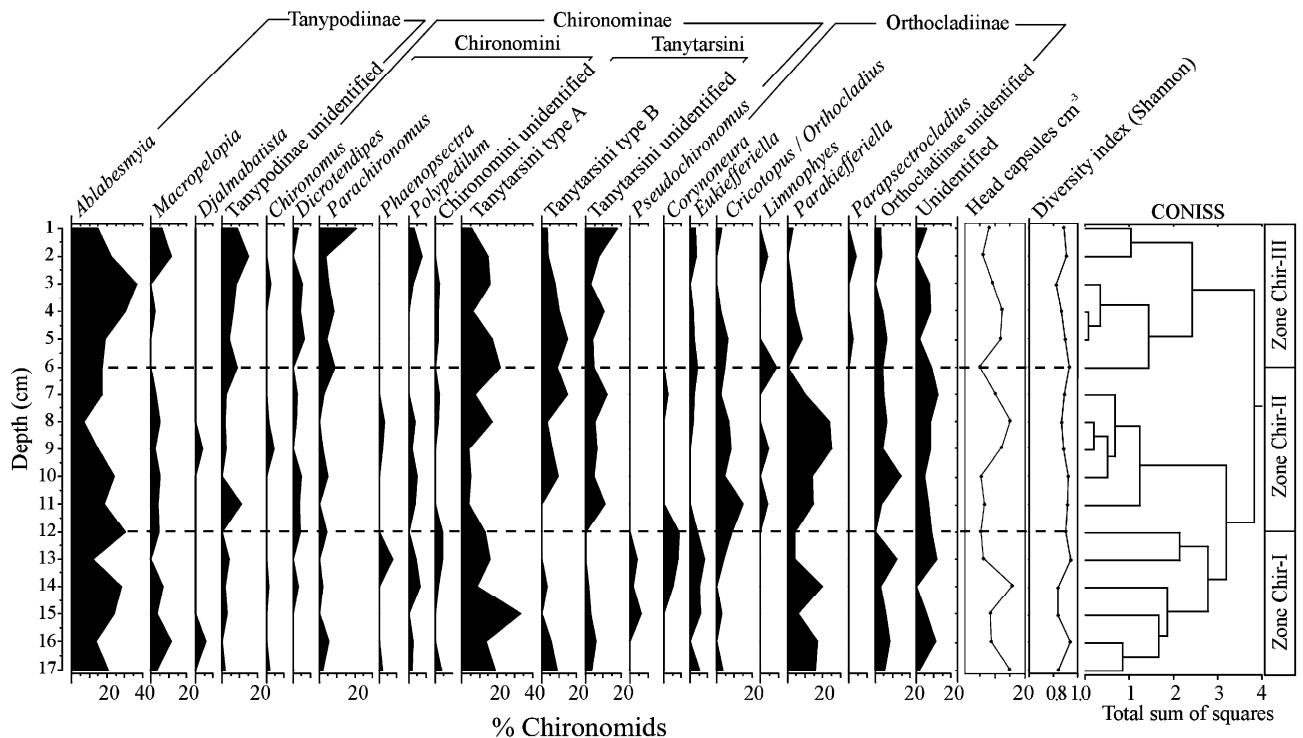
## DISCUSSION

### Physical analyses

The tephra layer deposited between 7 and 12 cm in the sediment column of Lake Galletué produced a marked change in the lake's sedimentological parameters. Compared with the rest of the core, the tephra induced a decline in organic content, an increase in mean grain size, and a dilution of $^{210}$Pb activity, which suggests that the tephra was deposited in a short period of time. Telford et al. (2004) stated that tephra with a size equivalent to fine sand will settle at a rate of around 40mh$^{-1}$. Considering the tephra grain size and the maximum depth of Lake Galletué (45 m), the tephra was expected to reach the lake bottom in approximately 1 h, reinforcing the fast sedimentation hypothesis.

According to the dating ($^{210}$Pb, $^{137}$Cs), the sediment core covered the last ~70 years and the tephra deposition was produced around 1957 AD. Some historical records of Andean volcanic activity (González-Ferran 1994) indicate that Llaima Volcano began an eruptive process in November 1956; Llaima is one of Chile's biggest and most active volcanoes (Moreno & Fuentealba 1994). This was one of the most violent eruptions of the twentieth century (Naranjo & Moreno 1991) and produced lava fluxes, ash expulsion, and lahars (González-Ferran 1994). Other descriptions of recent volcanic activity near Lake Galletué, specifically the December 1989, eruption of Lonquimay Volcano, are provided in Moreno and Gardeweg (1989). This eruption expelled ash, lava, and other pyroclastic material, which caused serious damage to crop and cattle in the region (Besoaín, Sepúlveda, & Sadzawka 1992). However, this eruption does not coincide temporally with the tephra deposition established by $^{210}$Pb dating. Therefore, and according to the $^{137}$Cs activity profile, the tephra layer deposited in Lake Galletué between 7 and 12 cm was probably generated by the 1957 eruption of Llaima Volcano. Naranjo and Moreno (1991) indicated that, during this eruption, volcanic sediment reached a thickness of 15-30 cm, 5 km east of the volcano. Since Lake Galletué is 38 km east of Llaima Volcano, it certainly received volcanic sediments from this eruption.

### Biological proxies

#### Diatoms

According to Barker et al. (2000), the supply of tephra in lakes principally increases the water's silica content, resulting in increased populations of diatoms within the assemblages that have higher assimilation rates for this element. This would explain the increase in *Cyclotella* af. *glomerata* with the tephra input into Lake Galletué. According to Haworth and Hurley (1984), *Cyclotella glomerata* Bachmann grows in habitats with high silica availability and, in many cases, the distribution of this species in sedimentary profiles is related to volcanic horizons with high silica contents.

The dissolution processes of tephra in the water would have released silica into the system and buried phosphorus in the sediment. Consequently, the limited phosphorus would have negatively affected *Aulacoseira granulata,* as this species is not a good competitor and is displaced by other taxa in habitats with limited nutrients (Barker et al. 2000; Barker, Williamson, Gasse, & Gilbert 2003; Kilham, Kilham, & Hecky 1986).

The increased *Asterionella formosa* and *U. eriensis* after the volcanic event suggests increased lake nutrients since these species are typical in high-nutrient environments (Alefs & Müller 1999; Clerk, Hall, Quinlan, & Smol 2000; Meriläinen et al. 2000). This result also agrees with the increased *Aulacoseira granulata* in the upper layer of the core, probably indicating the recovery of phosphorus levels in the water, which allowed this species to return to the abundance levels shown prior to the tephra input. The more recent decrease of *C.* af. *glomerata* would be the result of lower silica contents in the system, as this species is displaced in the assemblages by *Aulacoseira granulata,* a better competitor given decreased Si/P ratios.

According to the above results, changes in organic matter and dominant species in the sedimentary diatom assemblages of Lake Galletué indicate that the supply of tephra to the lake principally changed the silica content, modifying the nutrient availability in the water. However, once the tephra input ended, the system reestablished the conditions found during the previous period. A more detailed description of diatom changes produced by tephra deposition in Lake Galletué is found in Cruces et al. (2006).

#### Pollen

The impact of a volcanic eruption on vegetation can be direct, through biomass combustion by lava fluxes or modified soil properties and nutrient cycles, or it can be indirect, through short-term climate changes due to fine particle emissions into the atmosphere that block solar radiation (Birks & Lotter 1994). On the other hand, a volcanic eruption can supply nutrients to the soil, favouring vegetative growth. Besoaín et al. (1992) reported nutrient inputs (N, P, Ca, K, and Mg) into the soil due to the ash deposition from Lonquimay Volcano (southern Chile) in 1988.

When a volcanic eruption eliminates biomass, the recolonization by new species adapted to the new soil properties facilitates the later arrival of other taxa. Depending on its resilience capacity, the vegetation community can return to its original conditions before the volcanic impact (Molles 1999; Raven, Event, & Eichhorn 1992; Scheffer, Carpenter, Foley, Folker, & Walker 2001).

Birks and Lotter (1994) reported a slight increase in non-arboreal pollen after a tephra deposition near Lacher See Volcano (Germany). On the other hand, near our study area, Rondanelli (2001) indicated an important decrease in vegetable biomass (mainly arboreal) just after several volcanic events that occurred in the Holocene. The same author also described an important predominance of herbs where the Poaceae reached high abundances after the tephra deposition.

For the last ~70 years, the pollen assemblages in the Lake Galletué sediment record have shown a dominance of arboreal taxa, mostly *Nothofagus* and *Araucaria araucana,* although some non-arboreal taxa like *Blechnum*-type and Poaceae were also important.

The CONISS analysis (Fig. 6) clearly evidenced four palynological zones with noticeable changes in the pollen assemblage abundance and composition before and after the tephra deposition. Such zonification is driven mainly by changes in Poaceae, which increased drastically in zone Poll-2. This increment should be a response to the volcanic event, because this family has a short life cycle, profiting very quickly from the nutrients supplied by volcanic eruptions. This response of Poaceae is quite similar to the Rondanelli (2001) description, with the exception that, in our results, the change was recorded within the tephra layer and not above it. This difference could be explained by the small size of Poaceae pollen, which allows its percolation through the interstitial spaces of the coarse tephra particles (up to 1 cm diameter). Similar findings have been recorded for Lake Icalma, where the percolation of fine sediments towards a tephra layer is described (Bertrand, unpublished data).

The increment of Poaceae (zone Poll-4) could be explained by anthropogenic influences or a period of low rainfall, which would also explain the decrease in *Blechnum*-type. Human activities in the upper part of the Andes near Lake Galletué have been recorded since the eighteenth century (Villalobos 1989); these activities have been mostly focused on *Araucaria araucana* and *Nothofagus dombeyi* (Mirb.) Oerst exploitation, explaining the decrease in *Araucaria araucana* over the last 40 years.

Arboreal *Nothofagus*-type and *Araucaria araucana* pollen also changed within the tephra layer, increasing and decreasing, respectively. These changes agree with previous studies (Heusser, Rabassa, Brandani, & Stuckenrath 1988; Ugarte 1993; Veblen & Schlegel 1982) that describe the same behaviour as a response to volcanic events.

According to our findings, the volcanic event in Lake Galletué provoked some changes in the vegetation community around the lake, producing favourable conditions for increased Poaceae. However, despite the changes described, the volcanic eruption did not generate catastrophic changes; there is no evidence of vegetable biomass burning in the sedimentary profile.

**Chironomids**

Heinrichs et al. (1999) noted an increase in the abundance of *Cricotopus/Orthocladius* after a deposition of Mazama ash layer at Lake Kilpoola (British Columbia). This, in conjunction with other assemblage characteristics, indicated an increase in salinity as a direct result of the volcanic deposition. Tsukada (1967) also reported diminished *Tanytarsus genuinus* abundance after two volcanic sediment deposition events in Lake Nojiri, Japan.

Massaferro and Corley (1998), working with subfossil chironomid assemblages from Lake Mascardi (41°20'S; 71°34'W), found sharp changes in chironomid diversity and equitability after the deposition of tephra layers that caused extreme conditions unsuitable for many species. Their results also indicated a complete absence of chironomid fauna within the tephra layers and a rapid recovery of diversity and equitability to their pre-disturbance level once the tephra deposition had terminated.

Our results for Lake Galletué indicated an overall decrease in the concentration of head capsules just after the tephra deposition. However, *Parakiefferiella* abundance increased noticeably in the assemblage segment corresponding to the tephra layer, whereas *Ablabesmyia* abundance decreased in the same strata. The different abundances of these taxa indicate that the tephra deposition could have provided an advantage to *Parakiefferiella* in comparison with other taxa like *Ablabesmyia* that were affected negatively.

On the other hand, unlike the works of Massaferro and Corley (1998) and Massaferro, Ribeiro-Guevara, Rizzo, and Arribére (2005), our results did not indicate important changes in chironomid diversity during tephra deposition and head capsules were present throughout the entire tephra layer. We explained this situation by the percolation of fine sediments (Fig. 4) and chironomid head capsules into the tephra layer (for details see Araneda et al., submitted). Thus, the stratigraphical Zone II (during the impact) revealed by the CONISS analysis could represent changes produced after the tephra deposition; this could also be the case for Zone III.

## General analysis

Some diatoms increase (*Cyclotella* af. *glomerata*) when tephra is deposited. Since other information indicates that *Cyclotella* grows in siliceous enriched environments, it is possible to infer that the tephra input in Lake Galletué altered the lake's Si/P ratio, producing a phosphorous limit that negatively affected *Aulacoseira granulata,* which has low competition skills under nutrient constrained environments. The increase in *Asterionella formosa* and *U. eriensis* after the tephra deposition suggests increased lake nutrient levels since these species indicate high nutrient contents. This change coincides with the increase of *Aulacoseira granulata* in the upper part of the core and the increase in total diatom concentrations, which can reflect a recuperation of the water column's phosphorous concentration, and a return to conditions similar to those existing before the tephra fall, possibly even a little higher.

Whereas diatoms undergo a noticeable change after tephra deposition, pollen assemblages do not show any important changes in this period. However, Poaceae pollen increased and *Blechnum*-type pollen decreased slightly. Since the pollen's response to this change is expected to occur after the tephra deposition, the presence of pollen within the volcanic sediments could be explained by percolation processes among the high interstitial spaces of the tephra particles (up to 1 cm in diameter). Thus, the changes observed within the tephra could represent conditions after the tephra fall. In fact, Besoain et al. (1992) found that tephra falls from the Lonquimay Volcano eruption (1989) increased the nutrient level in the soil, providing an advantage to agriculture. Applying this to the Lake Galletué tephra fall, one could argue that the increased Poaceae is due to increased soil nutrients from the tephra. The chironomids reacted to the tephra deposition through a taxa replacement more than a reduction in total abundance. This change is evident within the tephra layer and, as with pollen, its presence could be explained by the percolation of chironomid remains among the tephra particles, representing the changes that occurred once the tephra was already deposited.

## CONCLUSION

Our results show that tephra falls in Lake Galletué generate a noticeable change in the sedimentological parameters of the sediment column, as evident in the decreasing organic content, $^{210}$Pb dilution, and increasing grain size. All the biological proxies reflected changes-some more sensitively than others-in their assemblages due to the tephra deposition. The changes in diatoms were stronger than in the other proxies, certainly because the tephra fall affected the water column first and the short diatom life cycle allows them to respond quickly to the changes. Poaceae increased in pollen assemblages within the tephra layer, whereas a taxa replacement was evident in chironomids. The hierarchical arrangement of proxy sensitivity to tephra falls in Lake Galletué was: diatoms > chironomids > pollen.

In contrast to other studies, we found microfossil records within the tephra layer, probably due to percolation processes through the tephra particles, which were very coarse in this case. In spite of tephra depositions are instant events, and its impacts are recorder above it, in our case the effects of volcanic eruption are registered within the tephra.

Finally, we can state that the three proxies coincided in identifying the lake's recovery to conditions similar to those occurring before the volcanic event, indicating the lakes' high resilience, and on the other hand, to assess correctly tephra's effects on the aquatic biota, a good understanding of its sedimentological properties is required.

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