Special Issue:
Society and Volcanology (SOVOL)

PERCEPTIONS OF PAST AND FUTURE ERUPTIONS OF PUYEHUE-CORDÓN CAULLE (SOUTHERN CHILE): CONNECTING NEIGHBOURHOOD, SOCIAL COHESION AND DISASTER MEMORY IN VOLCANIC RISK RESEARCH

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ABSTRACT
As in 1921-1922 and 1960, a new eruption occurred in the Puyehue-Cordón Caulle volcanic complex (PCCVC) in 2011-2012, having dramatic transboundary impacts in northern Patagonia. Given its frequent and small-to-moderate eruptions, the PCCVC ranks 5th out of 90 in the specific threat ranking of Chilean active volcanoes. Therefore, understanding the importance of the risk perceptions of the nearby community can be critical for risk management and decision making during future eruptions. This article examines the narratives of heterogeneous inhabitants of rural settlements in Puyehue that share the influence zone of the PCCVC, which were selected through purposive and chain sampling for in-depth interviews. We analyse the role of social cohesion, disaster memory, and uncertainties as factors that influence the construction of people's perceptions of volcanic risk. The results highlight the facts behind natural hazards and their physical dimensions, but take into account the subjectivity of human perceptions of eruptions, which profoundly influence the hermeneutics of volcanic processes and thus the decision-making of communities. Understanding the connections between these factors thus becomes valuable and necessary to detect the elements of the social system involved in creating and reducing disaster risk in the Southern Andes.

KEYWORDS
Cordón Caulle; Volcanic risk perceptions; Rural livelihoods; Crisis response; Solidarity; Ethnovolcanology

PERCEPCIONES DE LAS ERUPCIONES PASADAS Y FUTURAS DEL PUYEHUE-CORDÓN CAULLE (SUR DE CHILE): CONECTANDO VECINDAD, COHESIÓN SOCIAL Y MEMORIA DE DESASTRES EN LA INVESTIGACIÓN DEL RIESGO VOLCÁNICO

RESUMEN
Al igual que en 1921-1922 y 1960, en 2011-2012 se produjo una nueva erupción en el complejo volcánico Puyehue-Cordón Caulle (CVPCC), con dramáticos impactos transfronterizos. El CVPCC ocupa el 5º lugar de >90 en el ranking de riesgo específico de volcanes activos en Chile. Por tanto, comprender las percepciones del riesgo volcánico puede ser fundamental para la gestión del riesgo y la toma de decisiones durante futuras erupciones. Este artículo examina narrativas de habitantes de asentamientos rurales de Puyehue que comparten la zona de influencia del CVPCC, los cuales fueron seleccionados mediante muestreo en cadena para entrevistas en profundidad. Desde allí, se analiza el rol de la cohesión social, memoria de desastres e incertidumbre como factores que influyen en la construcción de percepciones locales del riesgo volcánico. Los resultados evidencian los hechos que subyacen a los peligros naturales, pero consideran además la subjetividad de las percepciones humanas de las erupciones, que influyen profundamente en la hermenéutica de los procesos volcánicos y en la toma de decisiones de la comunidad local. Comprender estos factores es esencial para detectar los elementos del sistema social implicados en la creación y reducción del riesgo de desastres en los Andes del Sur.

PALABRAS CLAVES
Cordón Caulle; Percepciones del riesgo volcánico; Medios de vida rurales; Respuesta a crisis; Solidaridad; Etnovolcanología

DOI:
https://doi.org/10.55467/reder.v7i2.126

RECEIVED
12 September 2022

ACCEPTED
18 May 2023

PUBLISHED
1 July 2023

Recommended citation (APA style):
Vergara-Pinto, F. & Romero, J.E. (2023). Perceptions of past and future eruptions of Puyehue-Cordón Caulle (Southern Chile): connecting neighbourhood, social cohesion and disaster memory in volcanic risk research. *Revista de Estudios Latinoamericanos sobre Reducción del Riesgo de Desastres REDER, 7*(2), 88-110. https://doi.org/10.55467/reder.v7i2.126

Journal of Latin American Studies on Disaster Risk Reduction REDER

Revista de Estudios Latinoamericanos sobre Reducción del Riesgo de Desastres REDER

Design: Lupe Bezzina

INTRODUCTION

> *"Volcanoes shape the memories of those who visit it, those who study it, and especially those who inhabit its surroundings (...) It is a creator and destroyer of land. It is a site of almost mythological intrigue for some. For others, it is home" (Roscoe, 2013).*

Volcanoes are intrinsically linked to society through human memory (Roscoe, 2013). Extended periods of volcanic quiescence can also lead to a lack of experience in the volcano behaviour and the type of hazards that may potentially impact communities (Gomez-Zapata et al., 2021). In this sense, human-volcano coexistence produces memories (associated with learning) and uncertainties (linked to unawareness) on the inhabited territory. The conjunction of human experiences – individually and collectively – and what people ignore about volcanoes may influence their response to future eruptive events by constructing disaster risk perceptions (Oliver-Smith and Hoffman, 2002; Hoffman, 2015; Oliver-Smith et al., 2016). How heterogeneous populations living near volcanoes perceive volcanic risk and which factors influence the social construction of this perception are relevant questions regarding the human memory of volcanoes.

Addressing risk perceptions begins by recognising that human-volcano interactions persist from ancient times to the present (Cashman and Giordano, 2008). However, current public debates on volcanic eruptions focus on human habitation as a public issue because of the potential catastrophic consequences for populations and their wider social system (Marín et al., 2020. Examples illustrate the severe impacts of volcanic eruptions, including deaths (e.g., the 1815 Tambora eruption, Tanguy et al., 1998), continental transportation disruption (the 2010 Eyjafjallajökull eruption, Bursik et al., 2012), political and territorial conflicts (the 2008 Chaitén eruption, Sandoval, 2017), and transboundary economic impacts (the 2011-2012 Puyehue-Cordón Caulle eruption both in Chile and Argentina, Elissondo et al., 2016). In other contexts, eruptions may occur with significantly lesser consequences but affect resource-dependent populations impacted by the eruption on localised scales (e.g., the 2018-2019 Peteroa eruptive cycle in Argentina, Forte et al., 2022). Due to these types of impacts, one of the challenges for disaster management is the level of uncertainty and predictability of volcanic activity. For this, technic and scientific efforts are developed to monitor volcanic activity and reduce disaster risk.

Volcanic uncertainty also exists in communities and represents a condition that can better be managed or reduced with a prior sociocultural understanding of volcanic systems, social relationships, and memories of past eruptions. This uncertainty includes the absence of memories of old eruptions only preserved in the volcanic stratigraphy. Therefore, the experiences of populations that have faced past crises represent a source of learning for volcanic risk research, about actions and decisions driven by specific conditions gathered at the territorial scale, sometimes imbricated in neighbourhood dynamics (Kwok et al., 2016, 2019). Considering that "everyone possesses a unique set of knowledge, skills, and resources that are often shared and combined with those of relatives, kin, neighbours" (Gaillard et al., 2019: 863), a territorial scale analysis of volcanic risk gains relevance.

While the risks and impacts of an eruption are related to multi-scale processes (Lavell, 2000; Scoones, 2009; Tucker et al., 2021), disaster risk is constructed and expressed heterogeneously according to specific human-environmental, geographic, economic, and social dynamics. Hence, the impacts of eruptions as well as the practices and perceptions of people can be diverse and unequal depending on the local context in which they occur (Gaillard, 2010). In this regard, recent literature shows that communities usually perceive, evaluate and balance different volcanic risks in daily life and in emergency contexts (e.g. Donovan, 2010; Donovan et al., 2012; Gaillard, 2008; Kelman y Mather, 2008; Sharpe, 2021). Likewise, the risk of the same hazard can be perceived in different ways amongst the members of a community and other social groups (e.g. scientists, policy-makers, visitors, or tourists), which influences the effectiveness of risk communication processes (Hernández et al., 2020; Marín et al., 2020). Therefore, disaster risk is a multi-vocal category varying according to its perception and tolerance (Gaillard, 2008; Bachri et al., 2015). Far from constituting a problem, exploring the diversity of volcanic risk perceptions and engaging with communities represents a path to better understanding human-volcano relationships in specific geographies (Marín et al., 2020). It implies the recognition of risk perceptions that can only be understood from the internal logic and hermeneutics of the groups that coexist with volcanoes.

Can the perception of volcanism be related to sociocultural factors such as disaster memory and social cohesion? Answering this question involves considering the influence of people's past coping and rehabilitation processes on the actions they would take in response to future events. For instance, Kronmüller et al. (2017) point out that memory is a resource embedded in people's adaptation processes, providing a pathway for cultural continuity in the face of critical disturbances. This search for continuity of one's own culture during and after an eruptive crisis reflects the fact that, in periods of uncertainty, people cling to the memory that connects them to their familiar volcanic environment. Hence, risk perceptions allow us to investigate memories not only to obtain a descriptive account of the physical event but also of the social processes that took place during its evolution. Indeed, disaster memory can shed light on the capacities (also limitations) that populations have to face, including abrupt changes, as well as the mechanisms for overcoming an eruption after another in those cases in which communities decide to reoccupy their traditional volcanic lands (Vergara-Pinto, 2022).

In this article, the individual and collective behaviour and actions in the face of past eruptions are considered as essential factors in constructing people's memory, volcanic risk perceptions, and ultimately community social cohesion. Social cohesion is broadly defined as the "glue that holds society together" (Capshaw, 2005: 53), a feature of a society that depends on its level of social capital (Dayton-Johnson, 2003). Depending on the outcome of the management of previous crises, it would be possible to examine social cohesion by analysing the extent to which a community "works for the well-being of all its members, fights exclusion and marginalisation, creates a sense of belonging, promotes trust and offers its members the opportunity to move up" (OECD, 2011, cited in Ludin et al., 2017: 2).

In Chile, research on perceptions of volcanic risk in communities in the Southern Andes is still incipient, including volcanological reflections from science on people's uncertainties and priorities about hazards (Vergara-Pinto and Romero, 2022). Whether in the context of preventing to or overcoming a disaster, knowing the "perceived risk" in the study area contributes to avoid divergences between the economic priorities of policy-makers and the security conditions of the communities at risk (Thomas 2011). Particularly in rural territories, priorities often imply economic and rehabilitation processes, and community building capacity for future extreme events (Romero et al., 2022).

To explore this topic, we carried out research focused on populations that inhabit rural territories near the Puyehue-Cordón Caulle volcanic complex (PCCVC), in the Southern Andes of Chile. The most recent eruptions of PCCVC occurred in 1921-1922, 1960, and 2011-2012. The 2011 eruption was the largest among the PCCVC historical eruptions (Basualto, 2019; Seropian et al., 2021). It had severe transboundary impacts on the ecosystem, economy, transportation, tourism, agriculture, and critical infrastructure at a regional scale (Elissondo et al., 2015). However, during the last five decades of quiescence between eruptive cycles, communities were able to continue living in this territory, producing volcanic risk perceptions within a local social system characterised by rural dynamics. The main economic activities of the analysed human settlements include agriculture, harvesting, tourism, public services, and biodiversity conservation, some of them being developed within the PCCVC hazard zones.

In this context, this article aims to examine the role of social cohesion, memory, and uncertainty as socio-cultural factors that influence the construction of people's perceptions of volcanic risk. The research question focuses on how risk perceptions are produced in heterogeneous groups sharing the same geographical area and hazard zone, and their influence on the decision to reoccupy volcanic areas after eruptions. By documenting the experiences of diverse actors whose livelihoods depend on the volcanic environment, this article posits an association between local risk perceptions, volcanological understandings of hazards, and the ethnography of social heterogeneity within volcanic risk studies in the Southern Andes.

CONTEXT

Chile hosts 92 active volcanoes located on the active eastern margin of the Pacific (Amigo, 2021); most of them are inhabited and reoccupied after eruptions. 45 of them are monitored by the Chilean Geological and Mining Survey (SERNAGEOMIN), the National Volcanic Surveillance Network (RNVV), and the Southern Andes Volcanological Observatory (OVDAS). RNVV developed the Threat Ranking of Active Volcanoes, an instrument that includes all the active volcanic systems into

5 categories from lowest to highest threat. The highest-threat category consists of 14 volcanoes, and the PCCVC is scored 5th (SERNAGEOMIN, 2020). The localities studied are in the direct vicinity of the PCCVC.

The Puyehue-Cordón Caulle volcanic complex (PCCVC)

The PCCVC, located within the Puyehue National Park (Chilean Lacustrine District), has been erupting during the last ~300 thousand years at a high rate of 0.4 km3/thousand year (Singer et al., 2008). The complex is elongated NW-SE and its northwest end corresponds to the Cordillera Nevada caldera and the Southern end to the Puyehue stratovolcano, whereas the Cordón Caulle lies in the middle of both ends and is mostly constituted by fissures, lava flows, and pyroclastic cones. The most recent eruptions occurred in the Cordón Caulle area in 1921-1922, 1960, and lately in 2011-2012: all of them had hybrid behaviour with both lava effusion and widespread emission of high-silica pumice. The 1960 eruption started two days after the Mw 9.5 Chile Earthquake, which also represents an example of eruptions triggered by an earthquake (Lara et al., 2004).

The PCCVC develops an exceptional behaviour exhibiting increasingly explosive eruptions over time, and its magmas are somehow unique in composition for the Southern Andes (Lara et al., 2006b; Singer et al., 2008). Whereas the mild-explosive volcanism of the nearby Carrán-Los Venados Volcanic Group is mostly controlled by regional structures that prevent long-term magma evolution in the crust, extensional fault reactivation on apparently incompatible NW-SE arrays of volcanic chains controls the more explosive and silica-rich activity at the PCCVC (Lara et al. 2006a). On the other hand, the recurrent and compositionally distinctive eruptions of PCCVC contrast with the dominantly silica-poor, lower-frequency, and mild-to-highly explosive eruptions of the Antillanca volcanic complex (AVC, e.g., Carrasco, 2016), another volcanic system located in the commune of Puyehue, 12 km to the south of the settlements in the study area.

Human settlements in Puyehue

According to the 2017 Census, 11,667 inhabitants live in the commune of Puyehue (Los Lagos region). 57% corresponds to the rural population, and 34% to Mapuche indigenous descent, the largest ethnic group in Chile. The presence of the Mapuche culture ("people of the earth" in their language, *Mapuzugun*) in Chile dates back more than six centuries, being one of several native groups that inhabited south-central Chile (*Wallmapu*, or Mapuche territory) before the Spanish conquest in the 15th century (Bengoa, 1996, 2014). Mapuche people are characterised by the value of respect they place on nature (*Ñuke Mapu*, "mother earth") and other non-human beings (Alonqueo et al., 2022). It directly relates to the Mapuche worldview, belief system, and myths – reproduced by rituals and materialised in practices imbricated to their livelihoods – almost entirely sustained on sacred depictions of elements of nature such as water (*ko*), rivers (*leufu*), forests (*lemu*), mountains (*mawida*), and volcanoes (*zegiñ*). All of them are protected by a *ngen*, a kind of energy or life force that humans must respect in order to maintain the source of well-being and their identity: nature and landscapes of *Wallmapu*.

From its origins in the 19th century, the Chilean government sought to integrate isolated volcanic territories, encouraging colonisation processes that included establishing new colonies on the slopes of the Villarrica, Lanin, Choshuenco, Carrán-Los Venados and Puyehue-Cordón Caulle volcanoes, among others (Petit-Breuilh, 2004), most of them already inhabited by indigenous populations. Thus, from 1900 AD, Mapuche families began to be recognised as part of peasant populations, mainly engaged in small-scale agriculture and livestock farming. Mapuche's lands were expropriated and granted to Europeans colonisers alongside natural resources, unleashing oppression and discrimination, as well as a lack of control over their ways of life as Mapuche (Pilquiman et al., 2020). It implied difficulties for the Mapuche people due to the territorial conflicts that arose after the Spanish settlement and subsequent colonisation of Southern Chile promoted by the Chilean government, based on the application of the law of selective immigration (mostly of Germans) during the 19th century (Bavestrello, 2017).

However, the literature recognises the historical and current presence of the Mapuche people despite past periods of colonisation to their ability to collectively confront and overcome all kinds of crises (Atallah, 2016; Pilquiman et al., 2020; Pinto, 2000). In Puyehue, the landscape is dominated by active volcanic systems, numerous rivers, lakes and forests that make up these geographical spaces, and are inhabited by peasant and indigenous populations, forming a kind of mountain socio-ecosystem. Due to its geographical isolation, the area of Puyehue was one of the late settlers,

which explains the lack of records on ancient eruptions of the PCCVC by chroniclers or naturalists. It was constituted as a commune in 1938 and as a municipality in 1972 (PLADETUR Puyehue, 2016).

The main access route to Puyehue is Route 215-CH, which ends at the Cardenal Samoré international pass (Pladeco Puyehue, 2020). The predominance of the agricultural sector characterises the economic structure of Puyehue; however, there is a high percentage of people who combine activities, mainly linked to tourism. In the mountains, peasant and indigenous families mostly participate in agricultural and tourism activities developed by themselves and by other private and public actors, including settlers (idem, 2020).

Impacts of the 2011-2012 eruption

In Chile and Argentina, nearly 8,000 people were evacuated during the first days of the eruption (Elissondo et al., 2016; Orozco et al., 2012). In the Argentinean Patagonia, the ash fall had a differential impact depending on the climatic region it affected; in the semi-arid steppe the damage and disruption were comparable to that of proximal areas despite the deposition of thinner deposits, mainly due to wind remobilisation. Contrarily, the impacts were minimised in areas such as Bariloche and Villa la Angostura due to the temperate environment and management response (Craig et al., 2016). Particularly, in the steppe regions, ash remobilisation events exacerbated the negative impact of primary tephra fallout, and only after five years the environment and the farming community began to show signs of recovery (Forte et al., 2018; Dominguez et al., 2020). About one million livestock died as well as chronic fluorosis in wild deer populations was reported, possibly as a consequence of F toxicity (12-167 mg/kg) across the Cordón Caulle tephra depositional area (Stewart et al., 2016). Less harmful impacts associated with ash consumption and fluorosis were registered in Chilean livestock around Puyehue (Araya, 2015). Human health impacts were not systematically reported, however increased medical visits for respiratory issues, eye problems, and stress were described in hospitals (Elissondo et al., 2016). In the proximal forest, tephra thicknesses varying from 10 to 54 cm experienced tree mortality from 8 to 54 % (Swanson et al., 2016). Other material effects of the eruption include electric outages, affectation to potable water and wastewater treatment, and severe disruptions to aerial transportation (Wilson et al., 2013). In addition, tephra accumulation caused the collapse of poorly constructed roofs (Elissondo et al., 2016).

In Chile, peer-reviewed volcanic hazard maps are published by SERNAGEOMIN (National Geological and Mining Survey), and they communicate information about the extent of several volcanic phenomena such as tephra/ash fallout, ballistic pyroclasts, lava flows, PDCs, lahars, debris avalanches, and susceptibility of new vents in monogenetic fields (Amigo, 2021). The hazards of only 28 of the currently active volcanoes have been mapped. Considering the probability of occurrence, hazard zones are classified into three categories (high, medium, and low) as a particularly relevant tool for decision-making in times of emergency. In the case of the PCCVC map (Toloza et al., 2020), based on the 2017 Census, the population exposed to high hazard is 3,620, while areas affected by moderate and low hazard include 10,447 people. Consequently, the population exposed to hazards from lava flows, dense pyroclastic flows, lahars and volcanic ballistic projectiles, reaches nearly 14,000 people. The most crowded area located south of the PCCVC included several settlements (Figure 1, namely Río Chanleufu, El Manzano, Anticura, El Caulle, and Pajaritos), within the high hazard zone.

METHODS

Fieldwork was carried out during 2019. Methods applied in this research included a qualitative case study design (Denzin and Lincoln, 2012; Yin, 2003), and an ethnographic approach to access the perspectives of local people (Florer, 2009; Guber, 2011; McGranahan, 2018). The case study allows for the empirical investigation of "a contemporary phenomenon in its real context, especially when the boundaries between the phenomenon and the context are not clearly evident" (Yin, 2003: 13). In the study areas (determined by their proximity to the PCCVC), the phenomenon relates to the simultaneous construction of risk (and how it is perceived) and livelihoods, and the context corresponds to the local-scale socio-ecological system where social relations, cultural and economic practices, human-environmental interactions and the production of vulnerabilities materialise. Linking ethnography to the study of disaster risk involves adding to its core attribute (understanding the internal logic of a culture), a necessary sense of ethnographic sensitivity (McGranahan, 2018), by respectfully and empathetically engaging the narratives of people who coexist with hazards and have survived critical or catastrophic events.

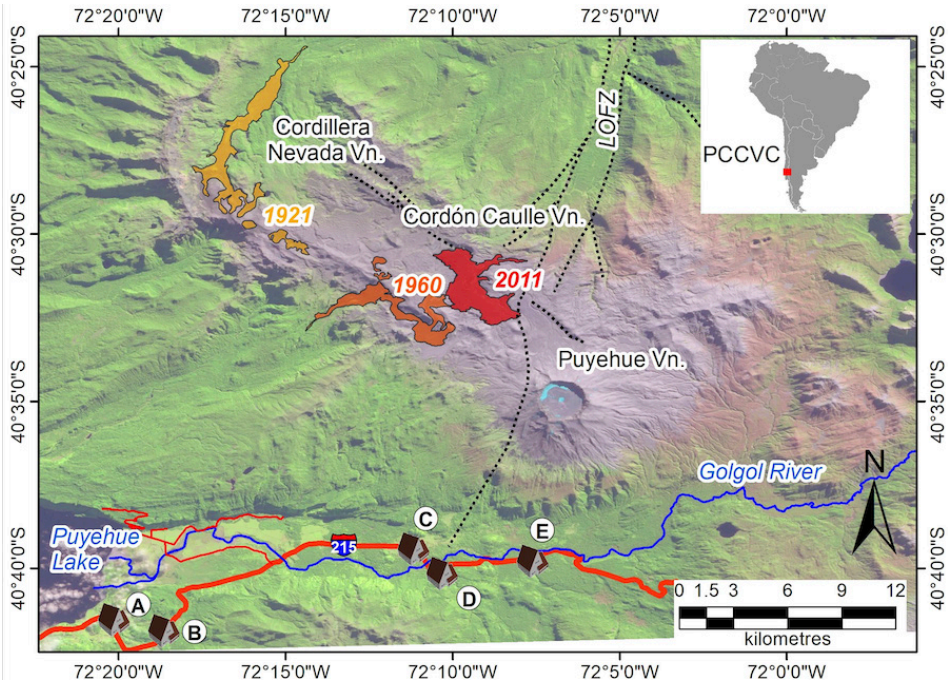

Figure I. Location map of the Puyehue-Cordón Caulle Volcanic Complex (PCCVC)
Source: Authors, 2023, based on Landsat base satellite image acquired from the Nasa Earth Explorer database (https://earthexplorer.usgs.gov/).

Notes: The Liquiñe-Ofqui Fault Zone (LOFZ) is represented by segmented lines. The coloured polygons are the lava flows of the historical eruptions. The five human settlements (houses) considered in this study correspond to: A=Río Chanleufu, B=El Manzano, C=El Caulle, D=Anticura, and E=Pajaritos.

This paper examines the narratives of 20 inhabitants of the five settlements in Puyehue, selected through 1) purposive sampling, since it is timely and allows a better approach to the informants, and 2) chain sampling, through which a first informant facilitates access to others (Quintana, 2006). Regarding the type of sampling chosen for this study, purposeful sampling allowed us to delve into a small number of observation units (5 settlements or sectors where diverse social and economic contexts take place, from family tourism to large estates and tourist concessions). In this type of qualitative approach, sample quantity is not fundamental here,

> "but rather the understanding of phenomena and social processes in all their complexity. Many of the questions revolve around the meaning these have for the subjects that star in them. For this reason, the place the participants occupy within the social, cultural, and historical context of which they are a part is of paramount importance" (Martínez-Salgado, 2012: 615).

The sample was defined according to the following criteria: Based on the review of communal Census statistics, the feature of low population density and high social heterogeneity was identified within the inhabited geographic space closest to the PCCVC - Route 215 - and located in the low hazard zone (within a radius of 18 km from Río Chanleufu sector to the border crossing in Pajaritos sector). After visiting the sites to observe these features, the five settlements were selected, and fieldwork was carried out in each one making rapport to identify inhabitants who, later through snowballing, led us to other informants (Table 1). Thus, the sample included actors from multiple strata whose livelihoods are very diverse, although they all share equivalent of exposure to volcanic hazards.

In-depth and ethnographic interviews were applied to inhabitants (Spradley, 1979; Guber, 2011), by the first author. According to Spradley (1979: 9), the ethnographic interview "is one strategy for getting people to talk about what they know" (1979: 9), in which some questions "arise naturally, adapted to the subjects and conditions of the context" (Garrido, 2017: 38). In addition, Guber (2011: 80) refers that the ethnographic relevance of the interview lies in the discovery of meaningful questions according to the cultural universe of the actors, which is "central to getting to know local meanings". Since the interview is an instrument has the property of eliciting experiences and memories from subjectivities and sensitivities, disaster risk research should avoid

the possibility of "urging people (...) to construct negative scenarios that have little or nothing to do with their spontaneous perception of risk" (Sjöberg, 2000: 411). In other words, the interview on volcanic risk should raise questions about elements that are generally unquestionable for the individuals themselves (e.g. why people live where they live, why after an eruption they decide to return home, what must happen in terms of disasters to decide to live in another place, what is the meaning of disaster for the inhabitant, etc.). Therefore, to gain access to their perceptions of risk, it is necessary to carefully elaborate a guideline of questions, avoiding the researcher to pre-establish links between aspects from an external perspective, which may bias how the inhabitant perceives and frames them.

Interviews, direct observation and field notes were carried out during the fieldwork. Direct observation is a strategy through which it is possible to glimpse from a privileged position the diverse social dynamics generated in space during a given time. It is positioned as an ideal tool for making discoveries, critically examining theory, and anchoring it in specific realities, giving space for communicating different reflexivities (Guber, 2011). The observation was carried out in private and public spaces where the authors interacted with the inhabitants. In the private sphere, interviews and observation were carried out in homes to elicit situated memories, experiences, and perceptions, as well as to awaken questions in the inhabitants by drawing on the proximity of the volcanoes. In this way, we inquired into the perceptions of the inhabited environment, as well as the economic matrices and dynamics that characterise each territory/family and empirically observable structural geographic conditions in the place (e.g., connectivity/isolation). On the other hand, a workshop was held in the El Caulle sector, in which the inhabitants and the researchers met and participated by sharing discourses on their relationships with the volcanoes and experiences of past eruptions. It was a space for dialogue between peasant families, settlers, indigenous families, an association of artisans, tourism entrepreneurs, CONAF officials and a scientist (geophysicist) who presented relevant data on the eruptions of the PCCVC and answered questions from the participants that arose in this space for interaction.

Interviews and workshop were conducted in Spanish and transcribed into English by the researchers. In accordance with the informed consent and ethical framework, when informants are cited, they will be identified by letters (e.g., A, B) or references to their occupation (Table 1).

Commune	In-depth interviews		Settlement	Workshop participants
Puyehue	1	Woman, rural indigenous tourism “Camping Donde Matías”.	Río Chanleufu	15 inhabitants: 7 women 8 men (Settlers “Fundo El Caulle”, CONAF officials, association of artisans, mapuche families, Anticura tourism)
	2	Man, rural indigenous tourism “Camping Donde Matías”.	Río Chanleufu	
	3	Man, peasant farmer, foreman of latifundium “Gol Gol”.	El Manzano	
	4	Man*, entrepreneur, “Anticura” tourism centre.	Anticura	
	5	Man, entrepreneur, “Anticura” tourism centre.	Anticura	
	6	Man*, indigenous peasant farmer, horseback riding guide.	El Caulle	
	7	Woman*, indigenous peasant farmer and president of the artisans' association.	El Caulle	
	8	Man, rural school teacher.	Pajaritos	
Total informants: 20				

Table 1. Details of the study sample. Persons marked with an asterisk participated in interviews and workshops
Source: Authors, 2023.

The qualitative data were transcribed and processed with the ATLAS.ti software, using the open, axial, and selective coding strategy (Strauss and Corbin, 1998). Emerging codes were identified in code families and categorised (Braun and Clarke, 2006). The thematic analysis allowed us to detect the influence of the three underlying factors involved in perceived risks (categorised as social cohesion, disaster memory, and uncertainty; see table 1 in Results section).

Shortly after the onset of the 2011 eruption (from 17 to 20 June), fieldwork was carried out by the second author in the area located south of the PCCVC along the 215-CH route. Measurements

of tephra thicknesses and tephra sampling were complemented by audio-visual evidence of the impacts produced by tephra fallout and lahars. Interviews during this period were not carried out because the area was evacuated and only accessible to authorities and scientists. Tephra samples were sent for analysis to the University of Durham and their results are reported in the work of Wilson et al. (2013).

RESULTS

In Puyehue, the inhabitants coexist with the PCCVC sharing a sense of social appropriation of volcanoes. This social process implies a qualitative evaluation of the volcanic hazard-benefit ambivalence according to the population's experiences about past eruptions. Two eruptive cycles emerge from the narratives (1960 and 2011, see Figure 2). From this, a wide ambivalent perception is built depending on the more or less harmful impact of eruptions on livelihoods: *the volcano* is considered to be *less or more benevolent*. In addition, a perception is produced based on the *geomorphology* of the volcano (e.g. Puyehue stratovolcano [cone] or the Cordón Caulle fissure [hill]), from which the location of the eruptive centres of the volcanic complex is recognised, ignored or confused in the landscape. Therefore, the inhabitants are aware that they inhabit a rural environment entirely dominated by volcanism. It is from this generalised, albeit partial awareness, that families perceive risks of living near the PCCVC.

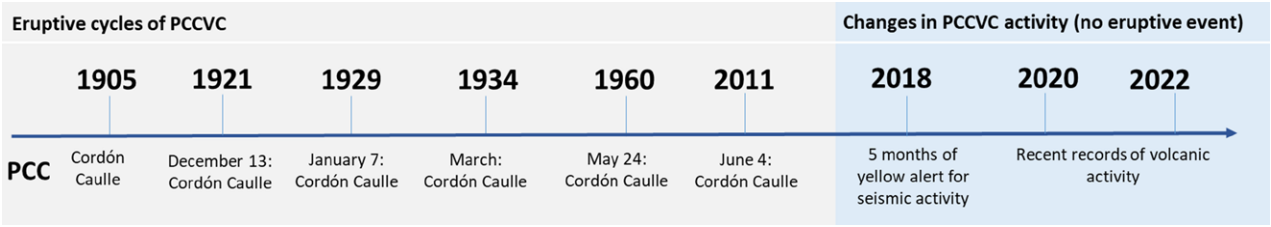

Figure 2. Historical volcanic activity of the PCCVC
Source: Based on Moreno (1980), Abumohor and Díaz (2012), and SERNAGEOMIN (2018, 2020, 2022).

In this context, we analysed the influence of three underlying socio-cultural factors in the construction of risk perceptions: 1) social cohesion, 2) disaster memory, and 3) uncertainty on environmental impacts of future eruptions. Based on these, we inquired into perceived risks among the community living near the PCCVC. Each category (Table 2) will be analysed in the following sections.

Category	Sub-category	Code family
Social cohesion: building neighbourhood between humans and volcanoes	Neighbourhood in the volcanic territory	• Inherited and borrowed lands: Senses of belonging • Shared geography, shared volcano: Interconnected rural livelihoods and senses of cooperation
	The countryside and the city: Acceptable risks	• Social fabric in rurality • *"It is preferred to live with the volcano than to leave the land"*: Senses of safety
Disaster memory: How PCCVC eruptions are recalled	More and less benevolent eruptions	• *"You simply cannot live in fear forever"*: the volcano in the daily dynamics • Neutral evaluation of active volcanoes: Eruption as accepted risk, and other hazards to avoid
Uncertainty about volcanic hazards: How PCCVC future eruptions are expected	Unpredictable environmental conditions	• Comparing eruptions: The impacts in Chile and Argentina • East wind: uncertain conditions, unimaginable eruptions

Table 2. Categories of analysis for the interpretation of factors influencing the perception of volcanic risk
Source: Authors, 2023.

Social cohesion: building neighbourhood between humans and volcanoes

The category of social cohesion refers to the neighbourhood built by social groups in the PCCVC territory and to the hierarchy of socio-natural risks tolerated in it. The geographic composition encompasses social groups of different social strata and origins inserted in diverse economic activities (from subsistence economies to tourist concessions and public services).

Inhabitants' livelihoods are mainly based on small-scale farming, large-scale ranching, and tourism associated with the Puyehue National Park, whose entry is by route 215 and culminates at the Cardenal Samoré international pass.

The populations share a geography where heterogeneous social realities coexist, and different senses of belonging are produced, marked by the Andean landscape surrounding them. Some of the inhabitants were born on site but they currently live as tenants (e.g., Mapuche and peasant families in El Caulle and El Manzano settlements); others migrated from cities like Santiago to manage their parent's large estate (e.g., a settler in El Caulle sector), or from Osorno to develop a tourist concession (e.g., entrepreneurs and tour guides in the Anticura sector); while others work daily in the Puyehue National Park (e.g. CONAF park rangers) or services around the border customs (e.g., a school teacher in the Pajaritos settlement).

Their sense of belonging includes the Puyehue volcano as an important element of the local rural identity, and the Cordón Caulle as part of their livelihoods. However, the territorial attachment and human-volcano relationships have nuance in these sectors: some inhabitants live or work in a section of the national park, such as in the case of a Mapuche family that works on El Caulle farm and a tourism company that owns a concession in Anticura. This serves as an example of the development of territorialities produced on land that is not inherited or owned in legal terms. This aspect eventually causes feelings of uncertainty, although most of the time life goes by without problems associated with this issue:

> *Researcher*: What things do you think are important to stay here considering that the volcano is active and may suddenly erupt?
>
> *C*: I enjoy living in the mountains and I try to do all kinds of activities; everything is nearby, but more isolated and calm, far from the city and from all that toxicity. I would leave here if I had a place with similar conditions, however it does not exclude me from continuing working here. Since the land is not ours (we only have the concession here) everything is uncertain (Man, tourism entrepreneur, Anticura sector, 2019).

The neighbourhood relations between inhabitants and owners [settlers who own the estate in the first case, and the Chilean state in the second] plays a key role in making it possible to build this sort of attachment in the volcanic territory.

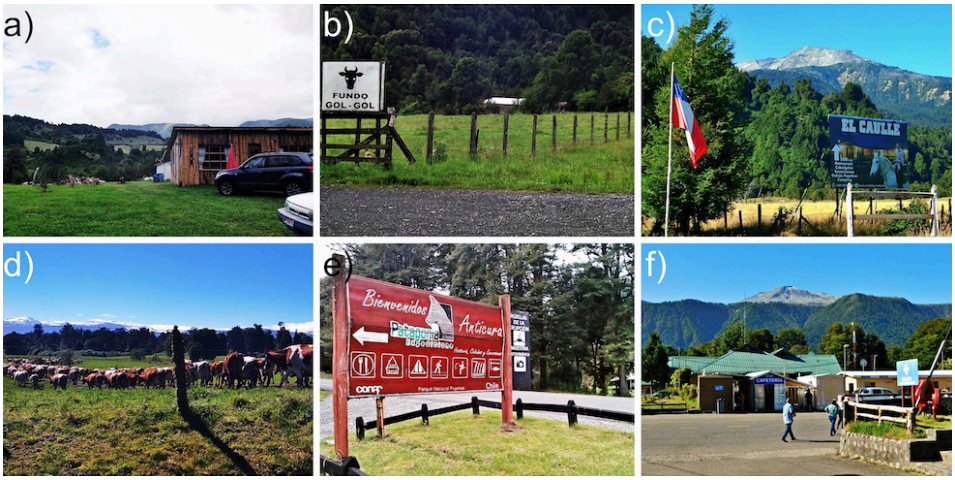

Figure 3. Location of settlements
Source: Authors, 2023.

Notes: (a) Río Chanleufu, (b) El Manzano, (c and d) El Caulle, (e) Anticura and (f) Pajaritos, on international route 215. In some sectors, the Puyehue volcano (c and f) and the Cordón Caulle (d) can be seen in the landscape.

Economic activities on the *borrowed land* are fully associated with nature, its resources, and the rural dynamics (Figure 3). A Mapuche woman artisan at the El Caulle sector expressed this when asked about the reasons to build her home in front of the Puyehue volcano. She mentioned the arrival of her parents there, in the mid-1950s, and the growth of her family for generations there, conveying the sense of attachment between generations. Despite living in a settler's state, she

mentioned that she "would never leave, even if getting paid or being offered a same-size land in a safer place. I have my life here, my land, and do my stuff that I couldn't do anywhere else". Her daughter who was also present in the interview and works as a restaurant assistant for the settler pointed out that she would not leave either. On the contrary, she said to be studying for an agricultural technician degree and hoping to come back to work there. This Mapuche family has developed strategies to meet their needs throughout the year. Her husband also does horseback riding to the Cordón Caulle crater. Their livelihoods are thus very intertwined with their neighbourhood relations:

> "We have farm animals for sale, also for eating. We get everything we need monthly from the town. In the summer a lot of tourists come to the hotels; the Anticura tourist centre or the El Caulle Restaurant, and they come to my house to buy homemade bread. I also prepare kuchen. The guys from Anticura [tourist centre owners] send their tourists to my house so they become my customers" (Woman, Mapuche artisan, El Caulle sector, 2019).

Most of the inhabitants of this sector participate in collective activities such as *we-tripantu* (Mapuche renewal ceremony) or *trafkintu* (exchange of food, seeds, and products between families). These practices reinforce the levels of trust between Mapuche and non-Mapuche inhabitants, contributing to the social cohesion and sense of social, economic, and food security reproduced in the volcanic territory.

On the other hand, in the Anticura sector, two tourism entrepreneurs have developed an attachment to the place since their arrival to the territory in 2011. Months before the eruption of Cordón Caulle in June 2011, both acquired the concession of a National Park sector. In June 2011, however, they faced the eruption and the effects of the yellow alert declared in the area for the following months, which limited the access of tourists to the affected area. Before investigating their experience with the eruption, they were asked about the reasons to develop a business near the PCCVC. In this regard, one of them indicated the need to live quietly, away from the city:

> *Researcher*: Are you attached to this place?
>
> *C:* Actually, yes. I've been coming here since I was a child because I liked the place, and the area was always unexploited for tourist activities. When visiting in 2010, a park ranger told me that it would be tendered, so I went to Puerto Montt to apply and here we are managing Anticura after almost 10 years. It is not a matter of money, it is about being in love with the countryside and spending a lifetime here (Tourism entrepreneur, Anticura sector, 2019).

Tranquillity in rurality is commonly associated with security and well-being. Comparing the risk of living in rural or urban contexts implies prioritising greater environmental, economic, food and health security, generally characteristic of rurality. On this basis, people recognise the influence of the rural volcanic environment on their lifestyles:

> *Researcher*: Regardless of the possibilities of work, or education for children, can you imagine getting old here?
>
> *A:* I would be happy to live here for the rest of my life as this place is safe enough. However, I don't know when I suddenly have to go out.
>
> *B:* That is. If you compare the volcano and the city, I think the city is more dangerous.
>
> *G:* Here I can leave the door open with no concerns of being robbed.
>
> *B:* Yes, nothing happens. The volcano may erupt, but living in a city everyday life is more dangerous than that.
>
> *B:* For instance, same-age children from a nearby city are different compared to those from here; here they live in a bubble with a better quality of life. Our children are not under stress, as people in the city are more aggressive (El Caulle workshop participants, November 2019).

There is a collective perception of the Puyehue volcano as a source of permanent benefits that the inhabitants integrate into their livelihoods. Hence, some risks of living near the PCCVC are accepted because "when the volcano does not erupt, things are quiet. This volcano is wonderful

and a tourist attraction. It is entertaining, and people come from abroad to ski down the volcano" (Male participant, El Caulle workshop, 2019). However, its dangers are also acknowledged, as described by a CONAF park ranger:

> "We wake up and see the snowy volcano. Most of us here have a certain attachment to it and this incomparable beautiful landscape. So, maybe we have to learn how to live near the volcano and be aware that a catastrophic event can suddenly happen" (Park Ranger, El Caulle workshop, 2019).

Figure 4. Puyehue volcano
Source: Authors (a, 2019; b 2018).

Notes: (a) Perspectives from El Caulle settlement (house of Mapuche family, view from the southwest), and (b) the international border (view from the southeast).

Since most of the inhabitants interviewed benefit from the volcanoes, they accept face exposure to future eruptions. However, perceptions of risk also include seeking to maintain their pre-existing social relations because "life is quiet, it is a nice place, but even though you would never lose respect for the volcano, you have a good time here. You breathe good air" (Workshop participant, El Caulle 2019; Figure 4a).

Disaster memory: how PCCVC eruptions are recalled

During the visit to the study area in June 2011, by the second author, it was observed different impacts related to the eruption. First, the 215 international road was closed for public transit 14 km west of Anticura (Fig. 5a), allowing only emergency teams, technical support, and scientists to access it. We observed 1-2 mm-thick ash fall deposits 8 km west of Anticura, covering the forest and the road (Fig. 5b, c). Farm animals were simultaneously fed with fodder transported in trucks (Fig. 5c). At 500 m from Anticura, the Golgol River had a brown colour as a consequence of the high volcanic sediment load, including pumices up to 5 cm diameter. In that area, ash fall thickness reached 1 cm (Fig. 5e) and civil protection authorities established a second control point for vehicles transiting towards the closed Pajaritos international customs (Fig. 5f; 4 km to the east). From this point to the east, ashfall was continuous, and explosions were noisy, whereas the deposit reached >25 cm at 4.5 km east of the customs.

Figure 5. Impacts of the 2011-12 eruption in the study area as observed in June 2011
Source: Héctor Moyano (a, c, and e, 2011) and authors (b, d, and f, 2011).

Notes: a) Road closure (14 km west of Anticura); b) ash fall deposit covering the vegetation (6 km west of Anticura); c) road covered by ash and truck transporting fodder (6 km west of Anticura); d) High load of ash in the Golgol River (0.5 km east of Anticura); e) 1 cm-thick ash deposit at Anticura; f) control point of civil protection authorities at Anticura.

People's narratives help to address uncertainty about such impacts. For example, one resident stated, "You just cannot live in fear. It is the cycle of nature, and something can happen to you anywhere. In the case of a magnitude nine earthquake in the city, a building can collapse, crushing you to death" (Resident, El Caulle, 2019). The frequency of small to moderate eruptions has allowed the transmission of values, experiences and perceptions at the family and community level to be understood as disaster memory. These elements are contained in human-volcano relationships and stratified volcanic memories (Vergara-Pinto and Marín, 2023), which can be inherited, transmitted or reinvented (rather than avoided).

The inhabitants of Puyehue conceive the 2011 eruption as a natural process that would inevitably occur after the prolonged quiescence since its last significant activity in 1960. The impacts on the environment (pollution of rivers and lakes), health (respiratory problems), and daily dynamics (local economy affected by loss of livestock, education in establishments and tourism suspended) are certainly remembered as critical and harmful. However, there was no substantive transformation of livelihoods after the eruption, so the inhabitants do not associate these events with a disaster. In this neutral perception of eruptive events, two aspects are distinguished: 1) they are spectacular extreme events that instil not only fear but also feelings of magnificence; and 2) their effects are often both harmful and beneficial, unlike other natural processes that are perceived as disasters, corresponding to unavoidable events that are framed as hazards that bring no benefit. Regarding the former, witnessing an extreme manifestation of nature surrounding their homes represents an ambivalent experience for the inhabitants: on the one hand, they notice how active the volcanic territory is and, on the other, they perceive it as a privilege to witness an event that, according to their past experiences, is infrequent and "will probably never be seen again in my life" (Mapuche farmer, El Caulle sector, 2019).

Researcher: How was the experience of the eruption? Were you afraid?

R: No. That night I remember that we stood with Flavio outside the house looking at the eruption. We could see the lights, the red colour, the lightning. It was beautiful. Not everyone is lucky enough to see something like this, it is nothing frequent to be seen every day.

Researcher: Do you feel that the volcano threatens your home and your family?

R: I'm not afraid. It's good that the volcano erupts.

F: The volcano has to breathe. After the eruption, the worst is over. We remain calm because it has already breathed, and released energy, an eruption like this will no longer happen again for long (Mapuche family, El Caulle sector, 2019).

As for the second, the inhabitants have periodically faced other natural phenomena that threaten their livelihoods and infrastructure, for example, the 9.5 Mw earthquake of 22 May 1960, which produced an eruption of the Cordón Caulle two days later. On this basis, they place volcanic risk in a position of greater foresight (in terms of the magnitude of its impacts) than other risks beyond families' control. One resident mentions, "The eruption [of Cordón Caulle in 2011] was not bad. A bad thing is the flowering of the *quila* (Chusquea quila) every 30 years (due to the proliferation of rodents). However, the volcano brought good things. The ash and sulphur fixed the grass. And the animals are used to it" (inhabitant, El Caulle, 2019). This result is similar to that reported north of the PCCVC near the Carrán-Los Venados volcanic field by Vergara-Pinto and Marín (2023), considering the proximity of both volcanic systems and settlements. The *quila* bloom and the 1960 earthquake (and not the eruption) are thus remembered as a disaster:

A: During the 1960 earthquake, I know that a column of ash also came out due to the 1960 eruption, and I think it was nothing dramatic. Ash fell when there was *puihua* (east wind) and the rivers were affected. A lot of ash accumulated, pumice stone, the riverbed rose, the rivers overflowed, but far from here. Well, at that time the earthquake was worse than the eruption.

C: Yes, a hill collapsed, which is the sector of the landslides that shattered Route 215 (Participants of the El Caulle workshop, 2019; Figure 6).

Figure 6. Workshop with the association of tourism entrepreneurs from Puyehue
Source: FONDECYT project No. 11171068 (2019).

Notes: Including participants from the Mapuche community, settlers of Fundo El Caulle and CONAF officials (b, c). The image a) shows the stage of the workshop in which the Cordón Caulle hazard map was discussed, asking the question "do we know enough?".

Uncertainty about volcanic hazards

Despite having memories of past eruptions and knowledge of impacts, vulnerabilities and collective coping capacities, the population also accepts the coexistence between local ecological knowledge and awareness of unpredictable environmental conditions. An example of this relates to *the conjunction of tephra and wind* in disaster memory. Regarding the former, the fall of tephra represents one of the most important impacts perceived by the population, as it has detrimental

consequences in different areas of life. At the same time, the inhabitants distinguish that the chemical composition of the ash from the Cordón Caulle is "favourable" in terms of its effect on the soil (fertilising ash); a distinction made after perceiving the ash fall from the eruption of the Calbuco volcano in 2015, located 78 km to the south of the volcano:

> *B*: With the 2015 Calbuco eruption we were more affected by the ash than with the Cordón Caulle in 2011.
>
> *A*: Here is not only the Cordón Caulle, but Casablanca volcano also is nearby, and Osorno is further south. Their eruptions can also affect us because the Calbuco erupted a lot of ash that fell here. The type of ash was different from the Cordón Caulle ash, which was like a talcum powder that stuck everywhere. In contrast, the Calbuco ash was like sand (Participants El Caulle workshop, 2019).

Therefore, considering that most of the population depends on both tourism and fertile land use, the category of *uncertainty* is mainly related to the type of impact that a future eruption may produce. In fact, in 2011, the population faced both the direct impacts of the tephra on their livelihoods and the indirect effects of the prolonged yellow alert on tourist arrivals to the area, resulting in a *catastrophic* perception of the volcanic event among tourists; very different from the perception of a *moderate* eruption among the resident population in the affected territories:

> "We work in tourism and in 2012 nobody was coming. In 2014 and 2015 we started to see a slight increase in tourism. Shocked people came and said they thought Puyehue disappeared, that it was buried under the ashes or the lava" (Anticura entrepreneur, El Caulle workshop, 2019).

In this sense, the common and shared question from locals about the volcanic risk of the PCCVC concerns whether or not the next eruption will be moderate, replicating the behaviour of the 2011 Cordón Caulle eruption, or will be *unimaginably different*. It is also recognised that wind was central to the *moderate* effects of the 2011 eruption. The ash dispersed mainly to the east (Argentina), severely impacting the trans-Andean territory. Inhabitants noted a significant difference between their material losses and the effects of the same eruption in Argentina, especially in Villa La Angostura and San Carlos de Bariloche. As one inhabitant mentioned, "The truth is that here it was not as dramatic as in other places. We Argentinians were hit by ash. I think the authorities who evacuated us expected the worst, and in the end, it was not so terrible" (Resident, El Caulle workshop, 2019). This becomes a point of comparison for assessing the perceived impacts in Puyehue: "Imagine an eruption like the one in 2011 but without the *puihua* (east wind), it is unpredictable" (Villager, El Caulle workshop, 2019). The conjunction of tephra fall and east wind represents a condition that people know they need to be aware of, which may also influence their response and behaviour in the face of future eruptions. Furthermore, due to the usual behaviour of the wind in past eruptions, in the Puyehue community, the perception of *Argentineans as more exposed to the hazards of the PCCVC* predominates, along with a perception of risk according to which future eruptions (and not those experienced) could be more catastrophic, but not necessarily impossible to overcome.

Despite this possibility imagined by all informants in accounts such as “the next one will be bigger”, “this last one was moderate”, and “an eruption of the Puyehue volcano could be worse than one of the Caulle”, there are no mentions of abandonment of land due to volcanic risk. On the contrary, people returned to occupy their lands after the eruptions of 1960 and 2011. Since then, the volcanic risk has continued to be accepted and tolerated in Puyehue. In this sense, families express a position as *agents*, able to contribute to disaster risk reduction in their territories through prevention and preparation to face a future eruption of the PCCVC. However, it must be accompanied by sustainable risk management for their communities. At the end of the workshop, the confluence of the three factors - social cohesion, memory, and uncertainty - was implicit in the participants’ reflection on living with the volcano. These related to the socio-cultural effects of the eruption as an event that interacted with the sense of attachment to the place (partly due to volcanic livelihoods), the sense of neighbourhood, and the need to reduce uncertainty by acquiring knowledge about unimaginable eruptions from the PCCVC to improve preparedness in the best and worst case scenarios:

Researcher: Anything good about the volcano after it erupted?

A: Yes, it improved the soil.

B: Another thing can be the union of the neighbours, especially some families.

A: As an experience, it was a good thing, we learned to get prepared and to be more alert, unlike before the eruption (Participants, El Caulle workshop, 2019).

DISCUSSION

Culture plays a crucial role in understanding the relationship between humankind and volcanism and the tendency to subsist, cope, evacuate, and return to volcanic territories (e.g. Bachri et al., 2015; Cashman and Giordano, 2008; Kelman and Mather, 2008; Németh and Cronin, 2009). In this respect, in cultural terms, a volcanic imaginary of the PCCVC considers that the next eruption may be worse than that of 2011-2012. Therefore, the inhabitants believe they must be better prepared to cope and recover. Hence, the tendency in the literature cited above is replicated in rural and indigenous contexts in Southern Chile. In the case of Puyehue, human habitation in the volcanic environment can be culturally explained by a consistent sense of belonging to the land, deeply imbricated with a sense of neighbourhood and a local economy based on the volcanic landscape. Despite social heterogeneity, the volcano is perceived as their own by all those who share the surrounding lands and are exposed to its hazards.

In the territory of the PCCVC, coexistence with volcanoes and the production of memories about their eruptive cycles influence the acceptability of the risk of inhabiting a disaster-prone land (Hoffman, 2015). From an outsider's perspective, the latter may go unnoticed and be misinterpreted by a disinterested community. However, inhabitants remember past risks, accept current risks and imagine future risks, placing themselves and their livelihoods in a constant position of relative safety they expect to maintain. The volcanic imaginary supports the notion that the next eruption may be worse than the eruption experienced. Therefore, people accept that they must be better prepared to cope. By delving into experiences of past eruptions, triggered memories raise questions about the present and the future, such as “When will the next one happen, and will we be able to return to our homes when the volcano calms down?”. Far from influencing people to leave the area with active volcanism, these questions motivate them to be prepared for the unexpected. Considering these questions in volcanic risk analysis can help address issues related to territorial vulnerability and the population's pre-existing capacities, along with assessing hazard exposure. Overall, the results can be explained by analysing the influence of social cohesion, memory and uncertainty as socio-cultural factors in constructing volcanic risk perceptions.

Social cohesion: source of capacities

The level of the collective sense of belonging and social cohesion is one of the main factors involved in the social processes activated during the response to disasters and the development of capacities in heterogeneous community contexts (Capshaw, 2005; Ludin et al., 2017; OECD, 2011). In this research, the inhabitants expressed that they are used to rurality characterised by socioeconomic contrasts, but on which they depend. Moreover, establishing social relations mediated by interdependent economic practices positively results in constructing the social fabric. The position of every kind of actor deepens the social appropriation of the inhabited volcanic environment, expressed in a habitus characterised by shared values, as well as behavioural patterns (e.g. solidarity) that identify them. Even when there are different economic realities between settlements, the volcanic environment is a common source of employment and sense of well-being, which may explain the construction of a similar view on the quality of life that is developed there. Its relationship to volcanic risk research is based on understanding why the response of different populations sharing common geography (i.e., indigenous, settlers, locals, migrants, etc.) may be less or more collectively motivated during an eruptive event in the future.

Disaster memory: source of awareness

Depending on the effects and duration of the event, some phenomena are perceived as natural (implying both negative and beneficial effects) or disasters (only having harmful consequences, with no possibility of taking advantage of their effects). This is understood as a social construction of human-environment relationships that links temporalities, localised subjectivities, and subjectivised spatialities (Signorelli, 2008). These vary according to the experiences and the resignification that these experiences acquire over time through oral tradition and the reconstruction of autobiographies (Vergara-Pinto, 2022). The families of Puyehue who have faced past eruptions, usually frame volcanism as an acceptable hazard. For them, the eruptive cycle represents a temporary state

of the volcano, whose impacts can be coped with depending on the family's abilities. Afterwards, the volcanoes return to normal, and the inhabitants use and (re)establish links with geological structures. Traditional and also innovative uses attributed to the volcanoes are transmitted through collective memory, many of which are embedded in family traditions. Moreover, it is recognised that volcanoes are intrinsically related to unpredictable environmental conditions, prompting communities to be prepared for the unexpected.

Uncertainties: the need for people-centred volcanological learning

While volcanic memory contains references to specific eruptions experienced by the community, it also represents a source of questions about the characteristics of future volcanic activity. Along with the issue of knowledge gaps, some references to management issues also emerged in the workshop. For example, from the local perspective, uncertainty about what to decide in the face of contradictory calls from authorities and scientists should be answered with a sustained strategy of people-centred education (rather than outreach) about volcanic uncertainties in the community for autonomous decision-making while contradictions or false information circulates. In this way, inhabitants would act from their agency and avoid increasing their exposure to risk by waiting for confirmation of the veracity of such information (e.g. by wearing masks when they are unsure of the real impact of inhaling volcanic ash). In the workshop, participants also referred to their various needs concerning risk governance, which, if addressed by studies and policies, could be easily understood and appropriated by the community as they emerged from the community:

> "We want the communities to be incorporated into the municipality's contingency plan, how to evacuate them, the registration of people, where they are going to arrive, and the danger of the eruption because SERNAGEOMIN has that data. They know the type of volcano, and the damage it can affect... for example, here, the radius they had was about 6 km" (Park ranger, El Caulle workshop participant, 2019).

Indeed, volcanology can address community imaginaries of volcanic risk by better communicating available expertise. Unlike other Chilean settlements that emerged during the colonial period in the 18th century, the Puyehue area was characterised by its isolation due to its difficult access. Although there were always transit routes to the Argentinean pampas, it was in the 20th century that a road was opened through the Gol-Gol river valley (Moreno and Petit-Breuilh, 1999; Lara and Moreno, 2006). For this reason, the historical eruptions of the PCCVC could not be described by chroniclers (ídem, 2006). As a first step to fill this gap in the case of the PCCVC, our research considered a review of the main uncertainties of the inhabitants regarding the historical trajectories of tephra fall in past and recent eruptions, including those of unimaginable ancient eruptions (Lara and Moreno, 2006).

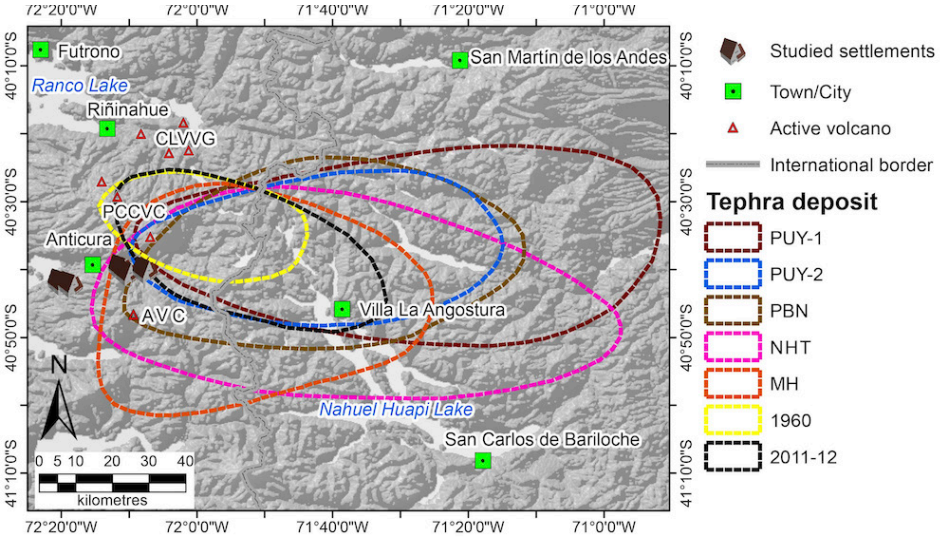

Figure 7. 10 cm-thick isopachs from Post-Glacial and Holocene eruptions of the PCCVC and the Antillanca Volcanic Complex (ACV)
Source: Base map from the SRTM DEM (30 m resolution) acquired from the Nasa Earth Explorer database (https://earthexplorer.usgs.gov).

Notes: PUY-1 and PUY-2 are eruptions at 13.9 and 10 thousand years of Puyehue volcano (Naranjo et al., 2020). PBN corresponds to Playa Blanca-Negra and NHT to Nahuel Huapi Tephra (Naranjo et al., 2020), both deposits sourced by the AVC. The Mil Hojas (MH) deposit corresponds to the youngest Puyehue tephra (Alloway et al., 2021). The historical 1960 and 2011-2012 tephras are based on the maps of Chapron et al. (2006) and Wilson et al. (2013), respectively.

According to Figure 7, a tephra fall deposit sourced from the PCCVC with an identical chemical signature to that of the 2011 eruption, dates back to ~13.9 thousand years and is dispersed east across the northern Patagonian Andes (Alloway et al., 2022). It suggests these events are not rare in recent geological history. According to the work of Naranjo et al. (2017) PCCVC accounts for at least three major eruptions during the Holocene (10.5 to 1.1 thousand years), all of them with larger erupted volume than the 2011-2012 eruption and dominant dispersal towards the east-southeast; these eruptions have deposited between 10 and 50 cm of tephra in the study area, however, two other recent (i.e. <3 thousand years) eruptions from Antillanca volcano formed extensive deposits up to 200 cm-thick in the same locations. The last major eruption of PCCVC before 2011 occurred ca. 1.1 thousand years BP (before present), and erupted nearly 4.3 km3 of tephra from which the revised dispersal is most likely to the southwest (Alloway et al., 2022) severely affecting the areas considered within this study. The area has also been recently affected by other eruptions from distant volcanoes, as exemplified by the Calbuco (78 km distance) 2015 eruption, which produced copious ash fall in the study area (Romero et al., 2016). Hence, both the geological and historical records support that severe tephra fall events usually affect this area, not always sourced by the PCCVC but from other neighbouring volcanoes.

The direct interplay between tectonic phenomena and eruptions is observed both in the 1960 and 2011-2012 eruptions. While the first was triggered by the Mw 9.5 megathrust Valdivia earthquake, the second should have been facilitated by the destabilisation of a Liquiñe-Ofqui fault branch during a magmatic intrusion in 2007-2009 (Lara et al., 2004; Novoa et al., 2022). In this respect, the displacement of regional or local tectonic features and their related seismic events should be accompanied by volcanic responses, initiating complex hazard chains affecting single territories. Moreover, in Chile and Argentina, the 1960 earthquake was coupled with lake-damming and tsunamigenic landslides (Davis and Karzulovíc, 1963; Chapron et al. 1960), thus demonstrating the complexity of such multi-hazard events. Future hazard assessment and risk management may encompass the already available disaster memory with the increasing knowledge on the activity of PCCVC, but also incorporate a multi-hazard approach and worst-case scenarios involving severe tephra fall deposition in these human settlements.

Micro-zoning in volcanic territories

Overall, the insights gathered on the community-volcanology interaction evidence the emergence of an approach to emergency planning and preparedness that needs to be engaged and binding with communities. In this sense, concerning development plans and institutional emergency plans, a micro-zoning of territorial vulnerability is suggested for the social management of the socio-cultural, economic, political and environmental particularities of inhabited volcanic areas. A micro-zoning of existing hazards (e.g., lava flows, pyroclastic density flow, landslides) relative to the location of households is also recommended for each volcanic system in order to estimate the specific hazard exposure of each human settlement and nearby infrastructure. This research also suggests assessing disaster preparedness and response for specific hazards, multi-hazard contexts, geohazard chains and volcanic crisis scenarios.

Such suggestions seek to contribute to designing culturally sensitive prevention efforts that communities can understand appropriately, facilitating the decision-making process during future volcanic eruptions. On the other hand, these efforts should be included in development planning that integrates the volcanic risk variable to reduce it rather than considering it as a limit to territorial development.

Towards ethnovolcanology: A Southern Andes approach to addressing volcanic risk

The analysis included in our research highlights the implications of risk perceptions and the community-volcanology connection within the emerging field of ethnovolcanology (see Vergara-Pinto, 2022; Vergara-Pinto and Marín, 2023). Ethnovolcanology can be understood as a field of anthropology and social sciences that uses its own methodological and theoretical tools to approach its subject of study - human beings in volcanic environments - and establishes bridges to bring this subject closer to the field of volcanology.

In theoretical terms, ethnovolcanology comprises the ethnographic study of human-volcano coexistence, including local knowledge on volcanoes, the dynamics of place attachment, and volcanic livelihoods from an ecological perspective, seeking its integration with *volcanological scientific knowledge focused on community priorities about volcanism* (e.g., its impacts, hazards,

benefits, interstices, etcetera). This emerging approach brings together elements of volcanology and anthropology and the study of local environmental knowledge (Toledo, 1992; Toledo and Barrera-Bassols, 2008). Building on the theoretical framework of Toledo and Barrera-Bassols, it offers a broad understanding for sociocultural studies of the perceptions and rationalities of communities based on (i) the set of symbolisms and perceptions about volcanism (Cosmos), (ii) knowledge-memory about eruptions and environmental changes (Corpus), and (iii) livelihoods and disturbance-recovery processes (Practices), which guide their habitation of volcanic lands. The relevance of studying this set of dimensions without separating the natural from the social world, as communities do, lies in the fact that "the interaction of the three domains of the K–C–P complex results in the merging of sacred and secular features, knowledge and experience, facts and values, and matter and mind" (Barrera-Bassols and Zinck, 2003: 173).

In this way, geosciences are vindicated with a social sense, motivating them to identify scientific research problems within the priorities of the community that coexist with the volcanic system. From this perspective, in practical terms, communication between science and community aims not only to disseminate scientific knowledge to the population but also to recognise the local ecological knowledge that people develop in their territories and to understand and answer people's vital questions about volcanic hazards, exposure, vulnerability and volcanic-related elements of interest. Thus, an ethnovolcanological approach aims to integrate both or more models of perceiving and knowing the volcano by inhabiting and studying it (Vergara-Pinto and Marín, 2023), allowing the emergence of dialogues between the epistemic multiplicity from which values and knowledge are assigned to volcanoes. On this basis, it aims to rethink the guidelines for creating safer volcanic environments and promoting disaster risk reduction with the participation of the community and volcanologists involved, considering that eruptions cannot be avoided or prevented. In this sense, it can help address persistent gaps between how communities, stakeholders and policy makers perceive and imagine society-volcano coexistence in the Southern Andes.

CONCLUSIONS

Our results show how risk perceptions influenced by social cohesion, disaster memory and uncertainties about hazards can play a key role in crisis response and coping during eruptive events. In this context, the three underlying socio-cultural factors we have analysed are expressed in risk perceptions in the following ways: 1) social cohesion refers to social relationships and common uses of volcanoes, collaborative practices and economic linkages between settlements in everyday life, in a rural territory where multiple life strategies and interlinked economies have been generated; 2) disaster memory is related to one's own or transmitted experiences of past eruptions, from which people recall the social and environmental conditions that influenced the impacts they faced; and 3) uncertainties arise about the environmental impacts of future eruptions and livelihoods recovery capabilities.

Furthermore, our research attempts to outline human-volcano interactions as well as the social fabric in heterogeneous territories as variables embedded in risk perceptions, memories of past eruptions of Puyehue-Cordón Caulle, community responses to future events, and senses of attachment based on multiple foundations from which to draw useful lessons for volcanic risk mitigation and reduction. It involves considering the facts behind natural hazards and their physical dimensions but taking into account the subjectivity of human perceptions about eruptions, which profoundly influence the hermeneutics of volcanic processes and thus on community decision-making.

In the particular case of the PCCVC, comprehensive risk management and preparedness are essential, given the frequent small-to-moderate eruptions. This management must consider unknown or unimaginable eruptive scenarios only scientists envision, such as those involving infrequent wind dispersion or activity from other active parts of the complex. On the other hand, disaster risk reduction must address scenarios in which communities perceive risks to their livelihoods and territories, make decisions to cope with a disaster, and resolve issues related to restoring their livelihoods, usually in the same volcanic environment.

Our study contributes to the development of socio-cultural research on volcanic risk in rural territories, highlighting the need to connect a social and volcanological understanding of inhabited volcanic sites. This approach implies integrating the community into ethnovolcanological research, considering that people can contribute to volcanic risk reduction by transmitting their adaptive

capacities, local knowledge and memories within the community, and by revealing vital questions about volcanic hazards that can be integrated into volcanological risk assessment. It also involves providing the most accurate volcanological explanation possible of past and potential impacts can help take preventive measures for the population in case of emergency, especially in the case of unimaginable eruptions. Thus, we emphasise the need to address social processes using social science methods to incorporate the culture, rural livelihoods and disaster preparedness of those who depend on volcanoes into risk analysis.

The projections of this type of research focus on collaboration between anthropologists and volcanologists from both sides of the southern Andes, in the case of binational volcanoes, to address especially the cultural, territorial and economic similarities of rural and Mapuche communities in Chile and Argentina. In the long-term, ethnovolcanological collaboration in other Andean contexts (e.g., central or northern volcanic zones) is foreseen to study cultural diversity and post-eruption reoccupation in South American volcanoes.

ACKNOWLEDGEMENTS

We thank all the workshop participants and the interviewed inhabitants of Puyehue, who live near the Puyehue-Cordón Caulle volcanic complex. We also thank Pablo Forte for his comments on an early version of the manuscript, and Cristian Farías for his participation in the workshop as a geoscientist invited to dialogue with the community. The study is based on FV's master's thesis, funded by FONDECYT-ANID 11171068 grant to Dr Andrés Marín, Universidad de Los Lagos, Chile.

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