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## Abstract

“Risk assessment” is a relatively new concept in Argentina, since the very first hazard map was only recently constructed on the basis of the 1992 eruption of Copahue volcano (Patagonia). Copahue is considered a very active volcanic system since 13 eruptive events have been recognized over the last 260 years. Most the events are phreatic and phreato-magmatic with  $VEI \leq 2$ ; nevertheless such eruptions represent a threat for the communities living in the surrounding areas of the emission centre, not only because of pyroclastic flows and tephra fall (the nearby villages, Caviahue and Copahue, have so far only experienced ash fallout), but also due to the possible formation of mud flows and flank collapse triggered by the volcanic activity. Owing to the frequent eruptions of Copahue, the most recent ones (2000, 2012) showed an increasing explosive character, hazard survey actions, such as thematic maps and contingency plans are constantly, though slowly, modified. The risk assessment described in this chapter calls for the implementation of the monitoring network in the Argentina side of the volcano, since the only currently active seismic stations (OVDAS) are located in the Chilean side of the volcanic edifice, Copahue volcano lying at the border between the two countries. Moreover, the Chilean observatory adopts criteria of alert levels, which

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are distinctly different with respect to those of Argentina Civil Defense, producing misleading information to the population. The villages of Copahue and Caviahue are regarded as extremely vulnerable to possible future eruptions if larger magnitude events should occur. A review of the presently available potential hazard map, an improvement of people's education about the volcanic risks and a more interactive cooperation between the Chilean and Argentina scientific and administrative institutions are some of the immediate countermeasures to be taken into account before a new explosive phase at Copahue.

## 10.1 Introduction

Volcanic hazard represents a special case of natural potentially catastrophic events due to the unpredictability of occurrence and duration of volcanic activity. A volcanic eruption can have immediate dramatic consequences on all forms of life under the threat of disaster, besides destroying properties, economic activities, public services, and all goods. Moreover, it may continue to impact on the environment for an indeterminable time span. For example, Arenal, a basaltic andesitic stratovolcano situated in Costa Rica, had a long-lived eruption that began in 1968 with a Pelean eruption after 530 years of dormancy (Alvarado et al. 2006). Since 1974, one of three newly formed craters (crater C) was the only active crater, whose activity lasted until 2011. Arenal has alternated long, predominantly effusive phases with shorter explosive phases (Oramas-Dorta et al. 2012). Damages can directly be related to eruptive activity, such as those caused by the accumulation of ash or indirectly connected. For instance, the phreatomagmatic eruption of the Hudson volcano (southern Chile) in 1991 caused the death of a great part of the sheep flocks in the Province of Santa Cruz, due to the considerable destruction of the vegetal cover. The distribution of the deposits affected a region greater than 300,000 km<sup>2</sup> and a > 1 m thick ash layer accumulated in the areas near the volcano. Bitschene and Menida (1995) evaluated that this eruption implied, in the provinces of Chubut and Santa Cruz, direct losses estimated in about US

\$10,000,000 and included cattle death, economic damages, restoration of water supply systems, airports, roads, communication and electric equipment, and so forth.

The active cordilleran magmatic arc, related to the subduction of the Nazca plate under the South American started in early Cretaceous time, has migrated to the west in recent geological times. Active and quiescent volcanoes are mostly located along the Argentina-Chile boundary or few kilometers to the west, in the Chilean territory. The eruptive centers along the arc are mainly Pliocene, Pleistocene, and Holocene huge stratovolcanoes, andesitic-dacitic calderas, and basaltic plateaus (Sruoga et al. 1993), related to the last great uplifting and faulting events in the Andean chain. Some of these volcanoes may be perceived as remote because of limited accessibility, but dispersal of fallout tephra produced by explosive eruptions easily overcomes the distances separating volcanoes from the urban areas, placing them volcanologically in the endangered vicinity (Dzierma et al. 2010). During the twentieth century, several eruptions occurred in this region (Descabezado-Quizapu in 1932; Tupungatito in 1952, 1980, and 1986; Peteroa in 1937 and 1991; Hudson in 1991; Copahue in 1992, 2000; Lascar in 1989 and 1993), all of them accompanied by ash rain, which in some cases extended over wide areas, including western Argentina.

The segment of the Andean chain named the Southern Volcanic Zone where Copahue volcano is located currently presents a big concern, although the volcanoes of this area do not

commonly show explosions of large magnitude (with the exception of Hudson volcano). Large parts of the regions adjacent to this segment of the Andes in both Chile and Argentina are indeed intensely used by the population for living, industrial zones, agricultural production, recreation and tourism (Dzierma and Wehrmann 2012). The increasing urban development implies that even relatively small phreatomagmatic explosions could cause both substantial economic losses and hazard.

Copahue volcano showed an intense activity over the last 260 years, with 13 recognized eruptions (see Caselli et al. this volume), the last of which occurred in December 2012. The eruptive style was mainly phreatic and phreatomagmatic, similar to those occurred in 2000 and 2012. Despite their low explosive character (VEI, Volcanic Explosive Index  $\leq 2$ ), the eruptions strongly impacted on the surrounding. The eruptive episodes that occurred in 2000 had negative repercussion on the tourist locality of Cavihue, populated by 800 to 1,500 inhabitants depending on the season.

In this chapter, a critical review of the risk related to Copahue volcano is presented. The description and characterization of the volcanic activity, that is to say the starting points to develop an appropriate risk evaluation, are detailed reported in dedicated chapters of this book. The spatial distribution of products ejected during the past eruptions was considered for the realization of the hazard maps aimed to mitigation strategies from the local authorities and scientist.

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## 10.2 Volcanic Risk Mitigation Measures

Volcanic hazard mitigation is based on three fundamental requisites: (i) construction of an updated volcanic hazard map to determine the best land use to minimize damages in case of eruption, (ii) continuous volcanic monitoring using geophysical, geochemical and geodetic

methods, and (iii) a contingency plan involving the whole community, known and practiced by all, in case of volcanic activity.

### 10.2.1 Hazard Map

Maps of potential volcanic hazards are to identify areas that might be affected by volcanic activity in accordance with the recent history of the volcano. Such maps do not imply analysis of vulnerability and therefore they cannot be considered in a strict sense as maps of risk (Parra and Cepeda 1990). The latter are obtained by combining the hazard maps with socio-vulnerability information. Hazard maps are considered essential tools in the communication of volcanic risk among scientists, local authorities and population (Haynes et al. 2007). Hazard and risk assessment is usually completed for specific authorities, who may have different concerns, i.e. civil defense bodies are mostly interested in evacuation and short term mitigation, while planners are responsible for land use planning (Lirer and Vitelli 1998).

In the last few decades, hazard maps were realized in densely populated areas characterized by active volcanism, often after the occurrence of catastrophic eruptions, as consequence of the low perception of risk due to the long (if considered at human scale) quiescent period between two volcanic events. This factor generates a wait before mitigation measures are taken, as in the case of Nevado del Ruiz volcano (Colombia) that in November 1985, after 140 years from the last explosive activity, produced a relatively small eruption that melted part of the summit glacier. The resulting lahar killed about 25,000 people. It was then decided to give immediate priority to prepare a volcanic hazard map for visual and geochemical surveillance of the volcanic activity and to improve the seismic network (Parra and Cepeda 1990). Merapi volcano (central Java) represents another case study where a detailed hazard map constituted a pivotal element to draft guidelines aimed to reduce risk exposure to persons and property and provide information for the productive use of land and water: here lahar deposition, associated to at least 23 of the 61 reported eruptions since the mid-1500s,

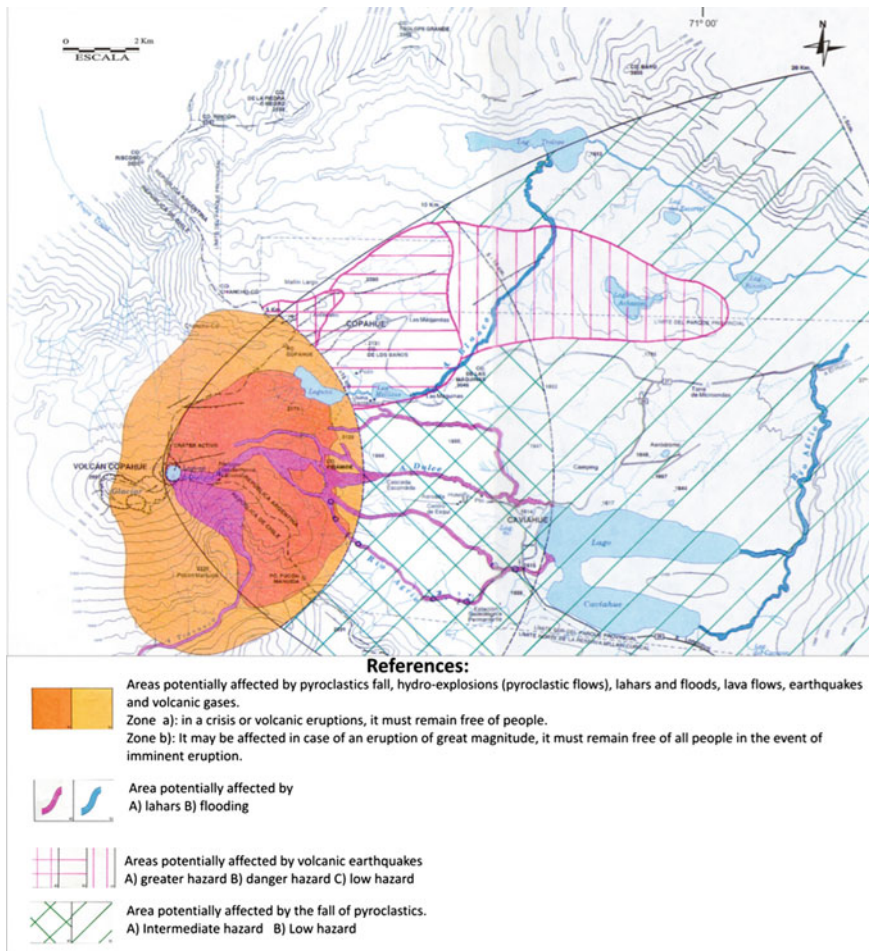
encompassed more than 280 km<sup>2</sup> of the volcano slopes and the surrounding lowlands. Hazard maps (1:10,000 and 1:2,000 for the highly populated areas) allowed the scientists to (i) provide correct values of the previous underscore risk in zone threatened by lahars and (ii) suggest countermeasures such as construction of dam structures to protect and shelter inhabitants and food production areas from disaster caused by lahars (Lavigne et al. 2000). Other noteworthy data emerging from the interpretation of a hazard map were the urgency of a drastic reduction of the density of population both in Pozzuoli town, located in the centre of a caldera, and in the adjacent extension of Naples city (Italy) on the eastern slope of that structure. The emplacement of pyroclastic flows and surges, typically produced during eruptions of this volcanic complex (Di Girolamo et al. 1984), strongly suggests that, even without the knowledge of absolute probability of eruption, the hazard can efficiently be mitigated by redistribution of population of inhabited areas close to volcanic centers based on the hazard map (Lirer and Vitelli 1998).

Volcanic hazard maps usually display the current or potential extent of dangerous volcanic flows (lava, pyroclastic or mud flows) together with the potential distribution of tephra. Topography is a major factor controlling the distribution of many volcanic hazards. Therefore, the presentation of relief, traditionally displayed with contour lines, is a very important component (Haynes et al. 2007).

Copahue volcano, characterized by a hyper-acidic crater lake hosted in the active vent, was the subject of several multidisciplinary investigations, e.g. lithostratigraphic (Pesce 1989; Mazzoni and Licitra 2000; Melnick et al. 2006; Sruoga and Consoli 2011), structural (Folguera and Ramos 2000), petrological (Delpino and Bermúdez 2002), and geochemical (Varekamp et al. 2006; Agosto et al. 2013, Agosto and Varekamp this volume; Tassi et al. this volume). The 1992 eruption (Delpino and Bermúdez 1993) gave a strong pulse for the creation of the Volcano Studies Group (Neuquino Geological Survey) who drew the map of potential hazards for this Argentine sector (Bermúdez and Delpino 1995).

These authors compiled a map indicating the potential geographical limits of: (i) hazardous lava spill, (ii) pyroclastic flows, (iii) pyroclastic fall, (iv) lahars, (v) the areas where volcanic gases emissions were observed and (vi) the zones where earthquakes could possibly generate fractures. The zoning was based on processes occurred during the 1992 eruptions, and geological studies updated to that moment. The phreatomagmatic eruption of July 1992 included three major eruptive phases that produced eruptive columns respectively 0.3, 1.4 and 0.7 km high, corresponding to VEI ~ 2. The columns generated plumes that dispersed ash up to 20 km away and led to the formation of lahars up to 4 km in length (Delpino and Bermúdez 1993). Based on these characteristics, two different potential hazard zones were recognized (Fig. 10.1), both lying inside a radius of 5 km from the crater and corresponding to a higher (dark orange) and a lower (orange color) hazard area, respectively. The innermost zone could potentially be affected by the fall of  $\approx 1 \text{ m}^3$  ballistics (Delpino and Bermúdez 1994; Bermúdez and Delpino 1995). In case of eruption, this zone must be evacuated not only because of the likely emission of lava and pyroclastic flows from the active vent, but also to the high probability of lahar formation triggered by the melting of the top glacier. The Travunco and Agrio valleys are the morphological depressions (Fig. 10.1), which are expected to be affected by these events. This simple subdivision, mainly established on qualitative observations, highlights the need of more detailed studies about the eruptive processes of Copahue volcano and the interaction between the crater lake and the magmatic fluids.

In 2000, the “Servicio Nacional de Geología y Minería de Chile” (SERNAGEOMIN), published a new version (after that of Bermúdez and Delpino 1995) hazard map of Copahue at 1:100,000 scale (Fig. 10.2). This map was updated on the basis of more recent stratigraphic studies (Polanco et al. 2000), which suggested the presence of several post-glacial pyroclastic flows outcropping around Copahue volcano. Furthermore, Polanco et al. (2000) recognized three pyroclastic flows interbedded with fluvial conglomerates to form a terrace in the Liay Valley (Chile). These flows were

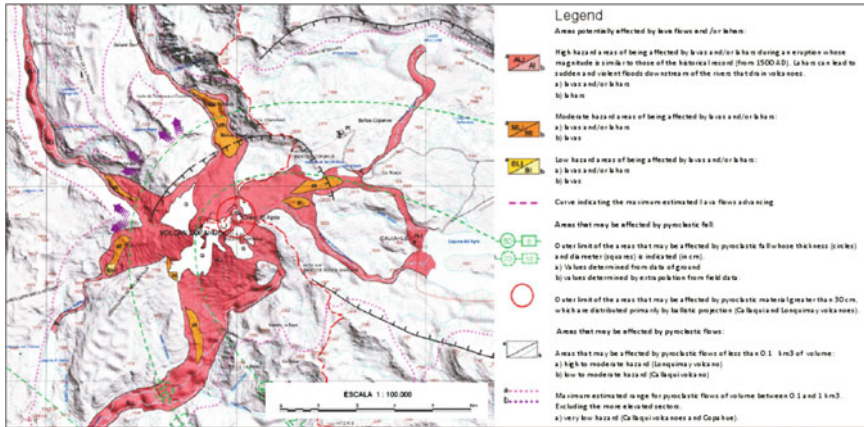


**Fig. 10.1** Map of potential hazards of Copahue volcano for the Argentina side. Modified after Delpino and Bermúdez (1993)

probably emitted from the western summit craters. Radiocarbon ages of these flows ranged from  $2,280 \pm 50$  to  $2,880 \pm 50$  years BP (Cecioni et al. 2000; Polanco et al. 2000). Polanco et al. (2000) also reported two  $^{14}\text{C}$  ages from pyroclastic flows of  $8,770 \pm 70$  and  $5,910 \pm 50$  years BP inside the caldera, probably emitted from the eastern craters. According to the authors, these ages and relations among the postglacial lavas indicate that during the Holocene the summit craters were intermittently active. According to these considerations, the actualized map (Fig. 10.2) shows areas likely affected by (i) lava flows and (ii) lahars (subdivided in low, moderate and high hazard zones), (iii) pyroclastic flows and (iv) pyroclastic falls.

Areas where pyroclastic falls are expected are contoured by lines indicating both the deposit thickness and the tephra diameter (Fig. 10.2). Ash-fall thickness up to 20 cm is located primarily east of the volcano on the Argentina side, reflecting the prevailing orientation of local winds. Directions of gravitational flows as lavas and pyroclastic density currents coincide with the purple arrows, reported only for the Chilean side of the volcano edifice (Fig. 10.2). The spatial limits of the pyroclastic flows refer to both past eruptions and interval of emitted volume between 0.1 and  $1 \text{ km}^3$  (dashed violet lines in Fig. 10.2), in order to take into account possible future events.





**Fig. 10.2** Copenhue volcano hazard map made. Modified after Naranjo et al. (2000)

Furthermore, it is observed that the proximal hazard areas (within 15 km) likely to be affected by lava flows and/or lahars do not include populated zones. During larger eruptions (low probability of occurrence), it is suggested that any pyroclastic flows could extend its effects further afield (within 25 km) (SERNAGEOMIN Volcanic Activity report n. 17).

The 2000 eruption was of greater intensity (VEI 2) than the previous ones, being the largest eruptive cycle until 2012, in both magnitude and duration (Naranjo and Polanco 2004). The eruption had different stages, the first and the third ones being the most intense when ash and gas columns reached up to 2–3 km above the crater (Caselli et al. Chap. 3 this book). Phreatic phases frequently occurred during the entire cycle, especially during the first stage that was similar to previous historic eruptions at Copenhue volcano (Delpino and Bermúdez 1993, Varekamp et al. 2001). During the eruption, the ejected materials included volcanic dust, sulfur particles, scoria bombs, accessory fragments and most abundantly, juvenile ash and gases. Ash was deposited early in the eruption around the village of Cavihue. The day after the beginning of the eruptive activity, 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) (Naranjo and Polanco 2004). 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. These ballistics did not affect the villages of Copenhue and Cavihue although, due to the continuous changes of wind direction, experienced ash-fall that affected the local ski resorts (tephra thickness between 2–5 cm), leading to disadvantageous consequences for the touristic winter season. Inhabitants suffered, for the first time, electric power and water supply cuts (Naranjo and Polanco 2004).

The 2012 eruption occurred on the 22nd of December (VEI 2, Caselli et al. Chap. 4 this book) and can be divided into three phases. The onset of the eruption was characterized by a phreatic activity that after few minutes transitioned to phreatomagmatic (Fig. 10.3), with the ejection of blocks and ash. Hours later, when the interaction with water ceased, a magmatic eruptive style established. Volcanic bombs from the crater and ash-fall dropping from the plume were observed. The ash plume rose about 3,000 m above the summit crater, and the NW prevailing wind blown it over 350 km away. Vesicular scoria were thrown from 0.15 up to 4 km away from the emission centre. Bombs and ballistic ejecta from the crater were launched up to 2 km of distance. No ash-fall was recorded at the villages of Copenhue and Cavihue. Apparently, only rural zones (dedicated to the summer



**Fig. 10.3** View of the volcano Copahue during the onset of the December 2012 eruption. The Villa Copahue village is located on the Caviahue lakeshore, 9 km from the active crater and at 1,000 m of altitude. Photo by the courtesy of Nicholas Elguero

grazing of transhumance) in the SE surrounding of the volcanic edifice were affected. This caused the evacuation of some Mapuche villages to the upper Río Agrio valley. Less than 1 cm of ash was deposited at Loncopue (54 km E-SE from the volcano crater).

As emerged from the previous description, the eruptive style of the latest (2000 and 2012) eruptions, which culminated with a magmatic phase (Naranjo and Polanco 2004) and ballistic projection of bombs (Caselli et al. Chaps. 3 and 4 this book), looms different from the previous low magnitude ( $\leq$ VEI 2) historical events. For this reason, together with recent geochemical and stratigraphic findings and relative interpretations (see below), a review of the potential hazard map by Naranjo et al. (2000) is needed, especially regarding the map scale, since the one proposed (1:100,000) does not provide the appropriate detail for a hazard map when referring to a populated zone.

Varekamp et al. (2001) suggested that the crater lake acidity, together with the relatively steep hill-slope, would generate leaching processes able to weaken the eastern slope of the

volcano. This might imply a potential flank collapse which, once triggered, may be promoted by the kinematics of the north-east dipping normal faults affecting the eastern side of the volcanic edifice (Rojas Vera et al. 2009).

The possible occurrence of collapse events poses a high risk for the inhabitants of Caviahue at which the water volume of the crater lake (ca.  $1.10^6$  m<sup>3</sup>; Pasternack and Varekamp 1997), the summit glacier and the snow accumulation able to generate lahars that could extend for several kilometers are to be added.

Petrinovic (2008) described diluted pyroclastic flow deposits along Agrio river, likely younger than the absolute ages proposed by Polanco et al. (2000) for those nearby of Caviahue. The proximal facies, 20 m thick, showed impact sags of 0.30 m in diameter at the distance of 1,500 m. Intermediate facies deposits were also recognized and characterized by coarse sand to lapilli grain size, while those of distal facies reached Caviahue with a thickness of 0.50 m with dune facies interbedded with flat layers. These features indicate that the flow did not significantly slow with increasing distance from the eruptive centre, but

rather suggest that it experienced a variable and discontinuous alimentation. The pyroclastic flow reached Agrio lake where by dilution it was able to overcome topographic highs exceeding 10 m in height, spreading beyond the lagoon. The origin of these pyroclastic flows, with the absence of fall deposits, indicates the prompt collapse of a dense, low-rise column eruption, or a “boiling over”-like process generated by repeated phreatic and phreatomagmatic explosions. The spatial limits of these deposits were not either mapped or referred to specific locations, but the information provided by Petrinovic (2008) should be verified since if his interpretation of such recent pyroclastic deposits is correct valid, a revision of the currently estimated volcanic hazard at Copahue has to be reconsidered.

### 10.2.2 Modeling Support to Hazard Maps

Modeling significantly contributed to the improvement of hazard mapping. In 1988, Wadge and Isaacs proposed a map of hazard from pyroclastic flows at Soufriere Hills Volcano by applying a mathematical model of gravitational flows on the local digital topography, constrained by field evidences related to the deposits of previous eruptions. Advanced modeling techniques are able to reproduce advection-diffusion dispersal of tephra from discrete sources, simulating the particles fallout from multiple plumes generated by dome collapses and vulcanian explosions (Druitt and Kokelaabr 2002). For instance HAZMAP is a suitable 2D physical model that produces two output results: (i) isomass and (ii) probability maps, showing, respectively: (a) the accumulation of mass per unit area for one specific wind profile and (b) the probability distribution of a particular mass loading around the volcano based on the statistical distribution of wind profiles. Fallout after highly violent explosions, such as strombolian events, is better represented by 3D numerical models such as FALL3D, which is also valid within the atmospheric boundary layer.

Inputs for models are: total erupted mass, eruption column height, bulk grain-size, bulk component distribution, and a statistical set of wind profiles (Druitt and Kokelaabr 2002).

The application of these models to Copahue volcano would enable to simulate multiple eruption scenarios and consequent spatial distribution of volcanic products, allowing the proper assessment of volcanic flows and tephra fallout hazard. For this purpose, a first step should be done by accurately completing the input information to produce a reliable output model. For example, Macedonio et al. (2008) used HAZMAP and FALLD3 to compute ground load probability maps for different ash loadings on populated area around Vesuvius (Italy). The various parameters referring to the exhaustively studied deposits of famous historical eruptions, together with a 36-year winds profiles data set, formed a suited input database.

The most comprehensive probabilistic modeling of possible future eruptive scenarios is the so called ‘Event Tree’ (ET). It was created to summarize in a numerical-graphical form, at different levels of detail, all the relative likelihoods relating to the genesis and style of eruption, development and nature of volcanic hazards, and the probabilities of occurrence of different volcanic risks in the next eruption crisis (Neri et al. 2008). Thus, the hypothetical ET of Copahue would provide, besides the plausible character and evolution of a prospective eruption, a quantitative information about the risk that events related to the volcanic activity, like flank collapse and lahar triggering, are to occur. Furthermore, probability maps obtained for the different scenarios resumed in the ET would support risk mitigation strategies. However, the apparently simple ET structure lies on a complex database that, for Copahue volcano, would require: (i) The compilation of all available historical data, (ii) geological surveys aimed to complete the stratigraphy (included radiometric dating to determine accurate stratigraphic columns) and a common interpretation of geological field data in the light of new fieldwork results (disagreements among authors about the definition



of lithostratigraphic units are resumed in Table 1 of Chap. 4 (Caselli et al. this book), (iii) the development of novel numerical modeling codes and of risk assessment techniques.

### 10.2.3 Volcano Monitoring

Volcanological investigations aimed to the assessment of the hazard of a certain volcanic system are consisting of two steps: (i) description of the eruptive history for understanding the eruptive mechanisms, and (ii) geophysical, geodetic and geochemical monitoring, to follow the evolution of the activity of the volcano.

Geophysical monitoring aimed to identify the seismic precursors of an eruption represents a powerful tool in volcanic hazard investigation. Seismic signals may occur with months or years in advance with respect to any observable external manifestation such as vapor, gas or ash emission, or water lake heating. The rise of volcanic fluids, as well as the generation of fractures or cavities of collapse caused by magma inputs in the area below and within the volcanic edifice, are expected to originate volcanic earthquakes with recognizable seismic signals, whose evolution in time may indicate the prevailing process on a certain time lapse (Zobin et al. 2012). For instance, long-period (LP) events (with dominant periods in the range 0.2–2 Hz) have received particular attention from scientists as they are thought to be associated with moving fluids or resonating fluid-filled conduits (Chouet 1996; Neuberg et al. 2000). Since increases in the occurrence rate of LP events often herald a new episode of unrest, monitoring and investigation of this kind of signals were performed at the active Etna volcano (Bean et al. 2008). The example of Mammoth Mountain (California) underlines the importance of reading the seismic activity as precursor of catastrophic events: in 1989, a seismic swarm was indeed followed by a plume of cold CO<sub>2</sub> that killed *ca* 70 ha of forest. Despite the fact that the emission of CO<sub>2</sub> was waning in a relatively short period of time, it still continues to pose a health hazard to the tourists who visit the area (Lowenstern et al. 2006).

The Southern Andes Volcano Observatory (OVDAS) of Chile, part of the National Network SERNAGEOMIN volcano monitoring, is a scientific-technical unit that performs the (discontinuous or permanent) monitoring of the 43 volcanoes, which are considered the most dangerous in the country due to their type of activity and proximity to populated areas, including Copahue volcano. OVDAS carried out sporadic seismic monitoring in the Trapa Trapa valley, located 13 km to the NW of the crater, and at the village of Copahue, 7.5 km to the NE of the crater, since July–September 2000. From the 22nd of July, 2000, about 2 months of discontinuous seismic activity recording were carried out and associated with strombolian explosions of intermediate energy.

Since May 2012 OVDAS started the permanent monitoring of the seismic activity related to Copahue volcano in real time, web-published in Volcanic Activity Reports (RAV). A pair of broadband seismic stations records such activity that, from the beginning of the monitoring, appeared moderated (with an average of 20 daily seismic events) until the phreatic eruption occurred from July 17–19th 2012, when the number of earthquakes considerably increased. Thereafter, the seismic activity shown a variable trend with peaks of seismic swarms until the eruption occurred on December 22nd 2012 with no precursory signals detected (or recognized) during the time span preceding the explosion.

The National Institute of Seismic Prevention (INPRES, San Juan, Argentina) carried out seismic surveillance recording the seismic activity at Caviahue from August 2000. During the 2012 eruptive period, INPRES provided the daily seismological information to the Civil Defense. In the aftermath of the eruption, the number of daily volcano-tectonic earthquakes increased of one order of magnitude (from *ca.* 20 to about 200), showing a higher frequency of seismic events with respect to those observed before the explosion. The geophysical investigations carried out from 2004 to 2008 (Ibañez et al. 2008; Caselli et al. 2009) employed a seismic array deployed equidistant from the volcano summit

and the exploited geothermal field close to the village of Caviahue. That survey, being the first systematic study of the seismicity of this volcanic region, helped to determine both the rate and the energy of the seismic activity during a period of quiescence. To date, a real-time monitoring of the Copahue volcano from the Argentine side has started in March 2014, from a collaboration between the UNRN (Universidad Nacional de Rio Negro) and the geophysical group of the Department of Earth Sciences of the University of Florence (Italy) when two seismic stations and an infra-sound array were deployed.

Geodetic methods, focused on the measure of the surface deformation of a volcanic edifice, can also successfully be applied to volcano monitoring. Geodetic data are indeed associated with changes in pressure/volume inside the deep magmatic reservoir (Dzurisin 2006). However, there are many causes that may produce surface deformation in a volcanic environment such as tectonic, magmatic and/or hydrothermal processes. Monitoring adopts in situ sensors, usually tiltmeters and strainmeters, able to (i) acquire a steady stream of data in real time for analysis and (ii) evaluate even subtle changes in the pattern or rate of deformation (Dzurisin 2006), commonly corroborated by a GPS network positioning system.

Remote sensing, based on the acquisition of images of the surface from satellite-borne sensors, constitutes one of the most recently developed instrumentations (Dzurisin 2006). Although its powerful potential (entire volcanic arcs can be surveyed, and magma movements can be detected even beneath volcanoes with no other sign of activity; Pritchard and Simons 2004 and references therein), this technique is better addressed to characterize the deformation field in space and time rather than to be applied to the survey activity (Dzurisin 2006).

At Copahue volcano, deformation analyses were realized by Velez et al. (2011) using the Differential Synthetic Aperture Radar technique (DInSAR). From Envisat radar images acquired between 2002 and 2007 a negative deformation rate of approximately 2 cm/yr was calculated, located mostly on the NE flank of Copahue

volcano. The source of deformation was related to a depressurization of the system that resulted from the release of magmatic fluids across the boundary between the brittle and plastic domains. These leakages were considered to be responsible for the weak phreatic events registered in between 1992 and 1995 at Copahue volcano. From the end of 2011 the deformation trend changed towards an inflation process (see Velez et al. this volume), showing a positive deformation rate before and after the eruption of December 2012.

In quiescent volcanoes the transition from repose to eruption is accompanied not only by the previously described geophysical variations, but also by the changes of the chemical-physical parameters of fumaroles and ground waters induced by magma upraise. Fluid geochemistry has a relevant potential with respect to eruptions forecast, as the gases released by progressive depressurization of magma during ascent are very mobile and reach the surface well before their parental magma (Carapezza et al. 2004). In high-T crater fumaroles or in volcanic gas plumes the most significant recorded variations are those of the ratios of gas components (such as  $\text{H}_2\text{O}/\text{CO}_2$ ,  $\text{SO}_2/\text{CO}_2$ ,  $\text{SO}_2/\text{HCl}$ ) that are differentially released because of their different solubility in the magmatic melts (Carroll and Webster 1994; Dixon and Stolper 1995). Variations of the  $^3\text{He}/^4\text{He}$  isotopic ratio provide clear evidences when new deep magma is entering the shallow volcanic system (Sano et al. 1988) as observed before and during two recent eruptions of Mt. Etna (in 2001 and 2002–2003; Caracausi et al. 2003) that were attributed to degassing of rising magma batches. Geochemical monitoring is usually performed on the hottest gas vents (eruptive gases, plumes, fumaroles) most closely connected to the magmatic volatiles uprising from depth but when the inherent character (high temperature, corrosive nature) or the local topography not allow the permanent access to such fluids, continuous monitoring of low temperature (below the boiling point of water) gases which discharge diffusively through volcanic piles, at a distance from active craters, can corroborate the surveying.

These emanations essentially consist of carbon dioxide, H<sub>2</sub>S, N<sub>2</sub>, rare gases (He, Ar, Rn), H<sub>2</sub>, CH<sub>4</sub>, CO and other species at very low concentrations (ppms and ppbs by volume) and their genetic link with crater fumaroles and/or magma degassing at depth can be verified both chemically and isotopically. Furthermore, gas species such as CO<sub>2</sub> represent useful markers of sub-surface thermal anomalies and/or active faults (Baubron et al. 1991), through which volcanoes in a dormant stage, e.g. in Italy, Lesser Antilles, Indonesia (Baubron et al. 1991 and reference therein), are studied by investigating soil diffuse gas emanations.

Changes in chemical and isotopic compositions of discharged fluids, showing a progressive enhancing of the magmatic signature, were detected at Turrialba (Costa Rica) since 2001 (Vaselli et al. 2010), during the reawakening of the system (also supported by geophysical and geodetical evidences) after almost 150 years of quiescence. Fluctuations of the physico-chemical parameters were also observed in hot springs and fumaroles discharges from El Chichón (Mexico) (Tassi et al. 2003) after the 1982 paroxysmic event: the analytical evidence allowed to identify the main processes acting on the magmatic-hydrothermal system, from which two possible future scenarios for the evolution of this volcanic complex were hypothesized.

The current geochemical information relative to the Copahue volcanic system is the result of several investigations carried on during 2004–2012, conducted on the (i) hyper-acidic waters of the crater lake, (ii) hot springs on the volcanic flanks and (iii) the fluid emissions (Fig. 10.4) from the geothermal field (i.e. Varekamp et al. 2001, 2009; Caselli et al. 2005; Agosto et al. 2012, 2013; Agosto and Varekamp this book; Tassi et al. this book). According to the chemical and isotopic features of the different manifestations of the liquid phase collected in the area, different subsystems were defined, based on the volcanic-hydrologic or the melted snow contribution (Agosto and Varekamp this book). Furthermore, a dramatic variation of the solute concentration in the Agrío River upstream and a

sharp temperature decreased were recorded and possibly induced by an obstruction of the fracture system underlying the crater lake, due to an oversaturation and precipitation inside the conduits as a consequence of the arrival of hyper-concentrated deep fluids (Caselli et al. 2005; Agosto et al. 2012, 2013). This mechanism is considered to be possibly responsible of the phreatic events occurred during the 90's (Agosto et al. 2012).

Despite the significant scientific information available, the lack of a proper monitoring network induced the Government of the Neuquén Province (Argentina) in April 2012 to announce the need to establish the Neuquén Volcano Observatory in collaboration with the UNRN. In April 2014 the formal agreement between the two public institutions was signed. The foundation of the Observatory and a partnership with OVDAS is aimed to contribute to favor the construction of integrated modeling of data from different scientific disciplines that can improve the knowledge of the state of the system and its behavior. Firstly, a seismic network, working in real time, will be deployed around the volcano. Secondly, further investigations in the geodetic field (GPS network) will be aimed to detect and measure changes in the surface of the volcano. Researchers from the universities of Rio Negro, Buenos Aires (Argentina) and Florence (Italy) will jointly be carrying out seismic investigation and studies on the geochemical investigation of fluids discharged from the natural emissions located in the surroundings of the volcano and in the summit crater (Tassi et al. this book).

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### 10.3 Contingency Plans

Copahue and Caviahue, as well as the indigenous communities that seasonally live in the valleys near the volcano, are exposed to different types of hazard related to possible rejuvenating activity of Copahue volcano. These two populated centers are located at 9.5 and 7 km east and northeast from the active crater, respectively, with a distance of approximately 19 km between them.

**Fig. 10.4** Sampling of fumarolic gases in Copahue thermal manifestation (*top*) and of Agrio River (*bottom*)



Caviahue lies on the shores of the homonymous lake, at 1,647 m. a.s.l., and has a stable population of 600 inhabitants, whereas Copahue is only inhabited in the summer season (December to May). Approximately 80 % of the total population was installed in the area a little more than 15 years ago. Tourism is the main economic activity of the local municipality, with ski fields of excellent quality during the winter and thermal baths throughout the summer (Copahue) (Monasterio et al. this book). The transhumance of livestock, when Mapuche bring their animals to graze in the fields near the volcano, represents another aspect of the summer activities.

The eruptions of 1992, 1995 and especially that of 2000 have significantly affected the perception of the risk posed by the volcano for the local community. The settlement of new residents and the limited information provided by the authorities, in addition to the episodes mentioned, have caused the sensations of doubts and fears that are still unresolved. The inhabitants have had little information about the volcano and the volcanic environment on which their life develops. The most serious consequence of this lack of knowledge is the wrong perception of risk perceived by people. In this sense, Naranjo and Polanco (2004) opined that the inhabitants of these villages perceive that the Copahue volcano

can give only rise to low magnitude eruptions, such as the ones occurred in the sixties, the nineties and even in 2000. However, emergency plans would not be effective to prevent possible effects of major events without implementing an educational program of constant application aimed at the local population.

After the precursory signals observed at the end of 2011, the municipal government of Caviahue-Copahue started to develop a contingency plan that was based on an unpublished report by Caselli et al. (2012) and contemplates the organization of Municipal Emergency Committee (EMCO) and the actions following the warnings. Three levels of alerts, displayed in three colors, were created: green, yellow and red. These levels indicate alert states for the community but they are not referred to the activity state of the volcano. Before a Yellow Alert, the Mayor convenes the EMCO and provides that the radio station keeps the public constantly informed on the status of the volcano. The community is organized in areas (or blocks), each one of these has a public representative, who is in charge of distributing masks, goggles and work in case of evacuation. In the Red Alert state, evacuation is ordered and security forces are dictated to trigger the safety plan. There is a map of the city with escape and alternative routes, depending on the magnitude of the event, the season in which it occurs and the weather conditions. Gas and electricity cuts are planned in the whole town and the representative of each "block" verifies that all the residents have left their habitations. The population is expected to assemble on the shores of lake in vehicles, and together will caravan to Loncopué village, at a distance of 60 km from Caviahue, as occurred during the evacuation of May 2013 (Fig. 10.5). OVDAS uses 8 levels of alert displayed by colors divided into four groups: green (levels 0 to 2), yellow (levels 3), orange (level 4) and red (levels 5 to 8). The yellow alert is reached when there are variations in the levels of monitoring parameters that indicate proximity to instability such as seismic swarms, ash emissions, increased

fumarolic activity, suggesting that the activity can evolve to an eruptive event. As these parameters intensify, the orange alert level is reached. The red alert level corresponds to an eruption in progress of various magnitudes.

Before the eruptive event of December 22nd 2012, Argentina and Chile governments declared yellow alert. The volcano emitted ash to SE, without affecting the villages of Caviahue and Copahue. In the same day, the Chilean OVDAS announced by web the red alert, while in Argentina, since no ash fall-out occurred in the inhabited centers, the Emergency Committee maintained the yellow alert and no evacuation took place. Such a situation of incongruity, with each authority (the Observatory and the Civil Defense) giving its own alert, generated confusion in the media and major concerns in the community.

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## 10.4 Final Recommendations

Although the historical eruptive activity of Copahue volcano has been characterized by activity with low explosivity index, pyroclastic flows and lahars, besides the possibility of flank collapses, are a serious hazard for population living in the surrounding lowlands. This stresses the importance of updating the hazard map for a better land use assessment and for actualizing the contingency plan. These goals require (i) new detailed stratigraphic studies and (ii) a comprehensive knowledge of the magmatic evolution of Copahue to determine the possible existence of eruptive cycles with different magnitudes or VEIs. Single hazard maps integrated with the aid of numerical models under a Geographic Information System, would allow to describe different scenarios as a function of different kinds of volcanic activity and relative magnitudes. To this aim, the application of physical models to simulate both the distribution of gravitational flows (lavas, pyroclastic flows, lahars) and tephra would greatly contribute to the understanding of





**Fig. 10.5** Evacuation of the village of Caviahue in May 2012

the risks at which the local population might be affected. The use of advanced probabilistic models (ET) is expected to provide quantitative information about the likelihood of the different (direct and indirect) events associated with the volcanic activity. Although there is a correspondence between the eight levels of alert of the observatory and the succeeding safety procedures (grouped into three hazard classes) pertaining to the civil defense, the creation of a uniform code, aimed to provide a unambiguous public information able to simplify the understanding of the risk by the community, is highly recommended. A common criteria of alert levels are to be adopted by OVDAS and the Argentina Civil Defense, so that in case of an alert situation the population can correctly interpret the information received. This can be achieved by implementing both the monitoring system at Copahue and the collaboration between the two countries, Argentina and Chile, to promote cooperation and

exchange of scientific information. Preparedness, mitigation and resilience plans in the case of high magnitude volcanic event should include education programs, periodical meetings with the population, information for tourists and evacuation practices.

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