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Key Points:
- The 2011-2012 Cordon Caulle tephra reached Puyehue Lake through river transport
- We show that lakes do not act as passive tephra traps
- Small lakes with limited watersheds are better suited for volcanological studies

Supporting Information:
- Readme
- Movie S1

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Deposition of the 2011–2012 Cordón Caulle tephra (Chile, 40°S) in lake sediments: Implications for tephrochronology and volcanology

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Abstract Tephras preserved in lake sediments are commonly used to synchronize sedimentary archives of climate and environmental change and to correlate them with terrestrial environments. They also provide opportunities to reconstruct volcanic explosive activity, e.g., eruption frequency and tephra dispersal. Although sedimentary processes may affect the record of tephras in lakes, lake sediments are generally considered as one of the best archives of tephra stratigraphy. The 2011–2012 eruption of Cordón Caulle volcano (Chile, 40°S) offered an ideal opportunity to study the processes affecting tephra deposition in lakes. Although the prevailing westerlies transported the erupted pyroclastic material away from nearby Puyehue Lake, the tephra was identified within this relatively large lake with a thickness ranging from 1 to >10 cm. This is in contrast with smaller lakes, where tephra thickness was in agreement with ashfall distribution maps. Geomorphological observations and sedimentological analyses provide evidence that the tephra deposited in Puyehue Lake entirely consists of material reworked from the upper watershed, transported by rivers, and distributed by lake currents according to particle size and density. Our results have important implications for tephrochronology and volcanology. They suggest that (1) lakes do not act as passive tephra traps; (2) lakes with large watersheds record more eruptions than smaller lakes, which only register direct ashfalls, affecting conclusions regarding the recurrence of volcanic eruptions; and (3) using lakes with large watersheds for isopach mapping systematically leads to an overestimation of erupted tephra volumes. Smaller lakes with limited drainage basins are generally better suited for volcanological studies.

1. Introduction

Tephra layers preserved in lake sediments are frequently used to reconstruct past volcanic activity, including eruption frequency and magnitude, volume of erupted pyroclastic material, and geochemical evolution of volcanoes [e.g., *Kilian et al.*, 2003; *Stern*, 2008; *Molloy et al.*, 2009; *Watt et al.*, 2013; *Weller et al.*, 2014]. Lake sediments are particularly attractive because they generally preserve tephras much better than subaerial terrestrial environments, in which erosion and chemical alteration often limit reconstructions to very large eruptions (>10 cm thick tephras) [*Lowe*, 2011; *Fontijn et al.*, 2014]. Conversely, tephrochronology is commonly used to synchronize lake sediment cores studied for paleoenvironmental and paleoclimate reconstructions, as well as to link them to marine and terrestrial records [e.g., *Lowe*, 2011; *Blockley et al.*, 2012; *Kilian and Lamy*, 2012; *Moernaut et al.*, 2014]. This tool is particularly promising in southern South America, where volcanic eruptions are frequent and other dating techniques show limited results [*Fontijn et al.*, 2014].

The use of lake sediment archives in volcanology and tephrochronology is based on the principle that tephra preserved in lake sediments mostly reflects direct volcanic ashfall, i.e., atmospheric deposition, and that postdepositional processes do not significantly alter the original characteristics of the deposits. Although it is known that sedimentary processes may affect tephra deposition in aquatic environments [e.g., *Lowe*, 2011; *Cassidy et al.*, 2014], these processes are rarely taken into account when interpreting past tephra records. A precise understanding of the processes involved in tephra transport and deposition in lake environments is, however, critical to ensure (1) the accurate use of tephras to correlate sediment archives of past climate and environmental change, (2) the correct interpretation of lacustrine tephra records in terms of past volcanic activity, and (3) the appropriate selection of coring sites for volcanological studies.

Recent and well-documented volcanic eruptions offer ideal opportunities to study the processes that affect tephra transport and deposition and therefore to assess the potential and limitations of lake sediment archives in volcanology and tephrochronology. One such recent eruption is the 2011–2012 eruption of the Cordón Caulle volcano (CC) in south central Chile (40°S), which emitted large amounts of ash that covered important areas of Chile and Argentina within a few hours. Within a few days, the ash plume reached the cities of Bariloche, Buenos Aires, Montevideo, Cape Town, Perth, Adelaide, Melbourne, and Auckland, and it completed a full circle of the Southern Hemisphere within 2 weeks. Since this eruption occurred in a region rich in lakes (i.e., the Chilean Lake District), it provides a unique opportunity to study the sedimentary processes driving tephra deposition in lakes.

The goal of the present study is therefore to investigate the deposition of the 2011–2012 CC tephra in several lakes located in the vicinity of the source volcano to evaluate the potential intralake and interlake variations in sedimentological properties and composition of tephra deposits and to understand the sedimentary processes that are responsible for these differences. Ultimately, these results should allow us to assess the potential and limitation of lake sediments for tephrochronology and volcanology, as well as provide recommendations for the best sites to use for volcanological and tephrochronological studies. We specifically focused on Puyehue Lake, for three main reasons: (1) it is located in the immediate vicinity of CC; (2) it is representative of the other large piedmont lakes of south central Chile, which are frequently used for tephra studies (similar morphology, size, location relative to the main volcanoes, and limnology); and (3) it has a proven record of postglacial tephras, mostly from CC [*Bertrand et al*., 2008a].

2. Setting

2.1. The Puyehue-Cordón Caulle Volcanic Complex

The Puyehue-Cordón Caulle Volcanic Complex (PCCVC) belongs to the Southern Volcanic Zone of the Andes (SVZ, 33–46°S; Figure 1), which results from the subduction of the oceanic Nazca Plate under the South American Plate [*Stern et al*., 2007]. It is located within the central segment of the SVZ (CSVZ, 37–42°S), which is the most volcanologically active segment along the entire Andes cordillera [*Stern et al*., 2007]. Between 39 and 42°S, this segment consists of a narrow chain of middle to late Pleistocene and Holocene stratovolcanoes, mostly to the west of the drainage divide between Chile and Argentina. Eruptive products from CSVZ volcanoes are generally basaltic to rhyolitic in composition, with a predominance of basalts and basaltic andesites [*López-Escobar et al*., 1995; *Stern*, 2004].

The PCCVC is a large Pleistocene to Holocene volcanic fissure complex composed of a cluster of eruptive centers along a 20 km by 4 km NW-SE oriented ridge [*Gerlach et al*., 1988; *Lara et al*., 2006] (Figure 1). The complex is limited to the SE by Puyehue volcano, which has a 2.4 km diameter circular crater and reaches an elevation of 2236 m above sea level (asl) (Figure 1). The PCCVC is one of the largest volcanic fields in the CSVZ [*Stern et al*., 2007]. It has produced lava flows, widespread tephra fall deposits, and ignimbrites, with a composition evolving from basaltic in the mid-Pleistocene to rhyolite in the Holocene [*Gerlach et al*., 1988; *Lara et al*., 2006; *Singer et al*., 2008]. All historical eruptions of PCCVC occurred along the Cordón Caulle fissure [*González-Ferrán*, 1994] and very likely originate from the same interconnected shallow (5–9 km depth) magma reservoir [*Jay et al*., 2014]. Prior to the June 2011 event, large explosive eruptions had occurred in A.D. 1921–1922 and in A.D. 1960, during which large volumes of rhyolitic ash and pumice were transported toward Argentina by winds from the west and NW [*Katsui and Katz*, 1967; *González-Ferrán*, 1994; *Lara et al*., 2004; *Singer et al*., 2008]. The 1960 event, which occurred 47 h after the M_w 9.5 Valdivia earthquake, was characterized by the emission of 0.2 km^3 of lava and 0.06 km^3 of pumice [*Katsui and Katz*, 1967] that was deposited in the upper part of the Puyehue watershed and across the border with Argentina [*Wright and Mella*, 1963]. The 1921–1922 eruption seems to have been larger in magnitude (1.2 km^3 of lava and 0.4 km^3 of pumice), although very few historical reports are available [*Katsui and Katz*, 1967]. Tephra layers ascribed to these two historical eruptions of CC have been identified in several lake sediment records in Chile and Argentina [e.g., *Bertrand et al*., 2008a; *Daga et al*., 2008] (see *Fontijn et al*. [2014] for a review).

2.2. The 2011–2012 CC Eruption

After 51 years of quiescence, the CC volcano reawakened on 4 June 2011. The 2011–2012 eruption followed a period of 2 months of elevated seismicity along CC, which had considerably intensified in the 48 h prior to the

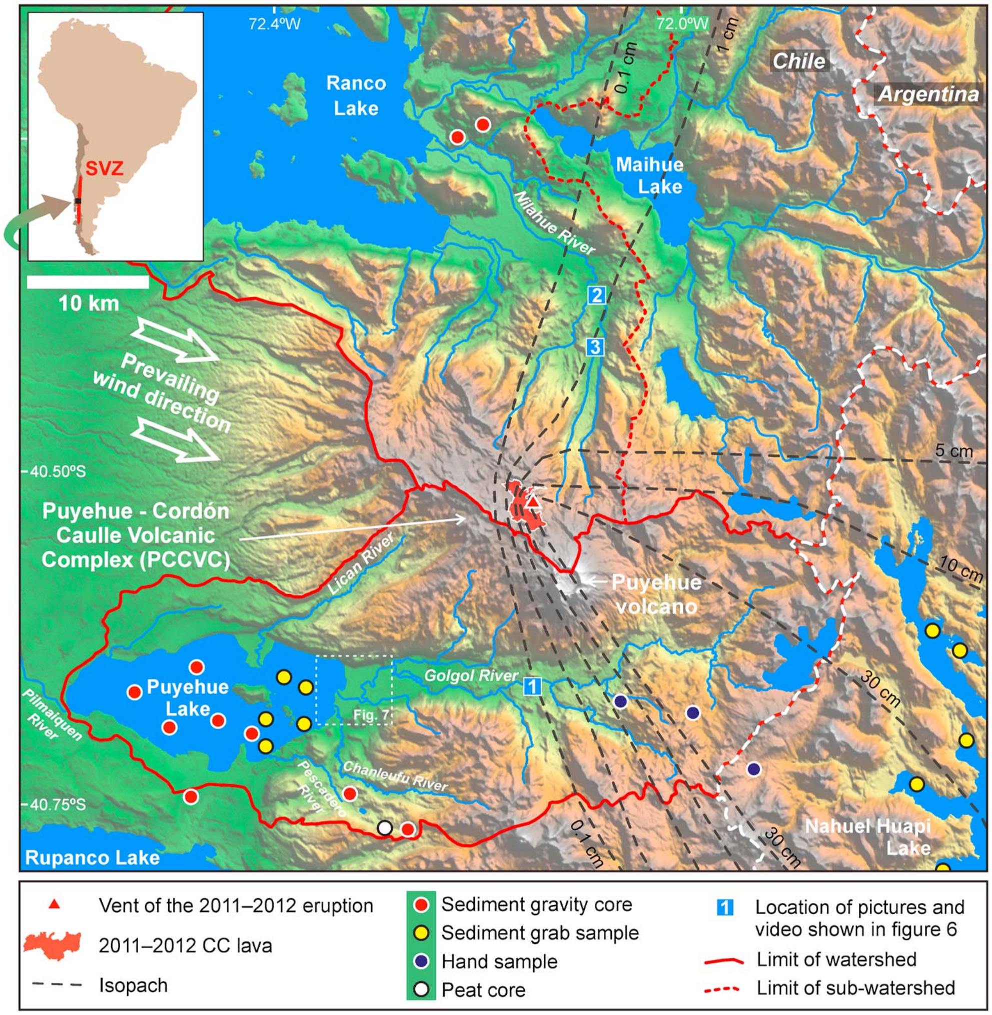

Figure 1. Map of the study area in south central Chile, showing the location of the sampling sites, lakes, and drainage basins discussed in this article. The map also shows the location of the 2011–2012 CC eruptive vent, the extent of the associated lava flow, and the isopachs of the associated ashfall. The isopachs were drawn by combining data from *Gaitán et al*. [2011a], *Romero* [2012], *Wilson et al*. [2013], and our own field observations. No lake sediment record was used to constrain the isopachs. Note the absence of direct ashfall above Puyehue Lake. An estimated volume of 0.12 km^3 of volcanic ash was deposited in the watershed of Puyehue Lake. SVZ: Southern Volcanic Zone (see section 2.1).

eruption, especially in the SE sector [*Abumohor and Díaz*, 2011; *Collini et al*., 2013]. It was a moderate size eruption (volcanic explosivity index 3–4) with an eruptive center, sometimes called the "We Pillán" vent, located on the northeastern side of the CC fissure about 7 km to the NW of the main Puyehue volcano (Figure 1). The eruption started with a 27 h long Plinian-style phase, during which the eruption column reached ~14 km above sea level [*Silva Parejas et al*., 2012]. Vigorous explosive activity continued over the next 7 to 9 days, with an eruptive column oscillating between 3 and 10 km in height (Figure 2a). Lava effusion started after about 10 days [*Castro et al*., 2013]. According to the daily reports of SERNAGEOMIN, the Chilean Geological Survey and agency in charge of monitoring the eruption, the emission of pyroclastic material ended on 23 April 2012, i.e., 324 days after the start of the eruption. During most of the eruption, the height of the eruption column oscillated between 2 and 8 km (Figure 2a). The eruption emitted several km^3 of pyroclastic products, although the exact volume remains poorly constrained due to the lack of a detailed and complete isopach map. *Silva Parejas et al*. [2012] estimated that between 0.5 and 1 km^3 of pyroclastic products (approximately 0.2–0.4 km^3 dense rock equivalent) were emitted during the first 27 h of the eruption alone, while *Gaitán et al*. [2011b] estimated that 1.46 km^3 of ash was deposited in the Argentine

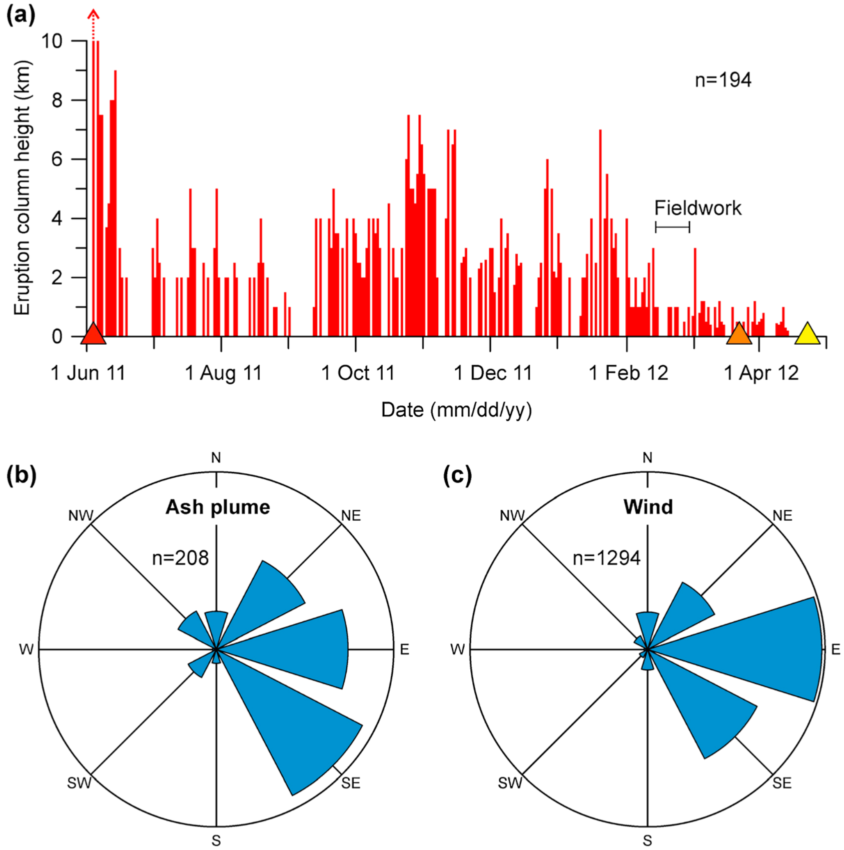

Figure 2. Observed height of the eruption column and direction of the volcanic ash plume during the 327 days of the 2011–2012 CC eruption (4 June 2011 to 23 April 2012). (a) Height of the eruption column according to the daily reports of SERNAGEOMIN (http://www.sernageomin.cl/volcan.php?iId=38). The triangles indicate the levels of alert set by SERNAGEOMIN (red, orange, and yellow). (b) Direction of the ash plume as detailed in the daily reports. (c) Wind direction at 700 mb (corresponding to an altitude of ~3000 m) for the 2.5 × 2.5° cell centered on 40°S and 72.5°W. The graph represents the direction the wind is blowing toward. Data from the NCEP/NCAR reanalysis 1 project (http://www.esrl.noaa.gov/psd/) in 6 h bins. Due to meteorological conditions, height and direction data in Figures 2a and 2b are limited to 59 and 64% of the days, respectively.

provinces of Río Negro and Neuquén (where roughly half of the tephra was deposited) during the first weeks of the eruption. In addition to the pyroclastic products, the eruption emitted an estimated volume of 0.45 km^3 of lava [*Bertin et al.*, 2012], which covered an area of about 7 km^2 (Figure 1). Part of the lava flow extended in the valley of Nilahue River toward the NE of the vent [*Tuffen et al.*, 2013].

Preliminary petrographic observations of proximal pyroclastic material demonstrated the dominance of white and highly vesiculated pumice lapilli and ash [*Collini et al.*, 2013]. The bulk geochemical composition of both pumice and lava is rhyodacitic to rhyolitic (69–70% SiO_2) [*Castro et al.*, 2013; *Collini et al.*, 2013]. The composition of the glass matrix is also predominantly rhyolitic (71–73% SiO_2) [*Castro et al.*, 2013], although there are indications of a cooccurring mafic component [*Collini et al.*, 2013; *Jay et al.*, 2014].

Due to the prevailing westerly winds, the volcanic ash was predominantly transported to the east and southeast toward Argentina, resulting in abundant ash fallout in the provinces of Río Negro, Neuquén, and Chubut [*Gaitán et al.*, 2011a; *Collini et al.*, 2013]. Wind direction, however, turned from toward the SE to toward the N-NE during the first 3 days of the eruption, which were the most explosive, (http://eoimages.gsfc.nasa.gov/images/imagerecords/50000/50882/puyehue_goe_2011155-157.mov), resulting in large amounts of volcanic ash also being transported toward Buenos Aires [*Collini et al.*, 2013]. A review of the SERNAGEOMIN daily reports shows that the direction of the ash plume had an easterly component during more than 75% of the observations (Figure 2b). Similarly, the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis wind direction data for the 324 days of the eruption display a dominant wind direction toward the east, with 81% of the observations containing a component toward the east (Figure 2c). The very few days with a wind direction component toward the north occurred during a period of weak volcanic activity near the end of June 2011 (Figure 2), which resulted in the transport of insignificant amounts of fine ash toward Ranco Lake [*Romero*, 2012] (Figure 1). Total ash thickness data show that the deposits are the thickest ($>$ 30 cm) in the upper part of Puyehue Lake drainage basin, in the direction of Nahuel Huapi Lake (Figure 1).

2.3. The Chilean Lake District

The CC volcano is located in a region rich in lakes (hence its common name "Chilean Lake District"), which was shaped by the complex interaction of Quaternary glaciations, volcanism, tectonics, and seismic activity. Most lakes are large piedmont lakes located at the western foothill of the Andes. They formed during the last glacial retreat, i.e., after 23 kyr B.P. [*Glasser et al*., 2008] and have since then continuously accumulated sediments, which have been used to reconstruct postglacial variations in climate [*Bertrand et al*., 2005], seismic activity [*Moernaut et al*., 2007, 2014; *Bertrand et al*., 2008b], and volcanic eruptions [*Bertrand et al*., 2008a; *Van Daele et al*., 2014]. These lakes are considered as one of the best archives of regional volcanic activity [*Fontijn et al*., 2014].

The present-day regional climate is humid temperate with Mediterranean influences. Precipitation is high year round but peaks in austral winter (June–August) [*Miller*, 1976]. It varies from $<$2000 mm/yr at the Andean foothills to $>$4000 mm/yr at high elevations in the Andes or on top of the regional volcanoes [*Parada*, 1973; *Hijmans et al*., 2005]. The region is also under the dominant influence of the southern westerlies, which strengthen in south central Chile during the winter months [*Miller*, 1976]. Mean annual air temperature is 6–9 °C, with maxima reaching 20°C in January and minima of 2°C in July [*Muñoz*, 1980]. The humid and temperate climate is responsible for the presence of a dense Valdivian temperate rain forest across the region [*Luebert and Pliscoff*, 2006].

2.4. Puyehue Lake: Limnology and Sediment Record

Puyehue Lake (40.65°S, 72.45°W) is one of the large glacial, moraine-dammed piedmont lakes that define the Lake District in south central Chile [*Campos et al*., 1989]. It is located at the western foothill of the Andes cordillera at an elevation of 185 m asl (Figure 1), and it is believed to occupy a glacial valley overdeepened by Quaternary glacial advances [*Laugenie*, 1982]. The lake is dammed to the west by several moraine ridges [*Bentley*, 1997]. It has a maximum length of 23 km, a maximum depth of 123 m, and a mean depth of 76.3 m [*Campos et al*., 1989]. Puyehue Lake covers 165.4 km^2 and is characterized by a complex bathymetry, with three subbasins and a series of small bedrock islands in its center [*Charlet et al*., 2008] (Figure 3). The largest subbasin occupies the western side of the lake. It is isolated from the northern and eastern subbasins by a lake-crossing ridge, which is interpreted as the continuation of an onshore moraine [*Bentley*, 1997]. The eastern subbasin is the deepest, even though this part of the lake receives large amounts of sediment from the Golgol and Lican Rivers. The northern subbasin is locked between the bathymetric ridge and the delta of Lican River.

The lake catchment covers 1510 km^2 and extends far to the east of the lake (Figure 1). It is mainly drained by the Golgol River, which originates at the border with Argentina and drains the southern flank of PCCVC (Figure 1). Golgol River discharge is approximately 3 times higher in winter and spring (274 m^3/s in August) than at the end of summer (73 m^3/s in March) [*Campos et al*., 1989]. The Lican River, which drains the southwestern part of CC, is the second largest inflow. Of lesser importance are the Chanleufu and Pescadero Rivers, which drain the southeastern part of the lake catchment (Figure 1). The outflow of Puyehue Lake (Pilmaiquen River) is located to the west. It cross cuts several moraine ridges [*Laugenie*, 1982; *Bentley*, 1997], merges with Bueno River, and flows westward into the Pacific.

According to *Campos et al*. [1989], the lake is stratified from spring to fall, the depth of the thermocline varying from 15 to 20 m in the summer months (January–March) when the vertical temperature gradient is the highest, to 40–60 m in spring (October–December) and fall (April–June). The lake waters are fully mixed in winter (July–September).

The sediment infill of Puyehue Lake has been investigated prior to the 2011–2012 CC eruption, using seismic profiling [*Moernaut et al*., 2007; *Heirman et al*., 2011] and sediment coring [*Bertrand et al*., 2005, 2008c], mostly

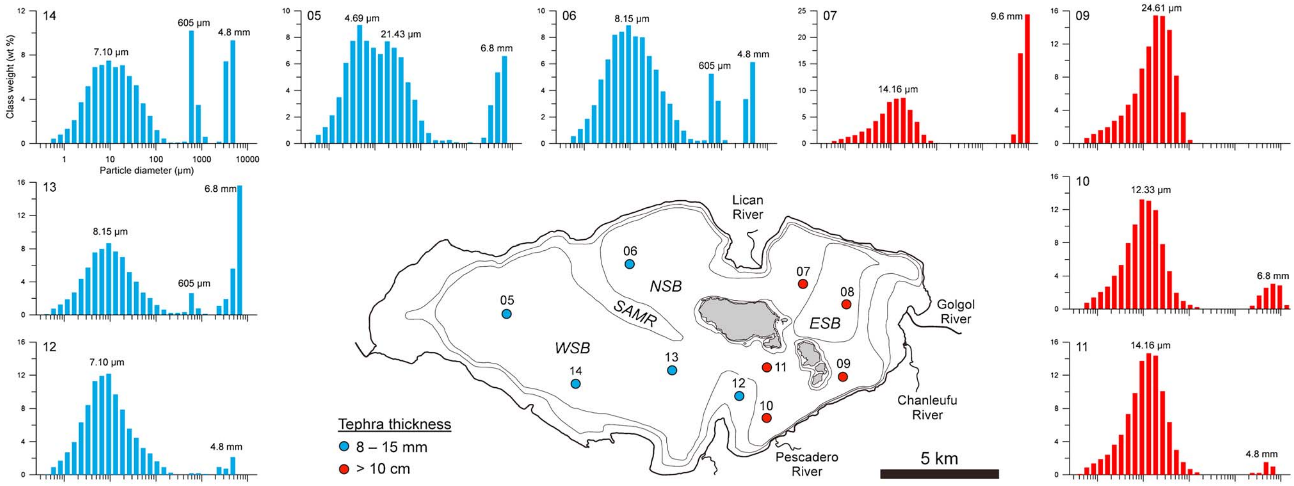

Figure 3. Thickness and grain size of the 2011–2012 CC tephra deposited in Puyehue Lake. The coring sites are located on the bathymetric map of *Campos et al.* [1989]. The isobaths are represented at 40, 80, and 120 m. WSB, NSB, and ESB refer to the western, northern, and eastern subbasins of the lake, as described by *Charlet et al.* [2008]. SAMR indicates the subaquatic moraine ridge. The 2011–2012 CC tephra was found at all coring locations. The values displayed on the grain size distribution plots correspond to the modes of the distributions. No grain size data were obtained at site 08 because sample amount was too small for accurate grain size analysis.

for paleoenvironmental and paleoclimatological purposes. In addition, the lake tephra record was studied by *Bertrand et al.* [2008a], who identified 78 tephra layers during the last 18 kyr. The two most recent tephras were attributed to the 1921–1922 and 1960 CC eruptions and consisted of thin (<1 cm) layers of fine-grained glass-rich particles and some pumice pebbles. Similarly, most prehistoric tephra layers consisted of ~1 cm thick grey or greenish clay layers frequently containing pumice pebbles. These clay layers were interpreted as the result of in situ weathering of pumice [*Bertrand et al.*, 2008c].

3. Methods

3.1. Sampling

Several lakes surrounding CC, including Puyehue, were sampled during a field expedition in 12–27 February 2012, i.e., toward the end of the 2011–2012 eruption (Figure 2). Our goal was to collect undisturbed sediment cores from lakes located in the vicinity of CC. We purposely did not focus on any specific lake, in order to represent all the natural environments that are used in tephrostratigraphy and tephrochonology. However, lakes in the region are of two main types: (a) large piedmont lakes at the foothill of the Andes, such as Ranco, Puyehue, and Rupanco (Figure 1) and (b) much smaller lakes randomly distributed on the western flank of the Andes. We therefore sampled (a) one of the large piedmont lakes (Puyehue) and (b) five relatively small lakes and one peat bog on both sides of CC (Figure 1). In Puyehue Lake, 10 sites were sampled, mostly at locations that had been sampled for sedimentological and tephrostratigraphical analysis prior to the 2011–2012 eruption [*Bertrand et al.*, 2008a; *Doom*, 2012] (Table 1). For the small lakes and the peat bog, we focused on sites that had previously been used for paleoenvironmental studies (e.g., Lago Pichilafquen [*Jara and Moreno*, 2014] and Los Mallines peat bog [*Vargas-Ramirez et al.*, 2008]), where Holocene tephra records had shown significant differences with the Puyehue tephra record [*Bertrand et al.*, 2008a]. In lakes that had never been previously investigated, we cored the deepest, generally central, part of the lake.

Where possible, the lake sediments were sampled using a short Uwitec gravity corer. Where tephra deposits were too coarse and/or thick to allow coring, samples were collected with a grab sampler. The samples collected with the grab sampler were directly transferred to plastic bags, avoiding the nontephra lake sediment, when applicable. In the laboratory, the cores were opened, photographed, and described (texture, structure, and Munsell color). They were then subsampled, focusing on the 2011–2012 CC tephra deposits that occurred at the very top of the sediment cores. Additional tephra samples were manually collected along international road 215 (Figure 1). All tephra samples were freeze dried prior to further processing.

Table 1. Location of the Samples Used in This Study[a]

Sample Name	Short Label	Sample Type	Latitude (°S)	Longitude (°W)	Depth (m)	2011–2012 CC Tephra			
							Grain Size (μm)		
						Thickness (mm)	Mode 1	Mode 2	Mode 3
				Puyehue Lake					
PU12-CCT05	05	UGC	40.66636	72.53761	100	8	4.69	21.43	6800
PU12-CCT06	06	UGC	40.64754	72.47665	120	8	8.15	605	4800
PU12-CCT07	07	GS	40.65503	72.39078	121	>100	14.16	–	9600
PU12-CCT08[b]	08	GS	40.66277	72.36925	123	>100	–	–	–
PU12-CCT09	09	GS	40.69012	72.37102	115	>100	24.61	–	–
PU12-CCT10	10	GS	40.70697	72.40878	111	>100	12.33	–	6800
PU12-CCT11	11	GS	40.68657	72.40868	114	>100	14.16	–	4800
PU12-CCT12	12	UGC	40.69738	72.42235	49	10	7.10	–	4800
PU12-CCT13	13	UGC	40.68768	72.45562	104	15	8.15	605	6800
PU12-CCT14	14	UGC	40.69277	72.50342	104	10	7.10	605	4800
				Los Mallines Peat Bog					
LM12-CCT01	01	PC	40.76790	72.29165	surface	0	–	–	–
				Lago El Toro					
TO12-CCT02	02	UGC	40.76896	72.26904	16	0	–	–	–
				Lago El Espejo					
ES12-CCT03	03	UGC	40.74242	72.32601	9.6	0	–	–	–
				Lago Pichilafquen					
PI12-CCT04	04	UGC	40.74468	72.48226	16	0	–	–	–
				Laguna Verde					
VE12-CCT15	15	UGC	40.24931	72.22021	23	1	16.26	–	–
				Laguna Lluvia (*Unofficial Name*)					
LL12-CCT16	16	UGC	40.23983	72.19521	16	1	74.31	–	–
				Forest Soils Along International Road 215					
PA12-CCT17	17	HS	40.68188	71.9887	surface	–	49	13600	54000
PA12-CCT18	18	HS	40.72414	71.92884	surface	–	32	9600	76500
PA12-CCT35	35	HS	40.67329	72.05987	surface	–	28	1200	26950

[a]The thickness and grain size of the 2011–2012 CC tephra are also indicated. See Figures 1 and 3 for graphical representation. UGC: Uwitec gravity core, GS: grab sample, PC: peat core, HS: hand sample.
[b]Not enough material for grain size analysis.

3.2. Grain Size

The grain size measurements were performed on a Malvern Mastersizer 2000 laser diffraction particle analyzer. Prior to grain size analysis, the samples were treated with boiling H_2O_2 (10%) and HCl (1%) to remove organic matter and possible carbonates, respectively. The samples were then boiled with sodium hexametaphosphate ($Na_4P_2O_7 \cdot 10H_2O$) to ensure complete disaggregation of the particles and subsequently introduced into the Hydro 2000G dispersion unit of the Malvern Mastersizer 2000 (pump speed: 2000 rpm, stirrer speed: 800 rpm, and ultrasounds: 20%). Grain size parameters are averaged over 10,000 scans. Since the detection range of the instrument is limited to particles < 2000 μm, samples containing coarse particles were first sieved at 500 μm, and their complete grain size distribution was analyzed by combining the laser diffraction and sieving methods. The fraction < 500 μm was measured as described above, and the > 500 μm particles were dry sieved in 0.5 phi steps. The final grain size distributions and statistical parameters were calculated with Gradistat 8.0 [*Blott and Pye*, 2001].

3.3. Geochemistry

Prior to geochemical analyses, the tephra samples were sieved at 32 and 500 μm, and only the 32–500 μm fraction was used for analysis, to avoid potential variations in geochemistry due to grain size differences (i.e., as a result of varying proportions of minerals in specific grain size fractions). The < 32 μm particles were discarded to limit bulk sample contamination by fine lake sediment particles and to ensure that the glass shards were large enough for electron microprobe analysis (EMPA). All the samples were then analyzed for bulk element composition by inductively coupled plasma-atomic emission spectrometry (ICP-AES) and for glass major element composition by EMPA.

For bulk geochemistry, the samples were prepared using a slightly modified version of the Li-metaborate (LiBr) fusion technique of *Murray et al*. [2000], which consists in mixing 50 ± 0.5 mg of sample with 200 ± 1.0 mg of ultrapure Li-metaborate (SCP Science) in 3 mL Pt:Au (95:5) crucibles, adding 10 μL of 25% LiBr, and fusing the mixture at 1050°C. The resulting glass beads were then dissolved in 25 ml of 5% HNO_3, and 13 elements, including Si, Na, and K, were measured on a JY Ultima C ICP-AES at the Woods Hole Oceanographic Institution, MA, USA. Analytical details are given in *Bertrand et al*. [2012]. The elemental concentrations were converted into oxide concentrations and normalized to 100%.

For glass shard geochemistry, between 8 and 36 shards per sample were analyzed by EMPA at the Research Laboratory for Archaeology and the History of Art at the University of Oxford, UK. The glass shards were first manually picked under binocular microscope and then mounted in epoxy resin following *Lowe* [2011]. Their geochemical composition was measured on a JEOL JXA-8600 Superprobe set at 15 kV and 6 nA. Beam size was widened to 10 μm, and Na was analyzed first. Accuracy was verified using three international glass standards (ATHO, STHS, and T1). The measured values were always within 2σ of the recommended values.

3.4. Satellite Images

To understand the impact of the 2011–2012 CC eruption on the regional sedimentary environments, e.g., lake watersheds and lake surface, and therefore ensure a comprehensive understanding of the sedimentary processes that may affect tephra recorded in lake sediments, we reviewed all regional images obtained by satellites Landsat 4–8 and EO-1 between the start of the eruption and 3 months after its end. The images were obtained through the U.S. Geological Survey Earth Explorer application (http://earthexplorer.usgs.gov/) and were processed in Global Mapper v14.2.

4. Results

In Puyehue Lake, sediment cores were obtained in the western subbasin, northern subbasin, and on the southern branch of the subaquatic moraine ridge (Figure 3). In the deep eastern subbasin and in the southeastern part of the lake, only grab samples could be taken due to coarse and/or dense tephra deposits that prevented penetration of the gravity corer (Figure 3 and Table 1). The 2011–2012 CC tephra was clearly observed at all sampling sites. Tephra thickness in the sediment cores varied between 8 mm (PU12-CCT05 and 06) and 15 mm (PU12-CCT13) (Table 1 and Figure 3). In the grab samples, tephra thickness could not be precisely measured but it was $>$ 10 cm. The grain size distributions of the 2011–2012 CC tephra samples in Puyehue Lake were generally bimodal or trimodal (Figure 3), with a silt mode (4–25 μm), a pebble mode (4.8–9.6 mm), and sometimes an intermediate coarse sand mode (~600 μm). The silt mode was consistently finer (4–8 μm) on the western side of the lake (i.e., at sites where tephra thickness $<$ 15 mm) than on the eastern side (12–25 μm) (Figure 3). In addition, the proportion of pebble size particles was generally higher in the samples collected on the western side of the lake (Figure 3). The particles composing the pebble mode always consisted of relatively rounded white pumice.

By comparison, the 2011–2012 CC tephra was not observed in the small lakes or in the peat bog located to the south of CC (Figure 4). In Laguna Verde and Laguna Lluvia, which are located immediately to the north of CC, the tephra occurred as a ~1 mm layer of grey beige silt particles (Table 1 and Figure 4). In Laguna Verde, part of these fine-grained particles was possibly still in suspension at the bottom of the lake during coring (Figure 4). By comparison, along international road 215 the 2011–2012 CC tephra occurs as a relatively thick (mostly $>$ 30 cm) deposit and is mostly composed of gravel size particles (lapilli), up to 10 cm in diameter (e.g., sample PA12-CCT35; Table 1).

The bulk geochemical composition of the 2011–2012 CC tephra samples is rhyolitic (Figure 5a). The tephra deposited in lake sediments was, however, significantly enriched in SiO_2 (72.78 ± 0.71%) compared to

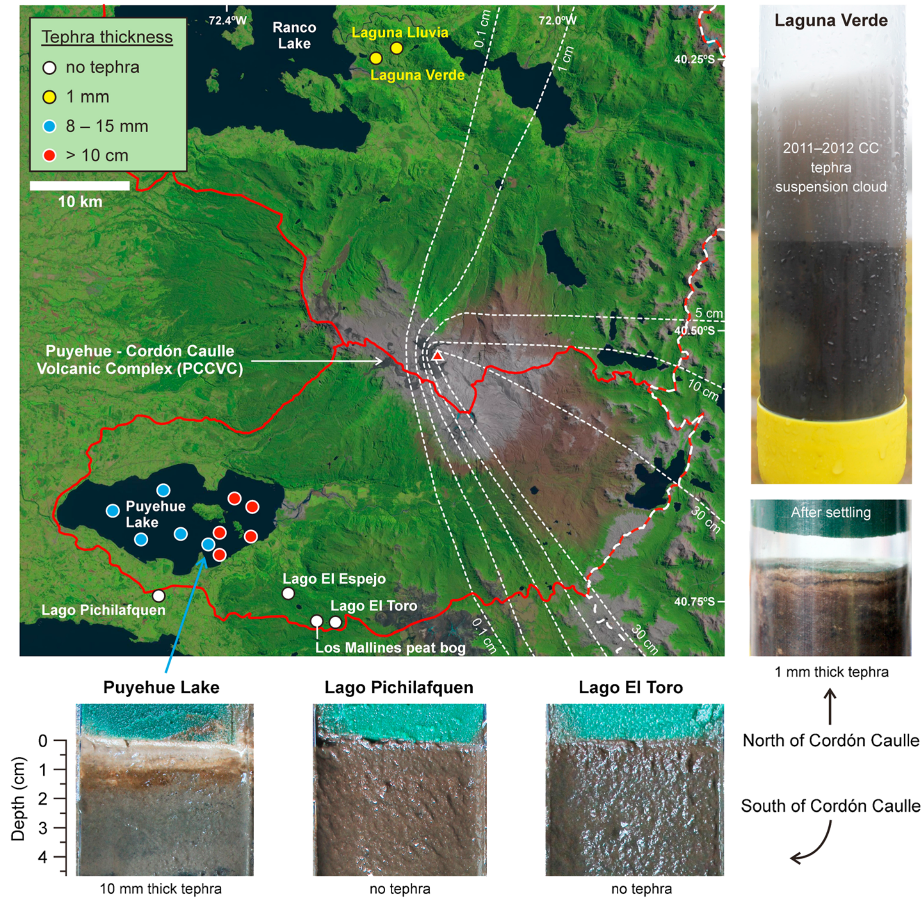

Figure 4. Presence/absence and thickness of the 2011–2012 CC tephra in Puyehue Lake and surrounding lakes and peat bogs. The background is a Landsat 8 image taken on 26 February 2014. The sediment core pictures illustrate the 2011–2012 CC tephra at several representative sites. The green material visible above the sediment is floral foam used to preserve the sediment-water interface at the end of the coring operations.

the samples collected along international road 215 (69.69 ± 0.76% SiO_2). The total alkali concentrations ($Na_2O + K_2O$) of the two sets of samples were indistinguishable (7.47 ± 0.32%).

The 203 analyzed glass shards were also of rhyolitic composition (70.49 ± 0.74% SiO_2; 8.03 ± 0.20% $Na_2O + K_2O$), with no significant difference between the samples preserved in lake sediments and those collected along international road 215 (Figure 5b).

5. Discussion

5.1. Source of the 2011–2012 CC Tephra Deposited in Lake Sediments

Due to the westerly winds that prevail in southern South America, most ash emitted during the 2011–2012 CC eruption was transported toward the east and southeast, i.e., toward Argentina (Figures 1, 2b, and 2c). During the first 27 h of the eruption, which were the most explosive and during which most of the pyroclastic products were erupted, the winds were blowing toward the SE, i.e., toward Nahuel Huapi Lake. As a result, the isopach map of the 2011–2012 CC tephra shows a distribution predominantly toward the SE (Figure 1). This trend is in general agreement with other regional eruptions, e.g., the 2008 Chaitén eruption [*Watt et al*., 2009]. Since only 11% of the eruption days had a wind direction toward the north or NW, direct ashfalls around Ranco Lake are limited to < 1 mm thickness (Figure 1). Similarly, wind direction toward the south and SW only occurred during 6.5% of the time, resulting in virtually no ashfall over lakes Puyehue and Rupanco (Figure 1).

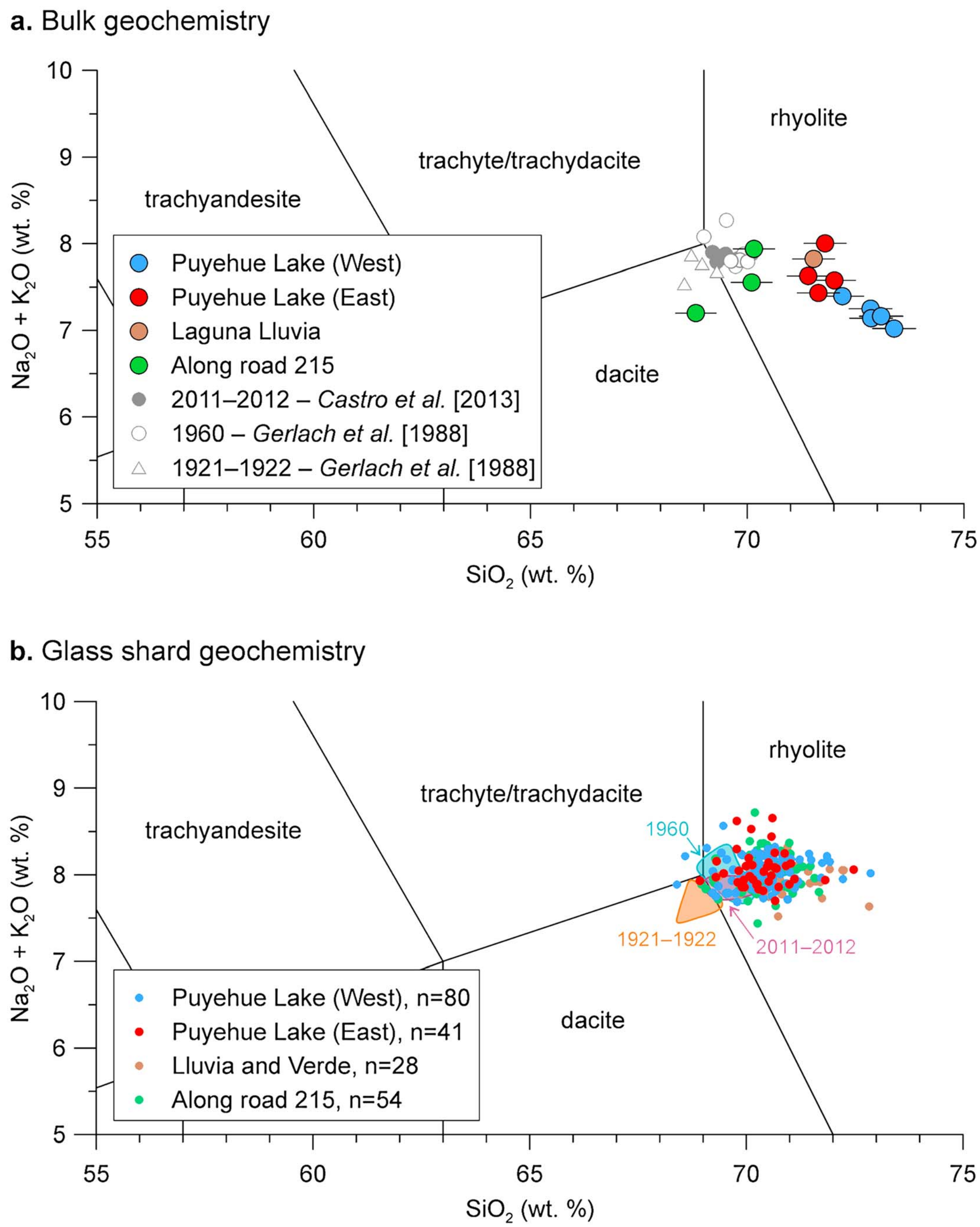

Figure 5. Bulk and glass shard geochemistry of the 2011–2012 CC tephra samples collected in Puyehue Lake and along international road 215, presented in a TAS diagram [*Le Bas et al*., 1986]. (a) Bulk geochemical data of the 2011–2012 eruption compared to those of *Castro et al*. [2013]. Bulk geochemical data of the 1921–1922 and 1960 CC eruptions [*Gerlach et al*., 1988] are also shown for comparison. The Puyehue Lake tephra samples likely contain some amount of lake plankton (e.g., biogenic silica) that could not be removed during sample preparation, resulting in an apparent enrichment in SiO_2. Sample PU12-VE15 (Laguna Verde) did not contain enough material for bulk geochemical analysis. The vertical error bars are smaller than the size of the symbols. (b) Glass geochemical data compared to the whole rock data of *Gerlach et al*. [1988] and *Castro et al*. [2013], as above.

The thickness of the 2011–2012 CC tephra in lakes Lluvia and Verde (~1 mm), which are located to the north of the CC, is in good agreement with the thickness of the terrestrial ashfall deposits (Figure 4). Similarly, the absence of the 2011–2012 CC tephra in lakes Pichilafquen, El Espejo, El Toro, and in the Los Mallines peat bog is in agreement with the isopach map, which indicates that virtually no ash fell over this region (Figure 4). The

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thickness of the 2011–2012 CC tephra in Puyehue Lake (from 8 mm to > 10 cm), however, is in contradiction with the isopach map, according to which no ash fell over the lake (Figure 4). A detailed analysis of the watershed of Puyehue Lake, however, shows the presence of abundant pyroclastic material from the 2011–2012 CC eruption in the upper part of the drainage basin (Figure 4), suggesting that tephra initially deposited in the upper part of the watershed was reworked and transported toward Puyehue Lake by rivers, mostly the Golgol. According to the available ashfall thickness information (isopachs in Figures 1 and 4), at least 0.12 km^3 of pyroclastic material was deposited in the watershed of Puyehue Lake. This interpretation is confirmed by reports from rangers of Puyehue National Park, who observed volcanic ash being transported downstream by the Golgol River during the 2011–2012 CC eruption (Figure 6a). Similarly, *Collini et al.* [2013] describe the fluvial remobilization of fine ash and low-density pumice in the mountainous environments near CC. In addition to the Golgol River, volcanic ash was also reported in Nilahue River, which drains the northern flank of CC and discharges into Ranco Lake (Figure 1). In Nilahue River, pumice up to > 10 cm was seen floating in the river and deposited on its shores (Figures 6b and 6c).

The transport of large quantities of tephra toward Puyehue Lake by the Golgol River is further supported by the geomorphic evolution of the Golgol delta during and after the eruption (Figure 7). Before the 2011–2012 CC eruption, the lower part of the river channel was oriented in a mostly E-W direction (Figure 7a). During the eruption, the main channel filled with tephra (C. Vejar, personal communication, 2013), resulting in the avulsion of the lower ~3 km of the river through two new meanders, from which pyroclastic material was discharged into Puyehue Lake,

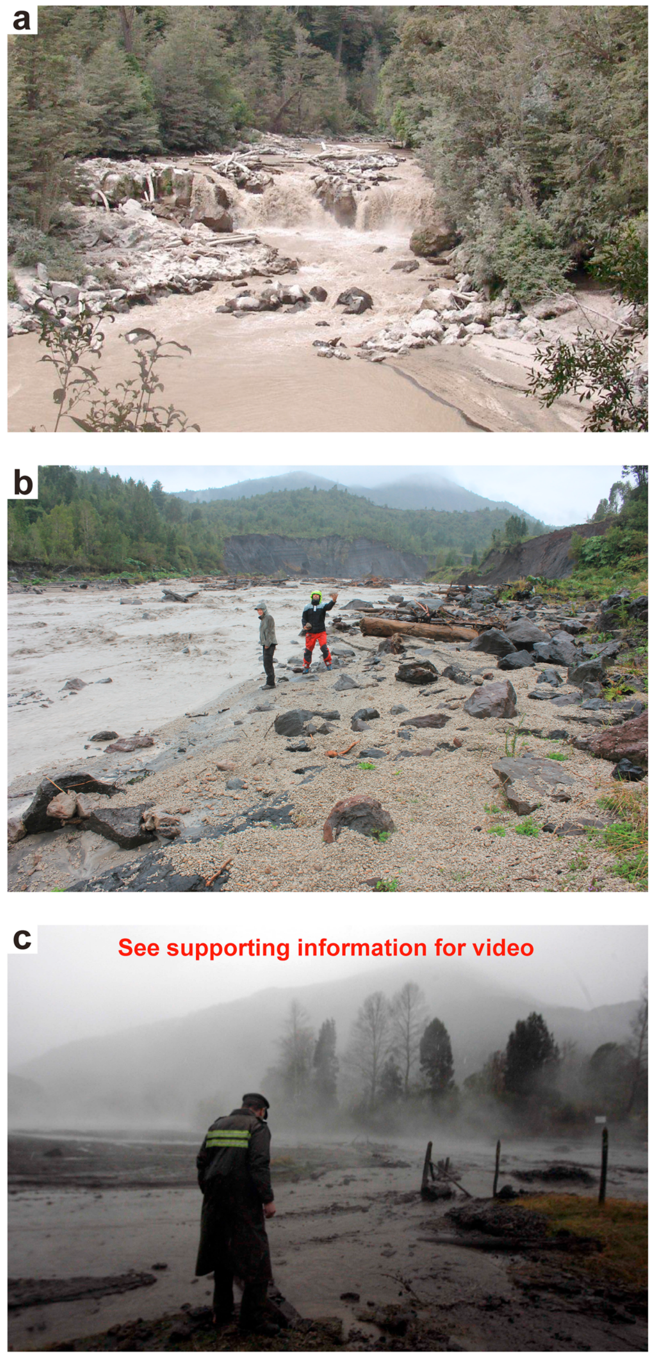

Figure 6. Photos of Golgol and Nilahue Rivers transporting pumice and ash toward Puyehue and Ranco Lakes, respectively. (a) Golgol River at Salto los Novios, approximately 20 km upstream of the lake, in July 2011 (credit: Eduardo Mora, CONAF Puyehue); (b) Nilahue River upstream of the junction with Rio Los Venados, approximately 20 km upstream of Ranco Lake, on 17 February 2012; (c) video of volcanic material being transported by Nilahue River on 9 June 2011. The location is approximately ~5 km upstream of Figure 6b (See Movie S1 in the supporting information for video; video credit: Reuters/TVN Chile.). See Figure 1 for location. Note the presence of ash and pumice up to 20 cm in diameter in Figures 6b and 6c.

including floating pumice (Figure 7b). Comparison of satellite images from before and after the eruption shows a progradation of the Golgol River delta by about 0.36 km^2 (Figure 7c), resulting from the deposition of at least 2.6×10^6 m^3 of pumice and ash at the river outflows. This avulsion and progradation process is very similar to what occurred in the Chaitén River during the 2008 eruption of Chaitén volcano in southern Chile [*Pierson et al.*, 2013]. In the Golgol River, the erosion and river transport of pyroclastic material was probably enhanced by the relatively high precipitation that fell in the region on the days that followed the eruption (15–18 mm/d on 6–8 June; Futacuhuin DGA meteorological station), which resulted in a fourfold increase of Golgol River discharge on 10–12 June compared to the previous 2 months (Golgol Puente 2 DGA station). Golgol River discharge may also have been amplified by the reduction of rainwater infiltration rates due to deposition of relatively impermeable pyroclastic material [*Pierson and Major*, 2014].

From this information, it is clear that virtually all the pyroclastic material that reached Puyehue Lake was supplied by local rivers, mostly the Golgol. A conservative estimate of the total volume of pyroclastic material deposited in Puyehue Lake (based on the measured tephra thickness) shows that about 5% of the material deposited in the lake

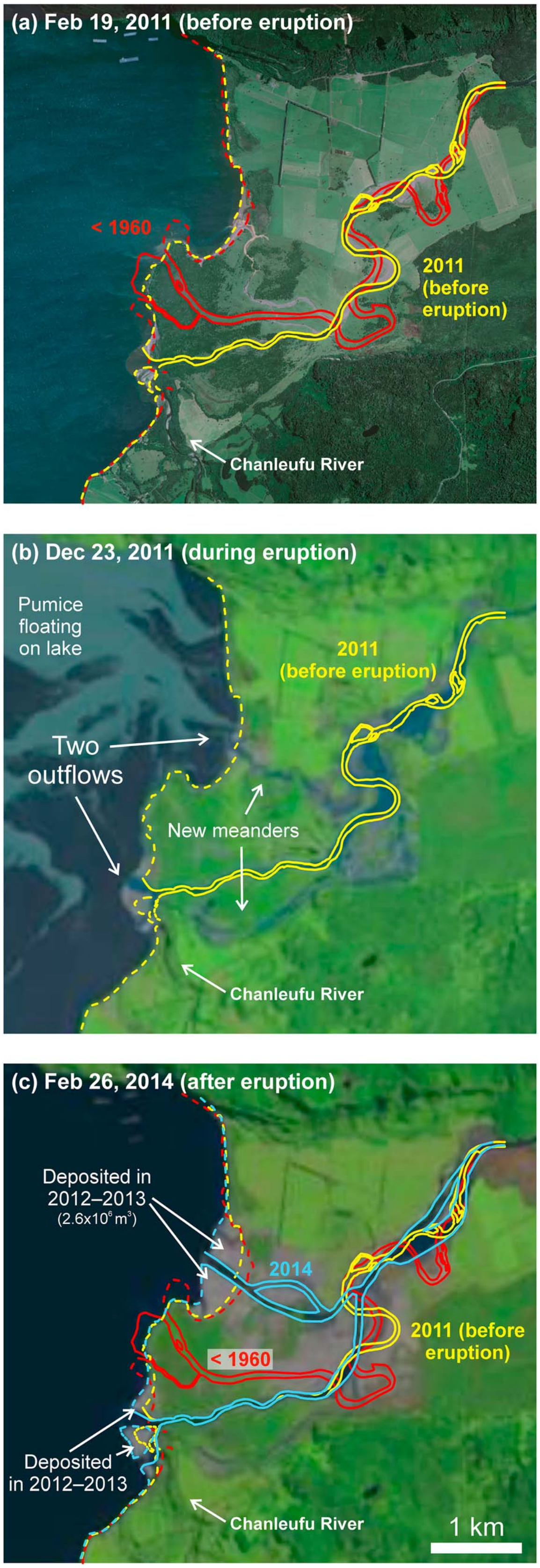

Figure 7. Effect of the 2011–2012 CC eruption on the morphology of the fluvial plain of Golgol River. (a) Immediately prior to the eruption (Digital Globe image of 19 February 2011; obtained through Google Earth). (b) During the eruption (EO-1 image of 23 December 2011), also showing pumice floating on Puyehue Lake. (c) Nearly 2 years after the end of the eruption (Landsat 8 image of 26 February 2014). Large amounts of volcanic material obstructed the main river channel during the eruption, which resulted in the formation of several new meanders and an additional inflow. The Golgol River currently flows into Puyehue Lake at two distinct locations 2 km apart from each other (see Figure 7c). Also note the accelerated progradation of the delta due to the rapid accumulation of volcanic material in 2012–2013 (see Figure 7c). Accumulation of volcanic material reduced the lake surface area by 0.36 km^2. The estimated volume of volcanic material that accumulated in front of the new northernmost inflow is 2.6×10^6 m^3, which represents about 2% of the volume of tephra deposited in the lake watershed. The location of the pre-1960 meanders is based on a Trimetrogon aerial image from 1944.

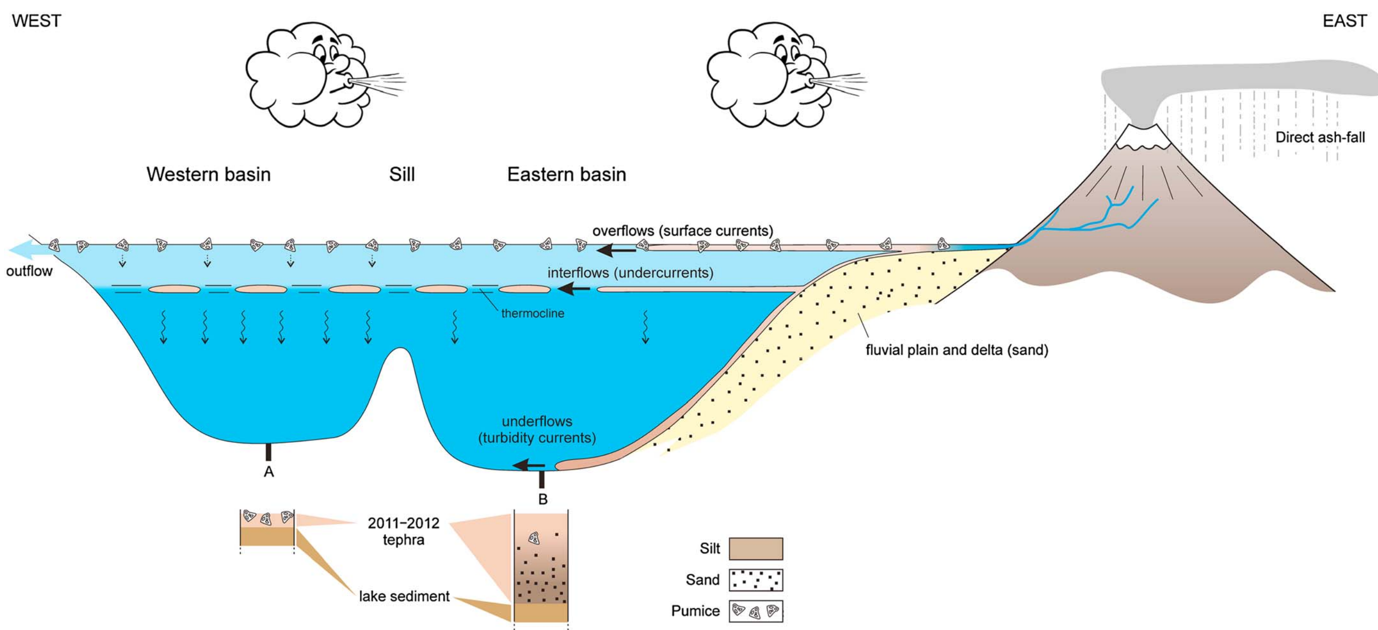

Figure 8. Schematic illustration of the lake currents that are responsible for transport of the 2011–2012 CC tephra in Puyehue Lake. In the proximal deep (eastern) basin, the tephra mostly consists of a thick layer of relatively coarse silt particles transported by underflows (schematic core B). A bathymetric sill restricts the underflows to the eastern part of the lake. In the distal (western) basin, the tephra is mostly composed of a thin layer of fine silt transported by interflows (schematic core A). It also contains pumice lapilli transported by overflows. Due to their low density, pumice generally settles after the silt size particles [*White et al.*, 2001]. Illustration inspired by *Sturm and Matter* [1978] and *Van Daele et al.* [2014].

watershed had been remobilized and deposited within the lake by February 2012, in addition to the ~2.2% that caused the progradation of the delta.

5.2. Redistribution by Lake Currents

Within Puyehue Lake, important differences in tephra thickness and grain size were observed between the proximal eastern basins and the distal western basins (Figure 3). In the deep proximal basins, the 2011–2012 CC tephra is generally thick ($>$ 10 cm), the silt mode is relatively coarse (12–25 μm), and the relative amount of pumice pebbles is limited (Figure 3). By comparison, the 2011–2012 CC tephra deposited in the shallower distal western basins is thinner (8–15 mm), the silt mode is finer (4–8 μm), and the proportion of pumice is higher. These differences highlight the importance of lake currents in transporting the pyroclastic material supplied to Puyehue Lake by the Golgol River.

We propose that these intralake differences are due to the redistribution of the pyroclastic material by lake currents, in the sense of *Sturm and Matter* [1978]. The thick and relatively coarse silty deposits in the deep proximal basins most likely represent particles transported by underflows (or hyperpycnal flows), which are restricted to deep proximal basins and typically do not go over bathymetric sills such as the subaquatic moraine ridge [*Sturm and Matter*, 1978; *Bertrand et al.*, 2005] (Figure 8). The finer particles that reached the western, more isolated, subbasins in lesser amounts, however, most likely represent pyroclastic material transported by interflows, which are typically able to travel across entire lake basins (Figure 8). In addition, we suggest that the pumice that is observed at all coring locations, except for site PU12-CCT09, results from the sporadic sinking of pumice transported at the surface of the lake by overflows (Figure 8). We attribute the higher proportion of pumice in the western basin to a lower degree of dilution by silt size particles.

The surface transport of floating pumice is supported by satellite observations, which show the presence of pumice at the surface of Puyehue Lake during the entire duration of the eruption, as well as during the months that followed (Figure 9). Most images show the short-term accumulation of floating pumice toward beaches on the SE part of the lake, most likely during days with strong westerly winds. The images, however, also show that in the long term, pumice is effectively transported to the western part of the lake, i.e., toward the lake outflow, in the direction opposite to the westerlies (e.g., Figure 9c). The presence of pumice in the

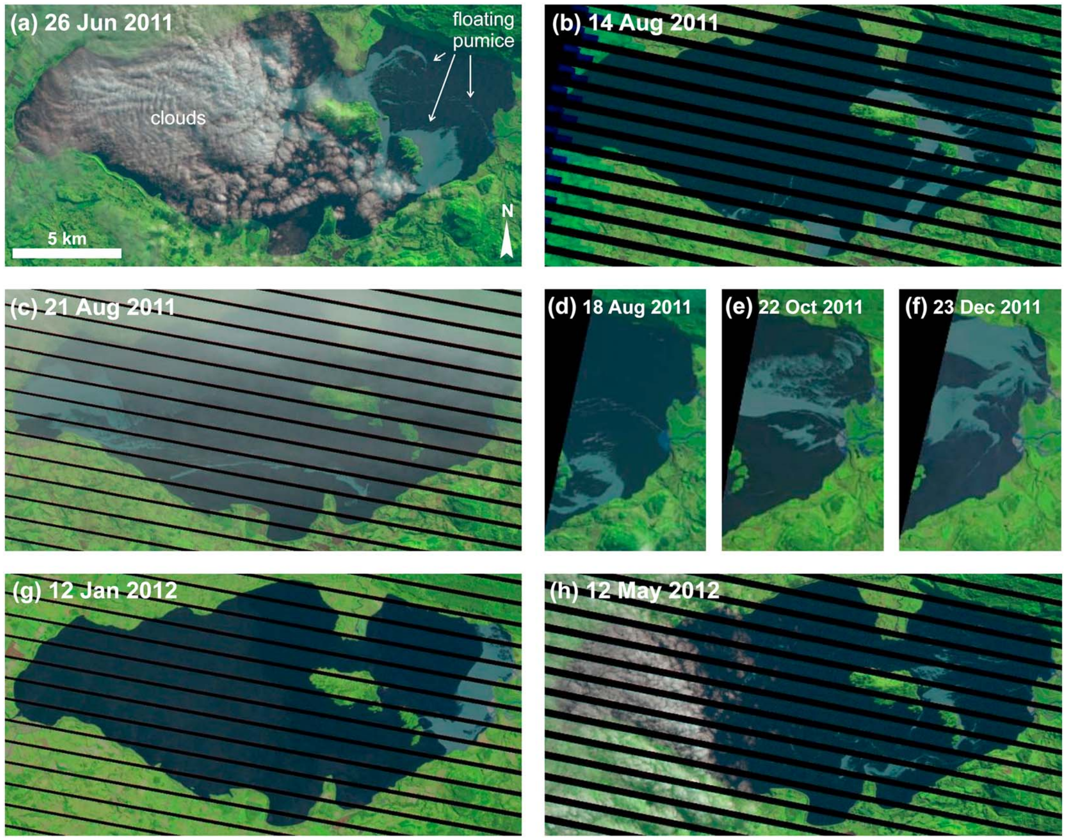

Figure 9. Satellite images showing the presence of pumice floating on Puyehue Lake during the entire duration of the eruption (Figure 9a was taken 22 days after the start of the eruption, and Figure 9h is after the end of the eruption.). The images show that despite the prevailing westerly winds, floating pumice reached most parts of the lake, including its western end (see image c). Image sources: (a) Landsat 5; (b, c, g, and h) Landsat 7; (d, e, and f) Earth Observing 1 (EO-1). The black stripes in Figures 9b, 9c, 9g, and 9h are due to the permanent failure of the Scan Line Corrector (SLC) of the Landsat 7 satellite on 31 May 2003. Floating pumice was also observed on lakes Ranco and Maihue (see location in Figure 1) and on other lakes located under the volcanic ash plume.

sediments of the western basin therefore results from the transport of floating pumice by surface currents and their subsequent sinking after water saturation, which typically occurs after a few weeks, depending on grain size and vesicularity [*White et al*., 2001].

The transport and sedimentation model proposed above implies the cooccurrence of overflow, interflow, and underflows, which requires lake thermal (and therefore density) stratification [*Sturm and Matter*, 1978]. Although Puyehue Lake is typically not stratified in winter (see 2.4 above) [*Campos et al*., 1989], i.e., when the eruption started, the discharge of pyroclastic material by the Golgol River occurred during almost an entire year, meaning that the lake was stratified during most of the period during which tephra was discharged from rivers. A similar process was recently described by *Van Daele et al*. [2014] to explain differences in the sedimentological signature of lahar deposits from Villarica volcano in the distal and proximal basins of nearby lakes Villarica and Calafquen.

5.3. Tephra Geochemistry

The bulk geochemical composition of the pumice collected along international road 215 is statistically indistinguishable from that of the 2011–2012 CC pumice lapilli reported by *Castro et al*. [2013] (Figure 5a). Compared to these tephra samples collected on land, the 2011–2012 CC tephra samples preserved in lake sediments are systematically enriched in SiO_2 and proportionally depleted in most of the other major elements. This can be explained by the contamination of the bulk lake tephra samples by biogenic silica, mostly diatoms, which is the most abundant form of plankton in Puyehue and nearby lakes [*Campos et al*., 1989; *Sterken et al*., 2008] and may bloom immediately after an eruption due to the increased nutrient input

[*Cruces et al*., 2006]. This explanation is supported by the association of the highest SiO_2 values with the thinnest tephras in the western part of Puyehue Lake (Figure 5a), in which contamination was likely proportionally more important. Although the tephra samples were sieved at 32 μm to eliminate most of the host sediment, it appears that this procedure did not completely prevent contamination, most likely because lake diatoms can reach up to 100 μm in size [*Bertrand et al*., 2008c]. These results show that the bulk geochemical composition of tephras separated from lake sediments is not appropriate to accurately determine tephra composition, in agreement with previous observations [e.g., *Lowe*, 2011]. It should therefore not be used as a correlation tool in tephrochronology. Compared to the geochemical composition of the lavas emitted during the 1960 and 1921–1922 eruptions [*Gerlach et al*., 1988], the bulk composition of the 2011–2012 CC terrestrial tephras is similar within 1 and 2 sigma, respectively (Figure 5a).

The glass composition of the terrestrial tephra samples collected along international road 215 is clearly rhyolitic (Figure 5b), in agreement with the composition of the lavas and pumice. The composition of the glass shards that were separated from the lake tephra samples is identical within analytical error, indicating that there is no contamination or alteration of the glass shard composition during tephra transport and deposition in lakes. This therefore confirms the usefulness of glass shard geochemistry to correlate tephras between aquatic and terrestrial environments. However, the major element composition of the 2011–2012 glass shards is also identical to that of tephra and lavas from the 1960 and 1921–1922 eruptions (Figure 5b), making it impossible to discern these three eruptions based on major element analysis of glass shards alone. This observation confirms previous statements by *Daga et al*. [2006, 2014], *Bertrand et al*. [2008a], *Silva Parejas et al*. [2012], and *Jay et al*. [2014], who emphasized the similar geochemical composition of the pyroclasts from the three historical CC eruptions.

One tool that could potentially provide clues to differentiate the 1921–1922, 1960, and 2011–2012 tephras is the trace element composition of glass shards. Preliminary results by *Daga et al*. [2006, 2014] revealed slight differences between the Cr and V concentrations of the glassy fraction of the 1921–1922, 1960, and 2011–2012 tephras, although large differences in these elements were also observed between tephra erupted on different days of the 2011–2012 eruption. Trace element analysis of glass shards, however, requires the use of laser ablation-inductively coupled plasma-mass spectrometer or ion probe instrumentation, which is not always readily available and remains relatively expensive [*Lowe*, 2011]. Another possible way to distinguish between the three tephras lies in mineral composition analyses, which have proven more successful than glass major element composition in a number of cases, especially where highly evolved magmas are involved [e.g., *Fierstein*, 2007; *Smith et al*., 2011].

5.4. Comparison With Previous CC Eruptions

Tephras related to the previous eruptions of CC in 1921–1922 and 1960 were identified in the sediments of Puyehue Lake by *Bertrand et al*. [2008a], as well as in several lakes located to the SE of CC, in Argentina, such as Nahuel Huapi and Moreno [*Daga et al*., 2008]. Similar to the 2011–2012 eruption, the 1921–1922 and 1960 tephras were not identified in the sediments of Lago Pichilafquen [*Jara and Moreno*, 2014] nor in the Los Mallines peat bog [*Vargas-Ramirez et al*., 2008]. In Puyehue Lake, the 1921–1922 and 1960 tephras bear strikingly similar characteristics with the 2011–2012 CC tephra in terms of geochemistry, color, thickness, and grain size. To the west of and on the subaquatic moraine ridge, the 1921–1922 and 1960 tephras are composed of 0.2–0.5 mm thick light grey or green layers that are fine grained (13–16 μm) and rich in volcanic glass [*Bertrand et al*., 2005, 2008a]. In cores collected in the deep eastern basin, on the other hand, the 1921–1922 and 1960 tephras are thicker, coarser, and darker.

Historical reports from the 1960s provide evidence that the 1960 CC eruption was in many aspects similar to the 2011–2012 event. The only significant difference was that several vents were involved in the 1960 fissure eruption, whereas only one vent opened in 2011–2012 [*Katsui and Katz*, 1967; *Lara et al*., 2006; *Collini et al*., 2013]. Similar to the 2011–2012 eruption, pyroclasts of the 1960 eruption were mostly transported toward Argentina by winds from the W and NW, and no ash was observed at 4 km to the NW of the 1960 vents [*Katsui and Katz*, 1967]. The greatest tephra thickness (~10 cm) was observed at the Chile-Argentina border along international road 215 [*Katsui and Katz*, 1967], suggesting that most of the 1960 tephra was deposited to the ESE of the source vents. This implies that in 1960, the upper part of the Puyehue watershed was also covered in a thick layer of pyroclastic material and that no ash fell directly over Puyehue Lake. Furthermore, *Wright and Mella* [1963] describe that intense rainfalls during the days that followed the 1960 eruption caused the rapid reworking of the pyroclastic material, which may be responsible for the formation of new meanders in the lower part of Golgol River, as in 2011–2012 (Figure 7). The rapid morphological evolution of the Golgol River delta after the 1960 eruption may, however, also have been due to the preceding earthquake that triggered landslides in the Golgol valley [*Wright and Mella*, 1963; *Chapron et al*., 2007]. Fragmentary reports about the 1921–1922 eruption indicate that it must have been similar to the 1960 event, with several active vents and the transport of pyroclasts toward the SE, although the estimated volume of erupted material was 6–7X higher in 1921–1922 than in 1960 [*Katsui and Katz*, 1967].

Given the similarities between the 1921–1922, 1960, and 2011–2012 eruptions, especially regarding the direction of the ash plume and the resulting distribution of pumice-rich pyroclastic material in the upper part of the Golgol River basin, we infer that the 1921–1922 and 1960 tephras identified in Puyehue Lake sediments do not represent direct ashfalls either but are also the result of reworking processes in the upper part of the lake watershed and subsequent delivery to the lake via river transport.

Based on the presence of pumice pebbles intercalated in prehistorical fine-grained grey-green tephra layers in Puyehue Lake sediments, *Bertrand et al*. [2008c] interpreted the 1921–1922 and 1960 grey-green fine-grained tephras in the western part of the lake as the result of in situ weathering of pumice. Analogies with the 2011–2012 event, however, demonstrate that the cooccurrence of silt size particles and pumice pebbles is the result of two distinct modes of transport. The fine-grained particles reflect transport across the lake by interflows, while the pumice pebbles represent transport by overflows. Therefore, the 1960 and 1921–1922 grey-green fine-grained tephras do not represent pumice weathered in situ but simply result from the redistribution of fine-grained pyroclastic material by lake currents.

5.5. Implications for Tephrochronology and Volcanology

The results of this study have important implications for applications in tephrochronology and volcanology. First, the comparison between the tephra records of the relatively large Puyehue Lake and of the smaller nearby lakes shows that lakes do not act as passive sediment traps but that they operate as tephra sinks, integrating and concentrating the pyroclastic material that fell over their entire watersheds. This is very clear for Puyehue Lake, which received no pyroclastic material from atmospheric fallout, but in which the 2011–2012 CC tephra was observed at every coring location. The tephra record of the small regional lakes, both downwind and upwind, however, reflects direct ashfalls (or their absence) much more faithfully. Hence, two nearby lakes can contain very distinct tephra records, simply due to the size and orientation of their drainage basins. In the CC region, this observation explains the significant differences that were previously identified between the postglacial tephra records of, for example, the relatively large Puyehue Lake (78 tephras over the last 18 kyr) [*Bertrand et al*., 2008a] and Lago Pichilafquen (30 tephras over the last 14.5 kyr) [*Jara and Moreno*, 2014], which is located only 7 km away from the Puyehue record and on the same side of the volcano but has a much smaller drainage basin.

Second, our results indicate that tephra redistribution by lake currents, which is particularly important in large river-fed lakes, can cause significant lateral differences in tephra thickness and grain size within the same lake. Deep proximal basins, which are mostly affected by underflows, tend to concentrate tephra deposits, whereas distal locations only contain particles that can be transported by interflows and overflows. The latter mostly affects pumice-rich tephras. When using tephras to correlate multiple sediment records from within one lake, large differences in tephra thickness and grain size can therefore be expected over relatively short distances. This is a natural process that should not be regarded as a drawback when evaluating the quality of tephrostratigraphic correlations. In this situation, geochemical fingerprinting can generally be used to refine or confirm the correlations.

Another important implication of our results is that extreme care must be taken when using lake sediment records for constructing isopach maps and/or isopleth maps of maximum grain size. Using tephra records from large lakes with extensive drainage basins, such as Puyehue, systematically results in a biased view of the spatial distribution of the tephra, both in terms of thickness and grain size, and hence in the overestimation of the derived eruptive parameters, such as area affected by ash deposition, erupted volume, column height, magnitude, and volcanic explosivity index (VEI) [*Newhall and Self*, 1982]. Although all lakes concentrate tephras to a certain extent, smaller lakes with limited catchments, i.e., those with a small drainage area (A_D) to lake surface area (A_0) ratio, are better suited for isopach mapping. In other words, the criteria to select the most appropriate lacustrine sites for isopach mapping are high atmospheric deposition and low river input, which resemble those used to select sites for pollen and dust analysis [e.g., *Jacobson and Bradshaw*, 1981;

Shotyk, 1996]. Ombrotrophic peat bogs also fall in this category, although postdepositional alteration of tephra in the acidic peat environment [e.g., *Pollard et al.*, 2003] may limit their use in tephrochronology.

The recently documented postglacial H_0 eruption of Hudson volcano in southern Chile [*Weller et al.*, 2014] may be an example of such an overestimation of the volume of erupted material. Based only on the thickness of tephras recorded in six lakes, *Weller et al*. [2014] estimated an eruption volume of $> 20\ km^3$, which would make H_0 the largest postglacial eruption ever documented in the southern Andes. Although the studied lakes are relatively limited in size, the thickness of the H_0 tephra was likely overestimated since the eruption occurred immediately after the deglaciation (~17.4 kyr BP), when vegetation and soils, which are the most important factors to preserve tephras in terrestrial environments [*Fontijn et al.*, 2014], were virtually absent, increasing the likelihood of tephra being washed into the lakes.

Finally, our results also have important implications for the use of lake sediment tephra records to estimate the recurrence rate of volcanic eruptions [e.g., *Watt et al.*, 2013]. Since lakes with extensive drainage basins have the potential to integrate tephras deposited at any location in their watershed, they systematically register more eruptions than small lakes with limited drainage basins. Volcanological studies based on these two types of lake environments could therefore result in significantly different conclusions regarding the recurrence rate of past volcanic eruptions. Although lakes with large watersheds may give the impression of providing records that are more complete and less dependent on ash transport direction, tephra records in these environments are very sensitive to the efficiency of reworking processes and therefore to external factors such as climate and vegetation density, which inarguably vary through time. Lakes with large watersheds may only be more appropriate than small lakes in some very specific cases, e.g., to reconstruct volcanic eruptions that generate lahar deposits [e.g., *Van Daele et al.*, 2014].

6. Conclusions

The eruption of CC volcano in south central Chile in 2011–2012 provided an ideal opportunity to investigate how volcanic eruptions are recorded in lake sediments. Our results show that lakes do not act as passive tephra traps but that they concentrate and integrate pyroclastic material deposited over their entire watershed, resulting in a biased view of tephra spatial distribution. This mechanism explains why two nearby lakes can have very distinct tephra records, simply due to the size and orientation of their drainage basins. Our results also indicate that lake currents play an important role in the redistribution of tephra particles. This can result in important differences in tephra thickness and grain size over relatively short distances within a single lake, which should not be seen as a factor diminishing the quality of tephrostratigraphic correlations. Since glass geochemistry is not affected by these processes, it should be used to refine or confirm correlations. Our results also highlight the importance of site selection for isopach mapping. Including records from large river-fed lakes systematically results in the overestimation of the area and volume of tephra deposits, and of other eruptive parameters such as the VEI. Site selection is similarly important for the calculation of recurrence rates of past volcanic eruptions. Records from lakes with large drainage basins generally contain more tephras than those from small lakes with limited watersheds, but these records may be affected by external factors such as precipitation and vegetation density. In general terms, although lakes are better recorders of volcanic explosive activity than terrestrial environments, we argue that it is important to take reworking and transport processes into account when interpreting tephra records from lake sediments. For accurate results in volcanology and tephrochronology, we recommend focusing on small lakes with limited drainage basins, i.e., those that are mostly fed by direct atmospheric deposition.

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