The 2000 AD eruption of Copahue Volcano, Southern Andes

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ABSTRACT

Although all historic eruptions of the Copahue volcano (37°45'S-71°10.2'W, 3,001 m a.s.l.) have been of low magnitude, the largest (VEI=2) and longest eruptive cycle occurred from July to October 2000. Phreatic phases characterized the main events as a former acid crater lake was blown up. Low altitude columns were deviated by low altitude winds in variable directions, but slightly predominant to the NNE. The presence of the El Agrio caldera depression to the east of Copahue volcano may have caused the variable plume divergences and disturb the prevailing wind direction which is normally to the southeast. Larger magnitude events, comparable to prehistoric eruptions, could occur in the future at Copahue volcano, seriously impacting the tourist localities on the Argentinean (eastern) flanks of this frontier volcano. Unless a constant educational program is implemented, emergency plans will not be enough to prevent catastrophic effects, because the local population strongly believes that only low magnitude eruptions such as those of the sixties, nineties and 2000 AD can be produced at the Copahue volcano.

Key words: Volcanic hazards, Explosive volcanism, Holocene, Copahue volcano, Andes, Chile, Argentina.

RESUMEN

La erupción de 2000 AD del volcán Copahue, Andes del Sur. Aunque todas las erupciones históricas del volcán Copahue (37°45'S-71°10.2'W, 3.001 m s.n.m.) han sido de baja magnitud, entre julio y octubre de 2000 ocurrió el mayor y más prolongado ciclo eruptivo. Las áreas más vulnerables de este volcán fronterizo se ubican sobre su flanco (este) argentino. Las fases más características de las principales erupciones fueron del tipo freático, habiendo sido evaporado su habitual lago ácido del cráter activo. Los vientos de baja altura desviaron según variadas direcciones las columnas eruptivas de baja altitud, aunque con cierto predominio hacia el NNE. La presencia de la gran depresión de la caldera El Agrio hacia el este, podría haber causado la distorsión de tan variable dispersión de la pluma eruptiva, modificando la dirección prevaleciente de los vientos hacia el sureste. Erupciones de mayor magnitud ocurridas en el volcán Copahue, comparables a erupciones prehistóricas, podrían repetirse en el futuro impactando severamente las localidades turísticas sobre territorio argentino. De no implementarse un programa educacional de aplicación constante, dirigido a la población local, los planes de emergencia no serían efectivos para prevenir los efectos de tales eventos mayores, pues esos habitantes perciben que el volcán Copahue sólo origina erupciones de baja magnitud tales como las de los sesenta, noventa y la del año 2000.

Palabras claves: *Peligros volcánicos; Volcanismo explosivo, Holoceno, Volcán Copahue, Andes, Chile, Argentina.*

Revista Geológica de Chile, Vol. 31, No. 2, p. 279-292, 11 Figs., 3 tables, December 2004.

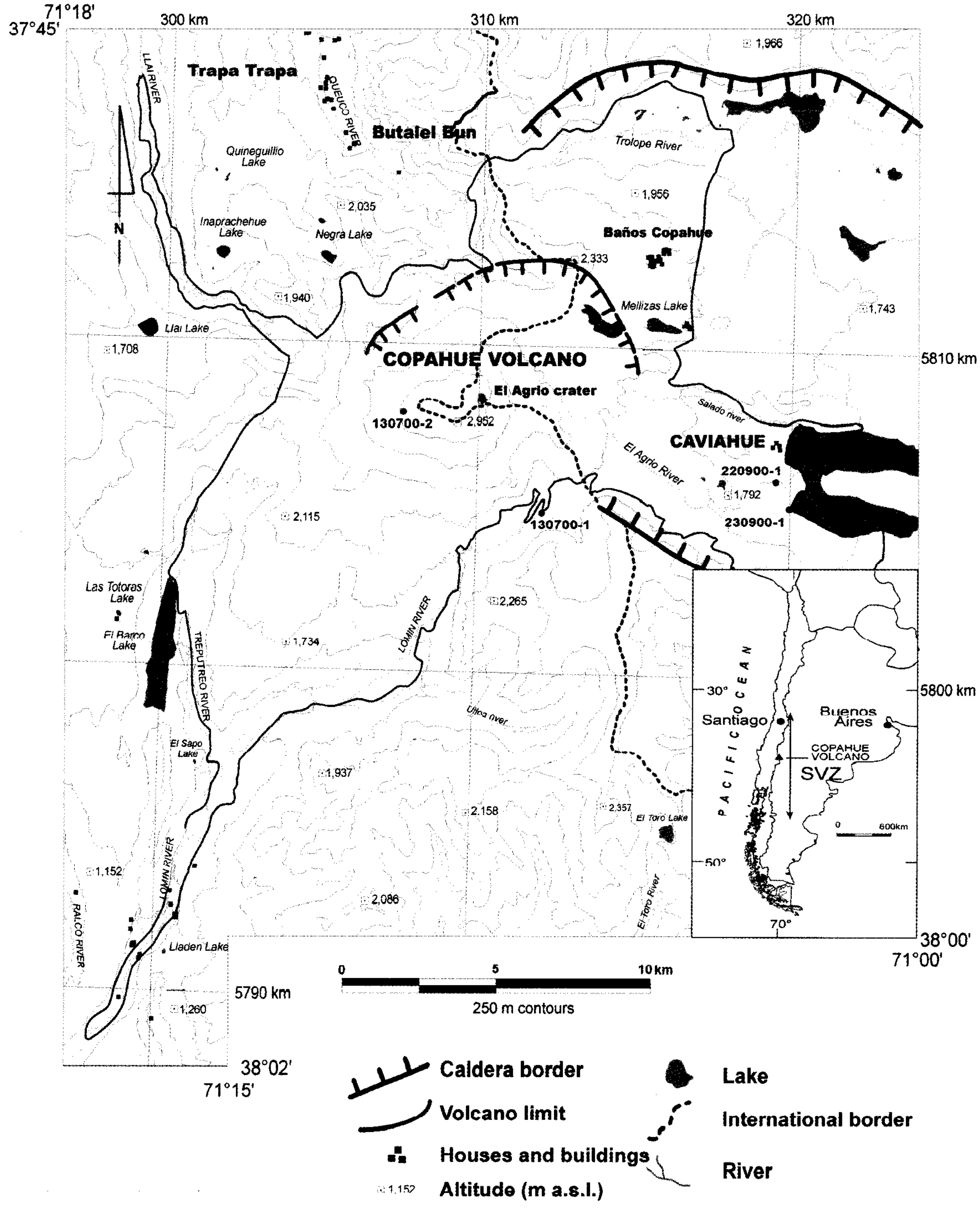

FIG. 1. Location of the Copahue volcano in the Southern Andean Volcanic Zone.

INTRODUCTION

The Copahue (37°45'S-71°10.2'W, 3001 m a.s.l.) is an active stratovolcano located in the central part of the Southern Volcanic Zone (central SVZ, 37°-41.5°S, Fig. 1; Stern, 2004), on the border between Chile and Argentina, *ca.* 30 km to the east of the present volcanic arc-front. Nine craters clustered along a belt with a N60°E orientation appear on the summit, and mainly andesitic to basaltic andesite lavas have spread down its flanks. The easternmost crater at 2,800 m a.s.l. is the only one presently active. The Baños Copahue and Caviahue hot spring resorts are located at 7 and 9.5 km to the northeast and east of this active crater, respectively. The alert that a new eruption had started on the morning of July 1, 2000, was given from Caviahue.

Some studies on this volcano (Delpino and Bermúdez, 1994; Naranjo *et al.*, 2000) have revealed that a series of volcanic hazards can be generated, including pyroclastic flows, tephra fall, lavas and lahars. However, the presence of an acid lake within the active crater (Fig. 2A, B) represents one of the most hazardous aspects that directly threatens Caviahue, the nearest inhabited locality, with a variable population of 800 to 1,500 people.

This paper describes the characteristics of the last low magnitude eruptive cycle of Copahue volcano observed by local witnesses and the authors through a simple but effective surveillance of this volcano. Since the eruption occurred mainly in winter time, bad weather conditions were predominant, making continuous monitoring impossible. Simple surveillance techniques included direct visual monitoring from Chile and Argentina, on land and from the air (direct overflights, as well as information reported by commercial pilots). Some microseismic monitoring studies were also carried out (GVN, 2000a, b).

HISTORIC ERUPTIVE CHRONOLOGY

Information about historic eruptions of Copahue volcano is scarce and incomplete. Including the present event, 12 eruptions have been reported during the last 250 years: 1750, 1759, 1867, 1937, 1944, 1960, 1961, 1992, 1993, 1994 and 1995 (Klohn, 1946; H. Moreno[1]; Delpino and Bermúdez, 1993; M.E. Petit-Breuilh[2]; Martini *et al.*, 1997). Most of them had a phreatic character. At least two phreatic explosions were observed during the 1961 eruption (H. Moreno)[1]. The best-documented

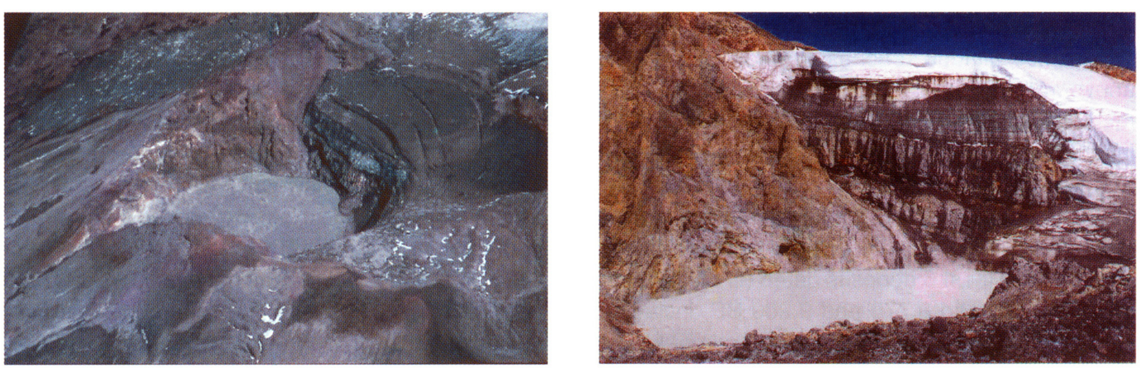

FIG. 2. **A-** oblique air photograph of the crater lake of the Copahue volcano as in March 1997. View to the south (photograph taken by J.A. Naranjo); **B-** the Copahue crater lake at present showing that it has recovered the water level as before the eruption. View from the eastern notch (courtesy of D. Maniero).

[1] 1992. Estudio preliminar del Riesgo Volcánico del área de Ralco (Unpublished), *Empresa de Ingeniería INGENDESA*, 118 p.

[2] 1996. Cronología eruptiva histótica de los volcanes Planchón-Peteroa y Copahue, Andes del sur, Proyecto de Riesgo volcánico (Unpublished), *Servicio Nacional de Gelología y Minería*, 45 p. Temuco, Chile.

eruption took place between July and August of 1992, when both phreatic and phreatomagmatic explosions occurred, which included sulphur pyroclastic emissions (Delpino and Bermúdez, 1993). Fine lapilli size fragments fell up to 20 km away from the crater and mudflows travelled more than 4.5 km to the east, together with intense micro-seismic activity and gas emissions. Finally, various isolated phreatic explosions also occurred in 1995 (Petit-Breuilh, 1996[2]; Martini *et al.*, 1997).

GEOLOGIC AND VOLCANIC SETTING

The basement of Copahue volcano corresponds to Eocene to Middle Miocene (Cura Mallín Formation) volcaniclastic to sedimentary rocks, as well as Lower Miocene and Pliocene (Trapa Trapa and Cola de Zorro or Hualcupén formations) volcanic rocks (Niemeyer and Muñoz, 1983; Muñoz and Niemeyer, 1984; González and Vergara, 1962; Vergara and Muñoz, 1982); R. Thiele, A. Lahsen, H. Moreno, J. Varela, M. Vergara y F. Munizaga[3]; (Pesce, 1989; Linares *et al.*, 1999).

The 20 by 15 km El Agrio caldera, with 500 m high interior walls, located to the east of Copahue volcano, was formed during the Upper Pliocene (*ca.* 2 Ma, Muñoz and Stern, 1989; Linares *et al.*, 1999; Folguera and Ramos, 2000), and generated extensive outflow ignimbrites to the east (Pesce, 1989). Copahue volcano started to build its shield-like structure *ca.* 1.2 Ma ago on the SW border of the caldera (Fig. 1). A smaller (6.5 x 8.5 km diameter) elliptic caldera (Copahue Caldera) was formed between 0.6 and 0.4 Ma that generated ignimbritic pyroclastic flows that travelled up to 37 km to the east (Polanco, 2003).

The alignment of the summit craters as well as the oblong orientation of the edifice and the Copahue Caldera (between N40-62°) seem to be controlled by the predominant regional tectonic transpressive regime (Muñoz and Stern, 1989; Cembrano and Moreno, 1994; López-Escobar *et al.*, 1995; Folguera and Ramos, 2000).

COPAHUE VOLCANO

The Copahue volcano has an elongated shape, aligned in a SW-NE direction, with a maximum and minimum diameter of 22 and 8 km, respectively. The edifice altitude reaches a mean of 1,350 m above the surrounding basement. Its lavas are medium- to high-K andesites to basaltic andesites in composition, but subordinate rhyolite domes and pyroclastic deposits also exit. Morphologically, the volcano flanks show gentle slopes similar to a small shield volcano. Holocene explosive eruptions generated at least 6 deposits dated (C^{14} in charred material) between 8,770 and 2,200 BP, including ash-flow, surge and two tephra-fall beds of ash to lapilli size scoria (Polanco, 1998; Polanco *et al.*, 2000; Polanco, 2003). These deposits have been preserved to the east and along the Llai River valley to the north, as well as to the SW along the Lomín River valley. In addition numerous well-stratified pyroclastic-fall and -flow layers were deposited on the summit area, generated by explosions associated with the formation of the craters.

The nine summit craters are oriented N60°E. The easternmost crater, with a diameter of 500 m, is the only one currently active. Before the 2000 AD eruption, a nested acid lake developed in this crater had a volume of 3 to 4.5 x10^6 m^3, a temperature of 21 to 54°C and the pH varied between 0.18 and 0.30 (Varekamp *et al.*, 2001). The normal discharge of the acid lake is through a 90 m deep, 'V' shaped notch located on the eastern 30° arc-segment of the crater rim. By 2003, the lake had recovered its previous level (Fig. 2B).

[3] 1987. Estudio Geológico Regional a Escala 1:100.000 de la hoya superior y curso medio del río Biobío (Unpublished), *Empresa Nacional de Electricidad-Universidad de Chile, Departamento de Geología y Geofísica,* 304 p. Santiago.

MONITORING METHODS

Because of the remote conditions, personnel of the Southern Andes Volcano Observatory (OVDAS) of the Servicio Nacional de Geología y Minería, located in Temuco, Chile, installed a seismic monitoring system with satellite transmission telemetry in March 1998. It used a SISMO1 HD model seismometer with a Mark L4C type sensor and a converting card, analog to digital (ADC) of 16 bits. The equipment was placed near the northwest coast of El Barco Lake, 11.5 km to the SW of the active crater. Seimic data were gathered as statistical records of the total amplitude signal or energy. However, the high cost of satellite transmission made the method inappropriate for the expected results. As a consequence, in March 1999 the emission station and the seismometer were taken off. Thus, there was no chance to get a continuous signal during the studied eruptive period.

Beginning in February 1999, an area of 5x5 km that includes the crater of Copahue volcano was incorporated in the GOES 8 meteorological satellite monitoring system operated for thermal anomalies by the University of Hawaii (USA). However, the unevenness of the thermal threshold, together with an excess of clouds, probably prevented a thermal alert associated with the forthcoming eruptive event. No alert resulted even during the night in August 2000 when local people photographed the glowing crater.

The Instituto Nacional de Prevención Sísmica (INPRES, San Juan, Argentina) and OVDAS in Temuco, Chile carried out seimic surveillance discontinuously. INPRES obtained 25 days of continuous recording of the seismic activity from the locality of Caviahue, from August 11 to September 4, 2000. They registered a maximum of 109 and 108 events/day for August 12 and 14, respectively, in addition to banded tremors associated with ash emissions and long period events (LP) probably associated with explosions with major ash emissions.

On the other hand, OVDAS carried out only sporadic seismic monitoring from Trapa Trapa located 13 km to the NW of the crater, and from Copahue, 7.5 km to the NE of the crater, on July 22-23, August 18-19, and September 26-27, respectively. Starting at 1100 h[4] July 22, 1500 h of continuous recording were obtained and events associated with strombolian explosions of intermediate energy were recorded. Another 15 hours of recordings were obtained from 1839 h on August 18. During that period, a seismic event that was associated with an explosion occurred at 1236 h on August 19, but no high frequency events were recorded. Finally, from 0900 h on September 26, 18 hours of data were obtained showing the occurrence of short period earthquakes and a set of events linked to small explosions within the crater. A long period event was detected coupled to a small ash emission, which occurred four hours after.

ERUPTIVE CHRONOLOGY

The chronology of the 2000 AD eruption of Copahue volcano summarised herein (Table 1) is based on our unpublished reports, direct eyewitness, newspaper information review, in addition to the data published on the Bulletin of the Global Volcanism Network (GVN 2000a, b). The eruption lasted from the beginning of July and was over at the end of October. During this period the eruption showed different stages. A more detailed account of the 2000 AD eruptive chronology can be requested from the library of Sernageomin.

[4] Local time = GMT-4.

TABLE 1. SUMMARY OF THE ERUPTIVE CHRONOLOGY OF THE 2000 AD ERUPTION OF COPAHUE VOLCANO.

Date: Month	Date: Day	Observation: Visual	Seismic	Satellite
July	1	Strong sulphur smell and 1 cm of ash fell in Caviahue and Baños Copahue villages.		
	2	Steam, ash, lapilli and bomb emissions (15 cm to 8-9 km to the E of the source). The eruptive column reached 2,000 m and was distributed to the ESE. Various hours of null to scarse visibility in Caviahue (Fig. 3). The plume was detected 50 km to the SE of the volcano A pH 2.1 was measured at Caviahue Lake. The ash was dispersed >100 km of the crater.		
	3	An explosion at 16:20 h originated an ash-cloud to the NW. A plume was detected >10 km to the NE of the crater.		
	4	Lapilli fell inside the crater; 3-4 cm of ash accumulated 8 km to the E of the crater and ash fell 60 km to the SE of the volcano. At least, three explosions occurred and strong sulphur smell was reported in Caviahue. Weak incandescence was observed inside the crater.		
	5	30-40 explosions. The largest originated a small pyroclastic surge flowing down the N and E flanks. Small dark-grey ash emission reached between 700-1,200 m above the crater border and was dispersed to the SSE of the volcano. At Salado and El Agrio gullies water pH was measured at 4 and 2, respectively. Dead fishes were reported in Lomín River, 10 km to the SW of Copahue volcano.		
	6	Incandescence inside of the crater. Small explosions every 1-2 hours. The ash was dispersed to the SSE.		
	7	Strong explosions with ash emission every 15 minutes. Brown greyish weak explosions <100 m of altitude alternating with steam. Fine ash distributed to the SE and W of the volcano. Lahar originated in El Agrio Creek changed to swelling downstream and produced outlet widening to 15-20 m, rising water level in 1 m in Dulce Creek (pH=2.5).	*Microseismic event detected in Caviahue coincident with an explosion.*	
	8	Strong explosion was listened from Caviahue. Small explosions occurred with ash and gas emissions. The ash was dispersed to the NNE.		
	10	The ash was dispersed to the SWW and reached 25 km to the SW of the volcano.		
	12	Explosions with dark grey to brownish ash <500 m high, every 1-3 minutes. The ash was distributed to the NNE, up to 250 km of volcano (Fig. 4).		
	13	Ash fall, 2 cm thick, 5 km to the NNE of the crater and a fine ash-cap 20 km to the W of the crater. Sulphur smell at 10 km to the E. Eruptive column of 200-300 to 1,000 m of altitude and explosions with emission of incandescent fragments at 1 km to the E of crater. The plume was distributed to the ENE. Lomin River with pH 5-6, at 5 km to the south of the active crater.		
	14	Brown reddish cloud at 3,000-5,000 m. Incandescence inside of the crater. The ash was dispersed to the NNE up to 50 km of the crater. Explosion sequence originating columns of 200 to 500-700 m. Ejection of lithic blocks (<50 cm of diameter up to 300 m of the crater) associated to the largest explosions.	*Some explosive events recorded in Caviahue village.*	
	15	Ash and steam explosions every 2 minutes with columns of 400-500 m above the crater. Large explosions every 1 hour reached 2,000 m (Fig. 5). The plume was traceable up to 70-80 km to the NNE and deposited ash up to 3-4 km.		
	16	Small explosions with increased steam emissions. Prevailing winds dispersed the ash to the E (Caviahue village) which had a strong sulphur smell.	*Explosive events recorded in Caviahue village.*	
	17	Eruptive column reached 1,500 m over the crater and the ash was dispersed to the N and SE. 2 mm ash fell on Caviahue village with strong smell sulphur. Acid rain and 5 cm of ash fell at Butalel Bun. Ash also fell at Baños Copahue, Sierra Trolón and Cordillera de Trocomán.		
	18	Explosions with steam and brownish-orange cloud emissions. Grey cloud emissions at 1 hour interval. Light grey eruptive column reached 500-1,000 m above the crater and 10 km wide dispersed to the NNW.		
	19	Explosions with ash and steam columns of 500 and 1,000 m above the crater. The plume was dispersed to the NE and deposited a thin ash layer on Baños Copahue. Ash and acid rain fell on Caviahue between 18:00 and 19:00 h with strong sulphur smell.		
	20	Minor explosions with gas and ash emissions. Ash was dispersed to the NNE, even farther north than Caviahue village and Trolope river, with a strong sulphur smell.		
	21	Explosions with ash columns of 700 and 1,000 m. At 09:20-10:20 h rhythmic explosions occurred every 1-2 minutes that originated dark ash and light grey cloud dispersal to the NNW.		
	22	Explosions with ash emissions <50 m above the crater. Ash dispersal to the NW.	*Seismic events were recorded in Trapa Trapa.*	
	23	Low to middle intensity explosions with ash and steam emissions and gentle noise. The plume was dispersed to the NNE and to the E (Caviahue) between 18:00-19:00 h.		
	24	Explosions with dark grey cloud emissions. Ash fell continuously at Caviahue during all day and on Cajón de Chanchocó (5 km to the N of the crater). Dead fishes were reported in Lomín River, 10 km to the SW of Copahue volcano.		
	25	Strong sulphur smell 250 km to the ESE of the volcano. Between 1,800-2,150 m the 10-15 km wide plume was detected up to 200 km to the ESE. Ash fell at Caviahue village.		
	28	The plume up to 500 m above the crater was dispersed to the NE (Fig. 6).		
August	4		*VT (volcanic tremors) event was recorded in Trapa Trapa.*	
	5	Thin ash fell at Trapa Trapa.		
	7	Strong sulphur smell at Caviahue village.		
	9-10	Rhythmic explosions every 5-10 minutes with 1,500 m high eruptive columns. The plume was dispersed to the W, NW and SSW.	*Seismic event was recorded at Caviahue village.*	
	15	Alternating steam and ash explosions every 4-5 minutes. Incandescence was observed at the crater, and bombs (<10 cm in diameter) were ejected inside the crater.		
	15-18		*Tremor events recorded at Caviahue village.*	
	17	Intermittent incandescence every 5 minutes with strong noise.		
	18	Weak light grey and low altitude eruptive plume.		
	19	Weak light grey eruptive plume with low altitude (~300 m). Strong explosions with gas and ash emissions. Incandescence inside of the crater.	*A LP (long period) event (34 s) detected at Trapa Trapa.*	
	20	Ash and gas emissions that reached 300 m over the crater. Some of them with strong noise every 8-10 s.	*A LP event (140 s) detected at Caviahue village.*	
	21	Ash and gas emissions reached 300 m above the crater.	*Two LP events (120 and 104 s) recorded at Caviahue village.*	
	22	Mainly steam explosions with a few minute intervals. The plume reached 500 m and was distributed 5 km to the N and S of the crater.		
	23	Strong explosion with ash and gas emission.		
	24-26, 28, 30-31		*Tremor events recorded at Caviahue village.*	
	31	Strong incandescence inside the crater. The column only reached 100 m above the crater.		
September	1	Small explosions (Fig. 7). A 1,000 m high plume was dispersed to the SE.		
	2	The plume was dispersed to the N at 700-1,000 m of altitude.		
	1-4		*Tremor events recorded at Caviahue village.*	
	23	Intense gas emissions every 0.5-1 minutes up to 150 m above the crater, dispersed to the NNE (Fig. 8). Incandescence inside the crater.		
	26		*A series seismic episodes associated to explosions and ash emissions.*	
October	5, 19			Thermal alert.
	1-15	Only pulsating gas emissions.		
	17		*Microseismic activity recorded at Copahue village.*	
	18	Continuous steam emissions, and brown ash clouds between 10:45 and 11:45 h.		

FIG. 3. In addition to darkness, ash fall accumulated up to 15 cm thick near Caviahue on July 2, 2000 (courtesy of D. Maniero).

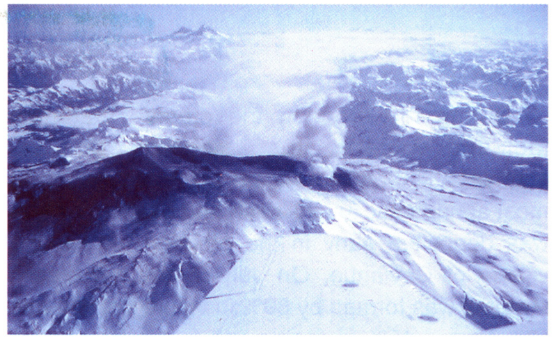

FIG. 4. Looking north, oblique air photograph taken July 12, 2000, between 1100 and 1130 h. Notice the weak volcanic dust and gas plume being dispersed for more than 250 km to the NNE; the ash layer deposited to the west two days before is also observed.

FIG. 5. During July 15, occasionally each one-hour larger explosion reached 2,000 m over the crater (courtesy of D. Maniero).

FIG. 6. Small explosions as viewed from the southern edge of Caviahue Lake, July 28 , 2000. Gas and ash plume was dispersed at low altitude to the northeast (courtesy of D. Maniero).

FIG. 7. Looking east, low altitude explosions were dispersed to the southeast the first day of September 2000. Notice people for scale (courtesy of D. Maniero).

FIG. 8. Intense water vapours and grey ash emissions dispersed just on the NNE flank as half to one-minute pulses were observed from Caviahue the September 23, 2000 (photograph taken by J.A. Naranjo).

EJECTED MATERIALS

During the eruption the ejected materials included volcanic dust, sulphur particles, scoriaceous bombs, accessory fragments and most abundantly, juvenile ash and gases. The ash was deposited early in the eruption around the village of Caviahue. On July 2, the pyroclastic material was formed by 80% in volume of fine ash (0.5-1 mm), 15% of coarse ash (> 1 mm) and 5% of fine to very fine ash (< 0.5 mm). Coarse ash was mainly composed of dark grey to yellow scoriaceous particles and accessory fragments including white to grey quartz.

Coarse lapilli and bombs ejected during the eruption were found at distances up to 1 to 1.5 km around the crater. Although very rare, bombs up to 15 cm across were found 8-9 km from the crater. Bermúdez *et al.* (2002) indicated that dark grey coarse lapilli and bombs (ave. 3 to 8 cm in diameter), basaltic andesite in composition, had irregular shapes and abundant spherical vesicles. These showed cooling fractures with spindle-like forms.

Ash samples (0.3-0.5 mm fraction) collected on 19 August and 1 September, corresponding to juvenile glass fragments, were geochemically analysed, giving a high-K basaltic andesite composition (Table 2). Like most rocks of Copahue volcano, they correspond to the subalkaline and calc-alkaline series (Polanco, 1998; Polanco, 2003).

TABLE 2. CHEMICAL ANALYSIS OF JUVENILE SAMPLES.

Sample	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	S	H_2O^+	Total
190800-1A	55.59	16.84	1.18	2.01	6.25	0.14	4.61	7.06	3.57	2.02	0.22	0.08	0.28	99.85
010900-1	56.04	16.52	1.20	2.12	5.88	0.14	4.31	7.01	3.57	2.06	0.26	0.19	0.40	99.70

Chemical analyses of snow with ash and water sampled from the Lomín River, El Agrio Creek, and Caviahue Lake during the eruption were classified as calcic-sulphide and magnesium-sulphide waters, respectively (Fig. 9). In addition, pH values from 2.5 to 4.4 were obtained. The samples also showed high fluorine contents (3.3 mg/l, sample 130700-1, Lomín River; 8.4 mg/l, sample 130700-2 of ash with snow; 4.7 mg/l, sample 220900-1, El Agrio Creek and 7.9 mg/l, sample 230900-1, Caviahue Lake at El Agrio Creek mouth, Table 3). These values clearly exceed the acceptable maximum of 1 mg/l for drinkable water (Fetter, 1999).

DISCUSSION

The Copahue eruptive cycle from July to October 2000 is the longest and largest magnitude eruption of this volcano during historic times. The Volcanic Explosive Index (VEI, Newhall and Self, 1982) never exceeded the value of 2.

In contrast to previous events and despite the bad weather conditions, together with the absence of a permanent seismic station, the monitoring information obtained was, for the first time, abundant and valuable enough to keep the authorities and the populations of Argentina and Chile adequately informed. Moreover, different kinds of phenomena were observed and described by local people: ash fall, ballistic bomb-ejection, small-volume pyroclastic surges, acid rain, mudflows and floods, incandescence inside the crater, among others.

During the four months of the eruption that began on July 1, there were five eruptive stages (Fig. 10).

The **first stage** (July 1-11) was the most intense and was dominated by successive low-magnitude,

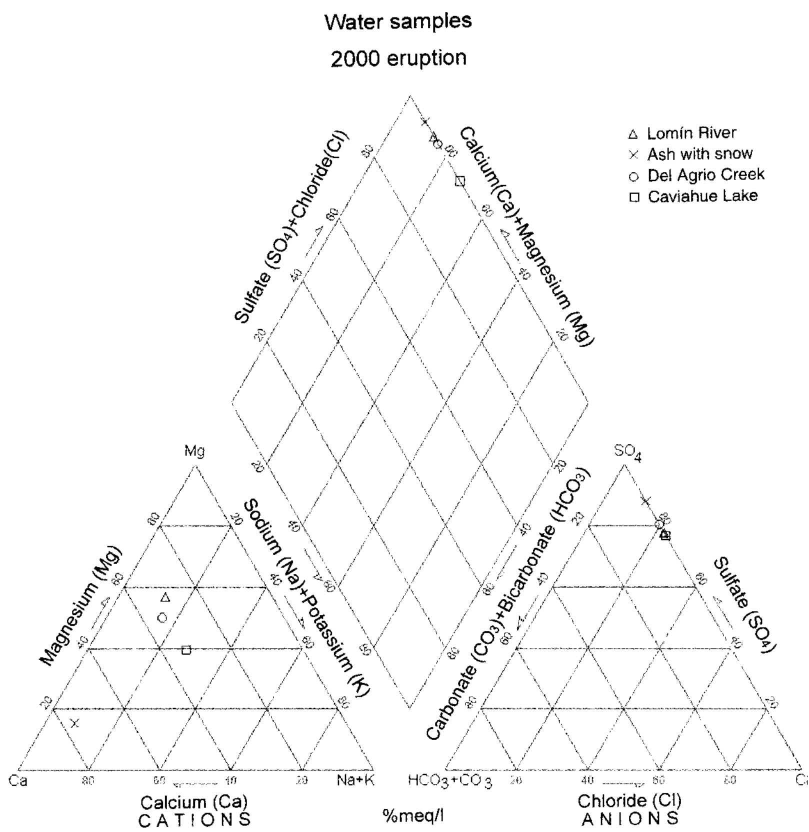

FIG. 9. Piper diagram showing the compositions of snow with ash and water drained from the streams from the volcano during the eruption at Lomín River, El Agrio Creek and Caviahue Lake.

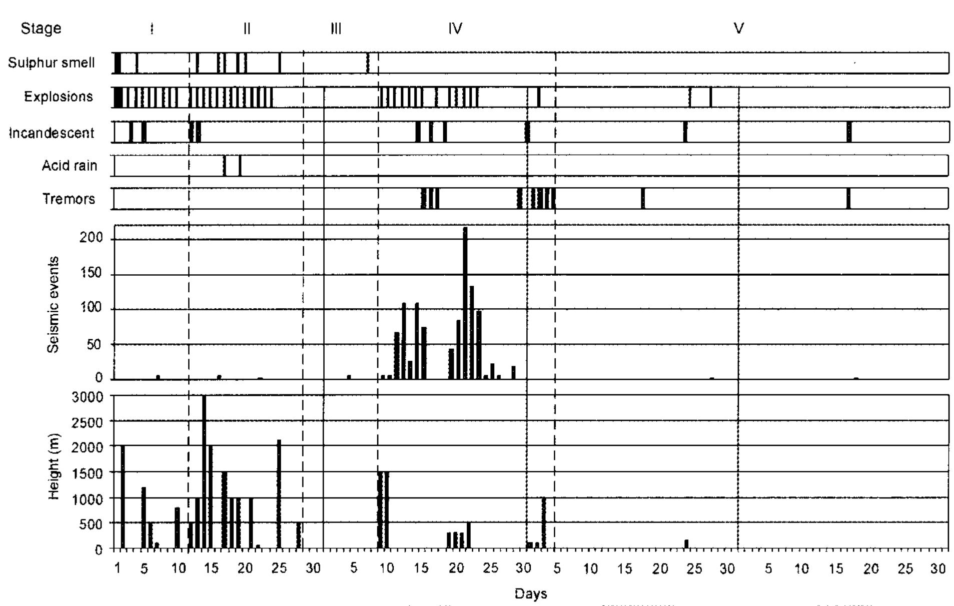

FIG. 10. Summary of the principal eruptive features of the July-October 2000 eruption of the Copahue volcano.

phreatic to phreatomagmatic explosions, similar to previous historic eruptions (Klohn, 1946; Moreno, 1992[1]; Delpino and Bermúdez, 1993; Petit-Breuilh, 1996[2]; Martini *et al.*, 1997). As a result, the entire acid crater-lake (Lago del Agrio) was emptied. The eruptive column reached a maximum of 2,000 m above the crater during this stage and scoriaceous bombs were ballistically ejected up to 9 km from the crater, whilst the ash- and dust-plume traveled 100 km to the ESE (July 2). Then, the intensity and violence of the eruption gradually decreased, as indicated by the heights of the columns and the distance that the plume reached thereafter. During this stage incandescence inside the crater was reported (July 3 and 5), dead fishes in Lomín River, and the formation of small-volume pyroclastic surges on the northern and eastern flanks (July 5), as well as the formation of lahars in El Agrio Creek (July 7).

The beginning of the **second stage** (July 12-28) was coupled with the renewal of intense explosions and, as a result, a gradual increase of the eruptive column. The highest columns occurred during this period reaching the maximum of 3,000 m above the crater rim on July 14. In addition, the plume also reached distances of up to 250 and 200 km to the NNE and ESE on July 12 and July 25 , respectively. Other aspects that showed remarkable increase were the number of explosions and their steam/ash ratio that was confirmed by the occurrence of acid rains (July 17 and 19), and again the presence of dead fishes along the Lomín River (July 24). However, even during this phase, the eruption behaviour remained at a low-magnitude level of a strombolian type (VEI=2).

A quiescence period may have occurred during the **third stage** (July 29 to August 8). Reports showed no activity during this period except for 5 seismic events that occurred on August 4.

The **fourth stage** (August 9 to September4) began with the renewal of intense explosions that produced columns up to 1,500 m high above the crater (August 9 and10), as well as seismic swarms (109 and 108 events on August 12 and 14, respectively), prior to the presence of glowing in the crater interior during the following days (August 15-18), associated with recorded tremors, probably related to degassing within the conduit at a very shallow level (McNutt, 1996). This behaviour preceded a stage of relatively intense explosivity and the maximum seismic activity recorded during the eruption (84-217 events between the August 20 and 23), but produced only a low-altitude column (500 m above the crater on August 19 and 22). The increase of tremors, the presence of incandescence and the increase of the column height were also evident during the short period of August 30 and September 2, when columns up to 1,000 m high also occurred.

The **fifth and last phase** (September 4 to October 31) corresponds to a period of clear decrease of the eruptive activity, with scarce explosions and seismic events. Commonly ash and steam explosions never exceeded heights of 50 to 100 m above the crater. During October the eruptive activity died out and the normal fumarolic activity of Copahue volcano was re-established.

One of the most conspicuous features of the eruption was the remarkable emission of sulphur gas (SO_2 y S_2), detected at Caviahue and in the Trapa Trapa River valley. This aspect was also observed during the 1992 event, when pyroclastic sulphur was ejected (Delpino and Bermúdez, 1993). These events probably occur due to the absence of the crater acid lake where magmatic sulphur gas normally transforms to sulphur dioxide or remains as diluted H_2SO_4 in the lake. The presence of sulphur evaporite in formations within the basement rocks has been cited as one possible cause of sulphur contamination of magmas during ascent (Mamaní *et al.*, 2000), but no isotopic data is available for Copahue volcano.

In spite of the high fluorine contents measured in streams around the volcano, as well as the persistent and extended ash-fall produced by the eruption, cattle were not affected as they were during the eruption of the Navidad Cone (Lonquimay Volcano) in 1988-1990 (Moreno and Gardeweg, 1990; Naranjo *et al.*, 1991). In addition to the low altitudes reached by the explosion columns of the Copahue eruption and the subsequent restricted juvenile (basaltic andesite, 56-57%SiO_2) ash-dispersion, the plume direction was also variable, but slightly predominant to the NNE (Fig. 11 A-B).

The large depression of the 20 by 15 km diameter El Agrio caldera, located immediately to the east of Copahue volcano may have played an important role in modifying the direction of the low-altitude prevailing winds, by blowing occasionally to the west. By comparison, eruptions in other

A

B

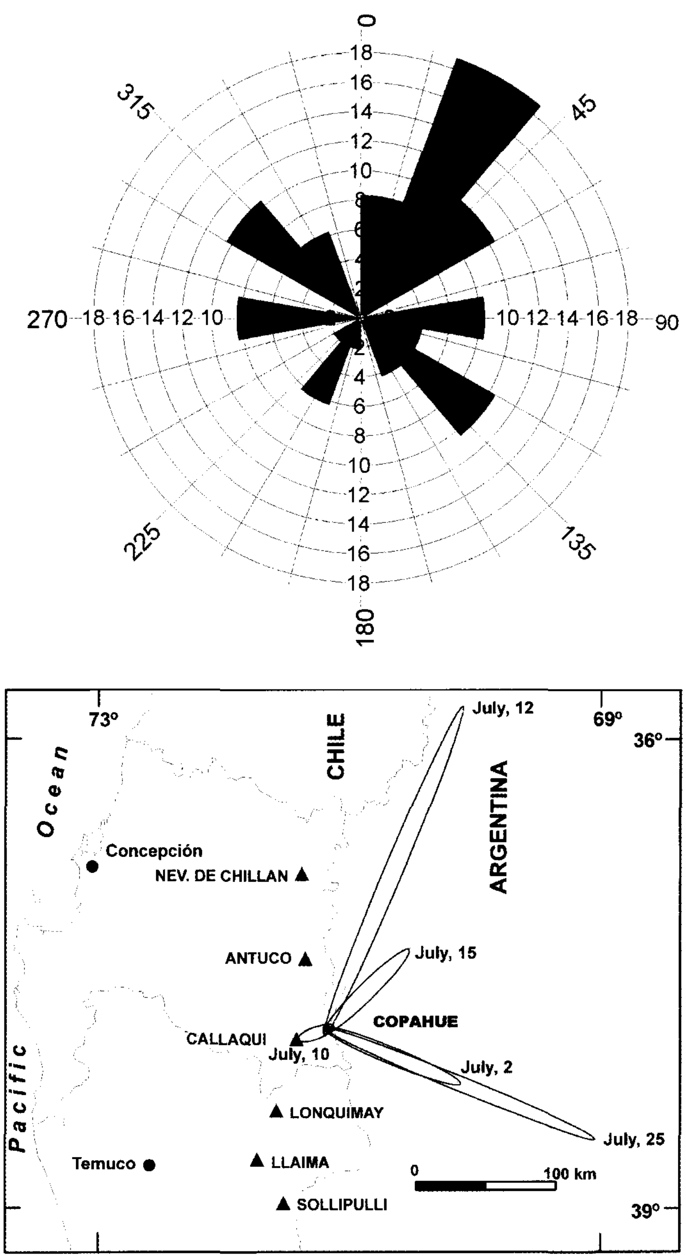

FIG. 11. Main directions (A) and maximum dispersions (B) of the eruptive plumes recorded during the Copahue AD 2000 eruption.

places of the Andes, such as the Navidad Cone (Lonquimay Volcano), located only 50 km to the SW, the plume was mainly directed to the SE during the 13 month long eruption, but never to the west. On the other hand, during the Copahue's eruption, the small volumes of juvenile magma ejected resulted in much weaker, lower column height, and therefore in a restricted dispersal, compared to those of Navidad Cone, during which, thousands of animals were killed by osteofluorosis (Moreno and Gardeweg, 1990; Naranjo *et al.*, 1991; Araya *et al.*, 1990). The fact that ash did not fall directly on the grass pastures, but on the snow, also reduced the health impact. Nevertheless,

TABLE 3. CHEMICAL ANALYSIS OF CONTAMINATED WATERS.

Sample	Date	Observation	pH	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	HCO_3 mg/l	CO_3 mg/l	Cl mg/l	SO_4 mg/l	F mg/l
Ralco 9A (*)	April, 1999	Lomín River	8.25	94	5.8	5.2	7	2.0	41		6	8	
Ralco 9B (*)	June, 1999	Lomín River	7.93	89	3.3	4.2	5.6	1.9	37.5		3.8	8.8	
Ralco 9C (*)	August, 1999	Lomín River	7.31	114	2.9	3.7	5.3	1.8	41.5		3.1	4.8	
130700-1	July, 2000	Lomín River	3.58	619	34	39	14.2	4.8	0	0	76	360	3.3
130700-2	July, 2000	Ash witn snow	4.43	924	172	21	15.6	10.6	0	0	60	592	8.4
220900-1	September, 2000	El Agrio Creek	2.79	649	35	31	15	5.7	0	0	76	425	4.7

* G.. Benavente, Ingenesa, written communication.

sulphur smells were always associated with ash fall periods, which produced high sulphide contamination of stream waters, both at the El Agrio and Lomín rivers (Fig. 9). Simultaneously, there was a dramatic decrease in pH values that produced fish mortality on July 5. The Mg and Ca contents increased by 10 times their normal values, whilst chlorine increased 20 times and SO_4 more than 40 times their normal values (Table 3).

The phreatic character of the early stages of the eruption was mainly due to the amount of water available in the crater lake. But, as this lake dried out, a weaker Strombolian character began, with more juvenile material (ash and bombs) and less accessory material (<15%) ejected. In addition, glowing explosions were observed.

The localities of Baños Copahue and Caviahue were the most affected areas due to their proximity to the active crater. Naranjo *et al.* (2000) already documented their high vulnerability to different volcanic hazards, mainly ash-fall processes. Although the wind direction varied continuously during the eruption, the probability of being affected by ash-fall was extremely high for both localities. Any larger magnitude event would have seriously impacted the whole area as much as 10 km to the east of the active crater. On the other hand, inhabitants of the area have only experienced the very low-magnitude recent historic eruptions, being this the largest. For the first time there were electric power and water supply cuts. Furthermore, ski slopes remained mantled by 2 to 5 cm thick ash, notably affecting the normal winter tourism. It was remarkable how local people were not prepared for such magnitude eruption.

No management planning for volcanic emergencies existed prior to the eruption, generating serious difficulties. Local authorities were unable to create a scientific committee, which might have provided discussion and consensus for useful recommendations. On the contrary, in Argentina, two independent groups gave opposite opinions. The scientists that assisted the Federal Government took one position, but those in charge of advising the Neuquén Province authorities, gave another opinion. More than once, both had serious discrepancies. Furthermore, there was a lack of communication between scientists and the community.

These factors led both the authorities and the community to a situation of not knowing what was happening or what to decide. In addition, on the Chilean side, this eruption made clear the lack of resources for scientifically monitoring the volcanic crisis, especially the lack of seismic monitoring capability.

CONCLUSIONS

The Copahue eruptive cycle of July to October 2000, although of low magnitude (VEI $\leq$2), was the longest and largest eruption of this volcano during historic times. The main related hazards were ash fall, acid rain and small-volume mud-flows.

The eruption was characterised by five eruptive stages, the first and the third being the most intense when ash and gas columns reached up to 2-3 km above the crater. Phreatic phases were common during the entire cycle, but particularly important during the first stage, which was similar to previous historic eruptions at Copahue volcano.

High fluorine concentrations were measured in stream waters, contaminated by the fallen ash (56-57% SiO_2). No impact on cattle resulted, due to the restricted area affected during the short periods of ash-fall and the remarkable drifting plume. The plume direction was controlled by variations of the low-altitude winds, probably controlled in part by local morphology.

Once again, Baños Copahue and Caviahue demonstrated their extremely high vulnerability to hazards related to Copahue volcano. Any larger magnitude event (VEI=3) would seriously impact them, partly due to the low awareness of the potential danger posed by the volcano it would be very difficult to persuade the local people and the authorities to make contingency plans to attempt to mitigate possible eruptive effects. Thus, an educational program is urgently needed.

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