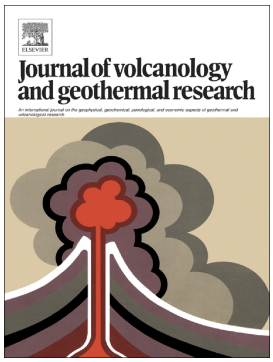

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Managing cross-border eruptions: Insights from recent crises in Chile and Argentina

Amy Donovan[1], Guillermo Toyos[2,3], Alvaro Amigo[4], Gustavo Villarosa[5,6], Gabriel Orozco Lafranco[7], Elizabeth Rovere[8]

[1]Department of Geography, University of Cambridge, UK
[2]Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Buenos Aires, Argentina
[3]Comisión Nacional de Actividades Espaciales (CONAE), Buenos Aires, Argentina
[4]Red Nacional de Vigilancia Volcánica, SERNAGEOMIN, Santiago de Chile, Chile
[5]Instituto Andino Patagónico de Tecnológicas Biológicas y Geoambientales, CONICET-UNCO
[6]Centro Regional Universitario Bariloche, Universidad Nacional del Comahue, San Carlos de Bariloche, Argentina
[7]Escuela de Geología, Facultad de Ingeniería, Universidad Santo Tomas, Santiago, Chile
[8]Universidad de Buenos Aires, Buenos Aires, Argentina

Abstract

This paper discusses the challenges and opportunities for cross-border eruption management between Chile and Argentina, focussing on an examination of the 2011-2012 eruption of Cordon Caulle in Chile and other crises between 2012 and 2015. We discuss the differences between Chile and Argentina in volcano monitoring, eruption impacts, eruption management and governance during this timeframe. We also discuss the issues in communication of the risks and the potential for future integration at the scientific level. The study is based on 31 interviews with scientists and local officials in 2014-15 (15 in Chile and 16 in Argentina), a questionnaire survey of 128 Argentinian residents in 2015 and a questionnaire survey of 25 disaster managers and residents of Pucón during the 2015 eruption of Villarrica volcano. We conclude that in 2011-12, there were issues with communication across the border, particularly at the political level, and that there are important ways that the scientific institutions in both countries complement each other.

Introduction

Border eruptions present a particular challenge for scientists (Donovan and Oppenheimer 2019) because they involve governments, scientific institutions and governance systems that may be strikingly different (Ansell et al. 2010): countries vary widely in how they structure their civil protection system and geological surveys, for example, and also in how those institutions are resourced and approach monitoring and mitigation of volcanic hazards. Instruments like alert level systems vary between countries and even between volcanoes in a single country (e.g. Colima and Popocatépetl in Mexico; (De la Cruz-Reyna and Tilling 2008)).

According to SERNAGEOMIN, (the Chilean geological survey, "Servicio Nacional de Geología y Minería"), there are ~92 active volcanoes on the Chilean borders with Argentina, Bolivia and Peru, 45 of which are now monitored by Chile (up from ~7 in 2008) (Amigo, 2021). The volcanoes have been ranked according to their hazard level using the USGS approach (Ewert et al. 2005, 2018)[1], and ten of the top twenty have experienced eruptions or crises in the last 50 years (Figure 1), including several cross-border crises (Chaitén, 2008; Cordón Caulle, 2011-12; Calbuco 2015; Copahue (persistently active)). Most of the ground-based volcano monitoring in the region is done by SERNAGEOMIN, as most of the volcanoes are wholly or partly within Chilean borders.

Following the 2011-12 Cordón Caulle and 2015 Calbuco eruptions, a new observatory was founded in Argentina (OAVV, from Spanish "Observatorio Argentino de Vigilancia Volcánica"), part of SEGEMAR and working in collaboration with SERNAGEOMIN under 2013 and 2016 agreements at intergovernmental level. Argentina is in the process of developing its own monitoring and outreach programmes.

This paper draws on volcanic crises within Chile and Argentina in particular, to (i) discuss the evolution of volcanic risk management in Chile and Argentina in recent years; (ii) use case studies of particular eruptions, notably Cordón Caulle in 2011-12 and Villarrica in 2015, to elucidate the issues that have occurred in managing different styles and magnitudes of activity; and (iii) suggest some lessons that have been learned from these crises for future reference. The paper takes a mixed methods approach to inform its discussion. It also uses the United Nations Office for Disaster Risk Reduction (UNDRR) terminology to distinguish between acute, "intensive" disasters (high intensity, low frequency) and chronic "extensive" disasters (lower intensity but high frequency).

[1] This approach involves ranking a range of indicators, some based on geological or monitoring evidence and some on population and exposure of infrastructure. It is a semi-quantitative way of ranking the threat from multiple volcanic systems, and has allowed allocation of monitoring resources in Chile.

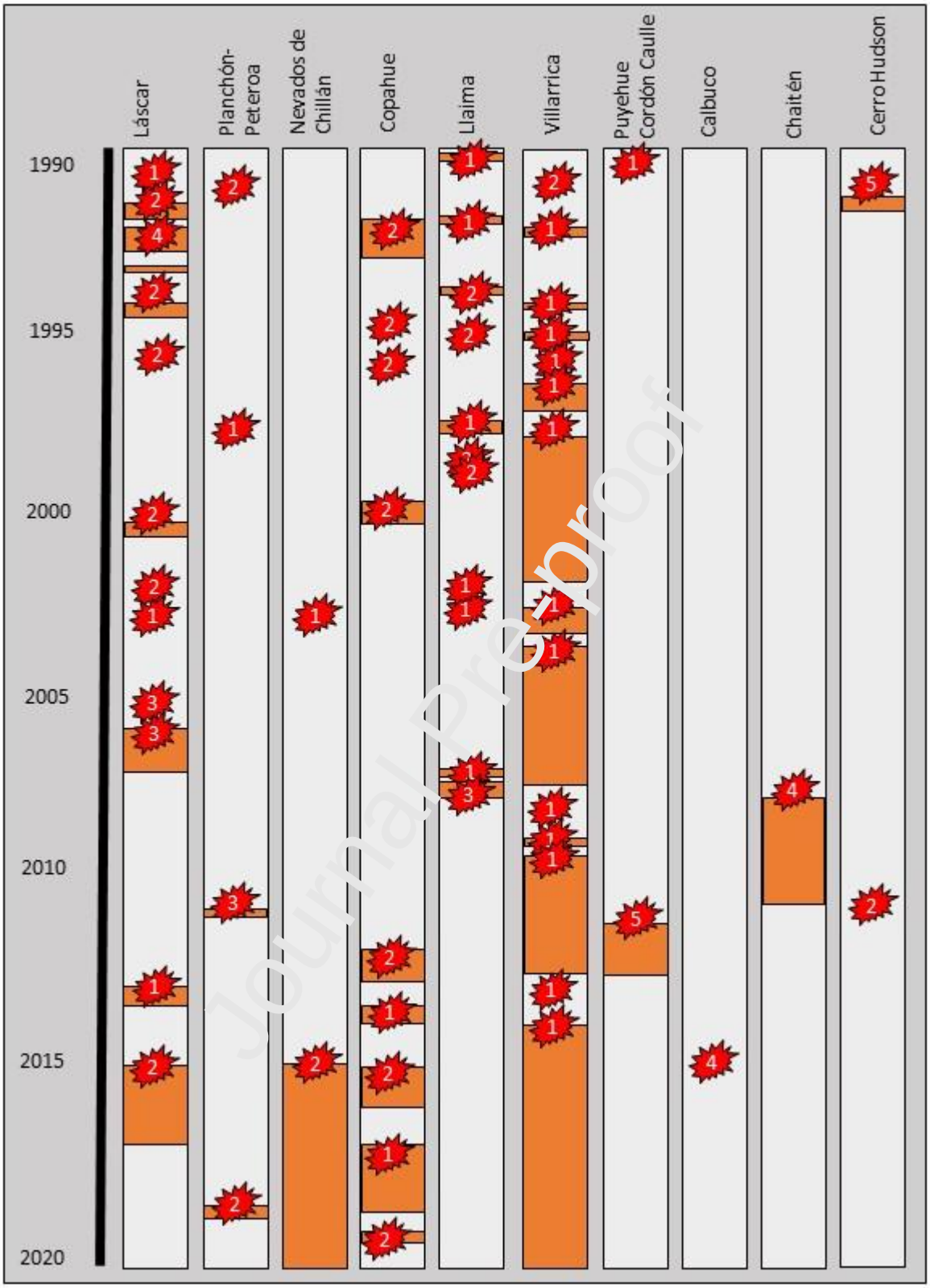

Figure 1. Simple timeline of eruptive activity at the Chilean/Argentine border from 1990 to 2020, N-S. The white text gives the VEI of each eruption as recorded by the Smithsonian Institution. Eruptions longer than 3 months in duration are represented with orange blocks showing the approximate length of activity. Lonquimay volcano is not shown but its 1988 eruption ended in January 1990. It is not discussed further in this paper.

Background: recent eruptions on the border

This section provides a general description of several recent border eruptions, focussing on the Puyehue Cordón Caulle eruption, which is the main topic in this paper, but outlining other key eruptions that are referenced in interview data and survey data. There are key differences between crisis management, which occurs with time pressures, complex logistics and requires rapid response, and risk management, which is the longer term process of land use change, hazard assessment and monitoring policies. The presence of an international border makes both particularly challenging and requires additional resources in terms of communications in particular.

An unexpected event: the 2008 eruption of Chaitén

While this paper focusses on the 2011-12 eruption of Puyehue Cordón Caulle, the 2008 Plinian eruption of Chaitén provides some important context. Chaitén erupted on 2nd May 2008, triggering the rapid evacuation, largely by boat, of 5000 people (Lara, 2009). There were no monitoring instruments on the volcano at the time, and the precursory activity was picked up by instruments 300km away, only 36 hours before the eruption at a previously quiet and poorly known volcano (Lara, 2009). The town of Chaitén was severely impacted by ashfall and lahars within days, and limited reoccupation was not permitted for several years. SERNAGEOMIN was supported by the Volcanic Disasters Assistance Program in deploying a temporary seismic network (Major and Lara, 2013), and subsequent analysis of the rhyolitic products showed that magma had risen very rapidly from depth at the start of the eruptive sequence (Castro and Dingwell, 2009). The eruption also impacted Argentina, primarily through ashfall and the blocking of the major route between Chile and Argentina. There was also significant ashfall in parts of the Patagonian Steppe and particularly in Esquel, and this impacted vegetation, animals and air quality (Martin et al., 2009). The border town of Futaleufu was badly impacted and had to be evacuated across the border from Chile to Argentina. In the aftermath of the eruption, the Chilean government made significant investments in volcano monitoring in Chile.

An intensive crisis: the 2011-12 eruption of Cordón Caulle

The eruption of Cordón Caulle (Figure 2) began on the 4th June 2011 at around 14:45 local time following a period of unrest detected by the seismic network of SERNAGEOMIN's Observatorio Volcanologico de los Andes del Sur (OVDAS, 2011). This followed almost a year of unrest, in which the volcanic alert level had been gradually raised (for a detailed chronology of this see Elissondo et al. (2016) and OVDAS reports for the period) and ash emission had been observed in April 2011. The final escalation of activity took place on 2nd to 4th June 2011, and involved swarms of hybrid and long-period earthquakes characteristic of magma movement (OVDAS 2011). The eruption generated a plume that travelled over the border towards Bariloche in Argentina (Figure 2). Bariloche and nearby areas experienced heavy ashfall over the next few weeks, and then episodically until February 2012 (Bonadonna et al. 2015). In January and February 2012, secondary lahars and fluvial remobilisation of ash caused minor damage around Villa La Angostura (Córdoba et al. 2015; Baumann Traine et al. 2019; Beigt et al. 2019). Over the next several months, small ash emissions continued, and the obsidian lava flow on Caulle continued to advance slowly (Tuffen et al. 2013). The alert level was lowered to green in August 2012. The volcano had experienced similar eruptions in 1921-2 and 1960 (Singer et al., 2008).

The eruption provoked a very acute crisis in a number of Argentinian border towns, particularly San Martín de los Andes, Villa La Angostura and San Carlos de Bariloche, and in the Patagonian Steppe.

The airports in Buenos Aires and across Argentina were closed for flights on multiple occasions and the ash traversed the globe – on 11 June closing airports in New Zealand and Australia (Elissondo et al. 2016) . On the Chilean side, a few small towns were evacuated (around 3500 people) but the impacts were much less – largely due to plume direction, which was almost always towards Argentina during this eruption (Raga et al. 2013; Collini et al. 2013; Nakamae et al. 2014; Alloway et al. 2015; Elissondo et al. 2016; Koffman et al. 2017). Pyroclastic density currents largely impacted the north of the volcano, which is uninhabited (Pistolesi et al 2015). Lahars were widely reported around the volcano in both countries (Elissondo et al., 2016).

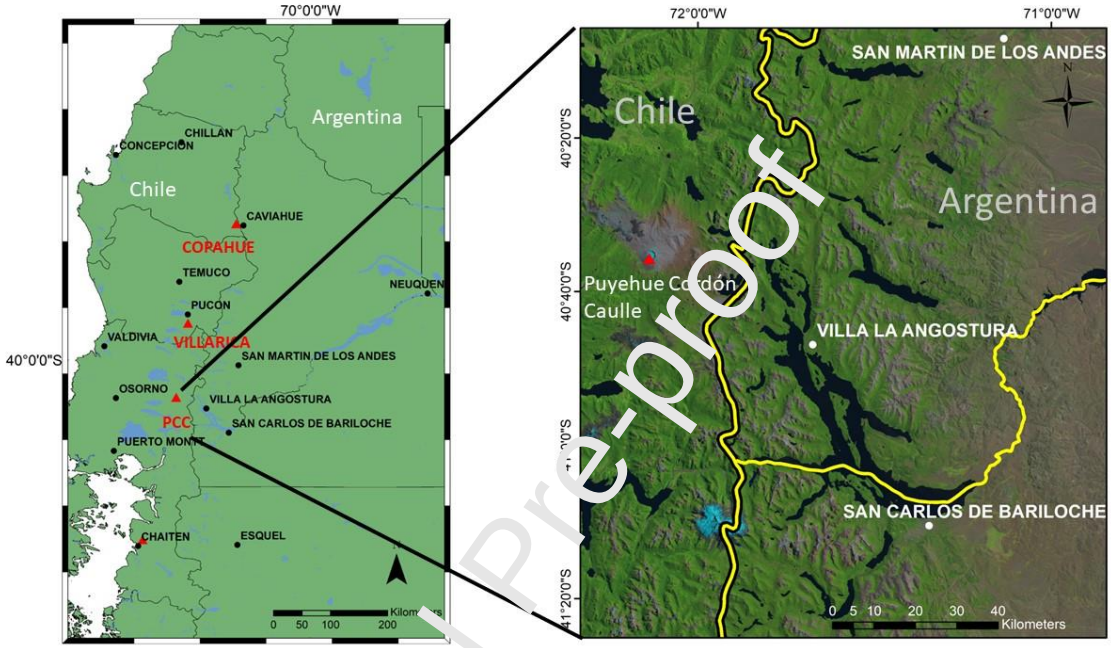

***Figure 2**. Map showing the location of the volcanoes discussed in the text. Landsat 8 image of Cordón Caulle Volcanic Complex, and key towns in Argentina mentioned in the text.*

Extensive activity: Copahue and Villarrica

Both Copahue and Villarrica volcanoes are persistently active (Petrinovic et al., 2014, Balbis et al. 2016; Delgado et al. 2017). Copahue, whose summit straddles the international border, experiences periodic and pulsatory strombolian and hydromagmatic activity and degassing, posing an ongoing threat to indigenous communities on both sides of the volcano, and to the larger town of Caviahue on the Argentinian side. Villarrica volcano is located within Chilean borders (around 50km from the border with Argentina) and presents a risk to the towns of Pucón and Coñaripe (which is just south of the volcano), popular tourist destinations. Coñaripe was badly affected in the 1964 eruption, with tens of fatalities. Villarrica has intermittent lava lake and strombolian activity. Both of these volcanoes therefore produce episodic minor crises for the communities that live on their flanks, and require continuous monitoring by scientific agencies. Copahue's position between countries presents a particular challenge, and has resulted in OVDAS deploying equipment in Argentina. In recent years, shared deployments have also been implemented at Lanín and Laguna del Maule, with Planchón-Peteroa to follow.

In 2016, the national geological surveys from Argentina (SEGEMAR, from Spanish "Servicio Geológico y Minero Argentino") and Chile (SERNAGEOMIN), signed an agreement to collaborate on monitoring

and hazard assessment, and in the same year Argentina formed its Observatorio Argentino de Vigilancia Volcánica (OAVV) within SEGEMAR, partly in response to eruptions in the border area that had significant impacts in Argentina. Recently, OAVV and OVDAS have collaborated in the further installation of monitoring equipment on Copahue. This followed on from a binational agreement that had been signed in 2013 on monitoring and management of border volcanoes, and this stipulated that SEGEMAR should manage communication, providing alerts to the Volcanic Ash Advisory Centre in Buenos Aires and to the Civil Protection authorities in Argentina (Dominguez et al., 2020). This paper is concerned primarily with the period before these agreements were in place.

Socio-natural approaches to risk

Recent work in disaster studies has sought to improve the integration of social and physical approaches to environmental risk, to address widespread shortcomings in the use of scientific information for preparation, forecasting and warnings around hazard events. This is not just a matter of communication, but also of understanding the widely variable remits of institutions in different countries, their histories and their economic, political and cultural limitations (Manyena et al. 2013; Boin and Lodge 2016; Gill et al. 2021; Ogra et al. 2021); understanding the philosophies and sociologies of scientific practices (Borie et al. 2019; Donovan 2019), and investigating visualisations, language and culture in communication both with policymakers and the public (in different contexts; (Bruen et al. 2010; Doyle et al. 2014; Fearnley and Beaven 2013; Budimir et al. 2020)). A key aim of this project was to use social scientific research methods (detailed below) to start to understand the social, political and cultural dynamics of transborder volcanism in Chile and Argentina so that future work can integrate some of the social challenges with the physical science.

This paper is structured as follows. The methods section outlines the methods that were applied in Chile and Argentina as part of this study. The results section then focuses initially on institutional structures in Chile and Argentina in 2011-12 at the time of the Puyehue eruption, and then discusses the challenges associated with that eruption in some detail. It goes on to discuss the slightly different challenges at persistently active volcanoes. Finally, questionnaire data from Argentina that relate to multiple eruptions are presented. The discussion picks up on some of the key themes that arise in the results.

Methods

This paper is based on data from 31 semi-structured interviews with elite actors in Chile (15) and Argentina (16), undertaken in 2014-2015 by the first author, and on results from two questionnaire surveys. Interviews were semi-structured, and focussed on the use of science in decision-making during eruptions, the practical and scientific challenges of managing the 2011-2012 eruption of Cordón Caulle, experiences of interviewees during that eruption and challenges and opportunities for future working between the countries. Interviewees included scientists, local officials, first responders and residents.

Additional data was collected through snowball sampling from the interviewees for an online survey in Argentina, which had 128 respondents (Table 1). This built on previous projects in terms of survey design (Donovan et al., 2018), with minor amendments for the cross-border context. A similar survey was given to emergency managers and residents in Pucón in Chile (n=25), in person, during the 2015 eruptions of Villarrica. It was not possible to conduct an online survey in Chile.

Table 1. Questions asked in the survey.

Variable group	Question	Response type

Affected	Have you ever been affected by volcanic hazards in the past? Which ones?	Multiple checkboxes (lavaflows; PDCs; gas emission; ash; lahar; explosion)
Concern	How concerned are you about volcanic eruptions?	7-point scale; 1=not at all concerned; 7=extremely concerned
Volcano	Which volcano are you most worried about and why	Open textbox
Home	Do you live near the volcanoes? Where do you live?	Yes/No and textbox
Time lived	How long have you lived there?	Single textbox
Hazard likelihood (in general)	How likely is the volcano to produce the following hazards? (lava flow, ash fall, pyroclastic flow, explosive eruption, debris avalanche, mud flow, gas emission)	7-point scale; 1=very likely; 7=very unlikely
Hazard magnitude	How far do you think a [lava flow, pyroclastic flow, ash cloud] could travel from the volcano?	Open textbox
Frequency	How frequent are eruptions at the volcano? (e.g. every day, every month)	Open textbox
Health	How big an impact do you think volcanic ash can have on human health?	1=none; 7= a lot; don't know
Health problems	If you are concerned about health impacts, how much could volcanic ash impact [the respiratory system; the skin; allergies; the eyes]?	7 point scale: 1=Not at all, 7= a great deal; don't know
Water quality	How much impact do you think that ash has on water quality?	7 point scale: 1=Not at all, 7= a great deal; don't know
Forecast	How easy or difficult do you think it is for scientists to forecast activity from the volcano from [week to week, year to year]?	7-point scale; 1=extremely easy; 7=extremely difficult
Knowledge	How much knowledge about volcanic activity do you think each of the following groups has? (scientists, Argentinian government, Chilean government, local government, Argentinian Civil Defence, Chilean Civil Defence, local civil defence, friends and family, religious leaders, social networks, news media)	7-point scale; 1=very little knowledge; 7=a great deal of knowledge
Accuracy	How likely are each of the following groups to over or underestimate the risk associated with the activity of the volcano? (groups as previous)	7-point scale; 1=not at all likely; 7=extremely likely
Altruism	How much importance would each of the following groups attach to serving their own interest in relation to the activity of the volcano? (groups as previous)	7-point scale; 1=no importance; 7=a great deal of importance
Trust	How much do you trust information from the following groups about the activity of the volcano? (groups as previous)	7-point scale; 1=do not trust at all; 7=trust completely
Statements on	To what extent do you agree with the following	7-point scale;

trust and precaution	statements? (If too many warnings are given, people stop taking them seriously; It's always better to be safe than sorry; If one thinks there's any risk at all, the public must be warned; Warnings that turn out to be unnecessary do more harm than good)	1=strongly disagree; 7=strongly agree
Evacuation	In the case of a major eruption of the volcano, how necessary do you think it would be to evacuate people in the area [temporarily/permanently]?	7-point scale; 1=not at all necessary; 7=very necessary
Impact	If a major eruption occurs at the volcano, how serious would the following consequences be? (damage to property, infrastructure, agriculture; loss of life if there were no evacuation; interruptions to civil aviation)	7-point scale; 1=not at all serious; 7=extremely serious
Plans	How effective do you think plans to [warn the population close to the volcano/warn the population more widely/evacuate people near the volcano] are?	7-point scale; 1=not at all effective; 7=very effective
Personal effectiveness	How effective do you think you would be if you had to improvise a response to an eruption if you were unprepared?	7-point scale; 1=not at all effective; 7=very effective
Statements on religion	To what extent do you agree with the following statements? (We must make offerings to the volcano so that it does not erupt; If we show respect to the volcano, it will not erupt; we must pray that the volcano does not erupt)	7-point scale; 1=strongly disagree; 7=strongly agree

Survey sampling

The online survey in Argentina was distributed by snowballing from interviewees, and not intended to reach a sample that would be representative of any particular population within Argentina. Rather, the intention was to gain a range of views from some residents in areas affected by the volcanic eruptions, and to see if there were any patterns that emerged from the data. This is intended to inform future research in the region.

The Chile survey sampling was purposive and focussed on emergency managers and civil servants in Pucón town, and was administered in person during the 2015 crisis. It was intended to assess their impressions and interpretations based on their activities and the activity of the volcano, and to understand how they – both as professionals and as residents of Pucón and the surrounding area – felt about the risk from the volcano.

Both of the surveys therefore used a form of purposive sampling rather than random sampling, and did not seek to "represent" the populations of Chile or Argentina. Purposive sampling identifies appropriate respondents in accordance with their role and links rather than randomly. To do a random or representative survey would require considerably more resources than were available for this study – and answer different research questions. Any survey ultimately speaks to the sample that it obtains – and extrapolation to a wider population is always challenging (unless the sample size is in the 10s of thousands for most countries).

The comments and comparisons that are made below thus pertain to these two samples only, and not to a wider Argentine or Chilean population. However, they do give an indication of the views of some of the people who experienced the two eruptive crises, and patterns that emerge from them can therefore inform planning in the region.

Survey analysis

The larger survey (Argentina; n=128) was analysed using standard statistical methods. Some new variables were computed – these were either related to specific answers (for example, whether people live in Argentina and whether they live close to the Andes or in Buenos Aires) or were averages of multiple variables that had similar scales (for example, taking all of the "trust in X group" variables). In the latter case, reliability analysis was first performed and group variables only computed for Cronbach's alpha > 0.7 (which signifies that the scale was measuring the same thing across all groups). The data were first surveyed for normality, and, as expected, were non-normally distributed. Non-parametric tests were therefore used in the analysis.

The Mann-Whitney (U) test is a non-parametric version of the t-test, and looks for differences in the median value for two groups (whereas t looks for differences in means). The Kruskal-Wallis (H) test is a non-parametric analysis of variance, and looks for differences in medians between groups. Spearman's ρ is a non-parametric measure of correlation. Pearson's r is a parametric correlation test.

The sample size for the Chilean survey was much smaller (n=25), and so care was taken in the use of statistical testing. This is discussed further in the presentation of the results. Effect sizes (r) as well as significance levels (p) were calculated from the test statistics using z scores (where available) or for individual tests by convention. For the Kruskal-Wallis test, the effect size is the test statistic H-k +1/n-k where k is the number of groups and n is the number of observations.

We used a hierarchical multiple regression analysis to test predictors for trust. We present these models in the results, giving the standardised coefficients as beta values along with the t-test results. The t-test establishes whether or not the beta values are significant.

Triangulation and qualitative analysis

One of the purposes of mixed method approaches to social research is to triangulate both opinions and factual information. Relevant documents and the interview transcripts were both coded thematically using NVivo software, applying two levels of coding (with nested codes). Qualitative responses within the survey were also coded. The information was then extracted and compared for contradictions or lack of clarity. In general, the consistency within the dataset was very good, with some interviewees better informed than others about the events – but there were no contradictions within the dataset. In the text below, the interviewees are described by a unique identifier code and by a broad description of their role (to avoid identification and preserve anonymity).

The analysis below represents the themes identified in the coding process (which are given as subheadings within the qualitative results sections), with quotes that illustrate the key points and that are representative of views across the dataset unless otherwise indicated. Some quotations are illustrative (so that stories are told in the words of interviewees rather than paraphrased) and others are more critical and illustrate the opinions of interviewees. In the latter case, these are the dominant view in the dataset. Most of the interviews were conducted in English. Interviews in Spanish have been translated and checked, and this was taken into account during analysis.

Results

This results section discusses two varieties of cross-border crisis: intensive eruptions from a previously quiescent volcano (in this case the 2011-12 eruption of Cordón Caulle) and extensive eruptive activity from persistently active volcanoes. There are, however, a number of overlapping

issues (such as the sharing or otherwise of data and reports). In order to avoid repetition, the paper first discusses some of the key scientific challenges and institutional issues that can arise in an eruption, the most prominent of which is that Chile has a centralised institutional structure and Argentina a federal system. The paper then focusses on Cordón Caulle and the acute crisis around the eruption, discussing the institutional issues that it highlighted and some of the questions about scientific products and communication – these issues frame the rest of the discussion. The paper then discusses broader societal challenges in both acute and long-duration eruptive events, focussing initially on public experiences of the Cordón Caulle eruption and then looking more broadly at the impact on lives and livelihoods, incorporating qualitative data from the online survey. A short section broadens this analysis out further to consider longer-term, extensive events. The final section then looks more broadly at cross-border perceptions of risk from Argentina, incorporating information from the survey and interviews together.

Institutional Organisation in Chile in 2011-12

Following the eruption of Chaitén in 2008, Chile had invested significantly in volcano monitoring infrastructure, significantly expanding OVDAS, which had started in 1996 in Temuco (close to the active volcanoes Villarrica and Llaima):

OVDAS was created as an answer to that problem when a great eruption occurred, and it destroyed Chaitén.... There are many volcanoes online with data and instruments… Forty-three volcanoes online, with instruments and data in real-time, seismographic and webcams. (I04 scientist)

This has since increased to forty-five volcanoes, prioritised according to their history and proximity to populations (Amigo 2021). However, the resourcing is focussed on infrastructure rather than personnel, which has led to some challenges – not least because the Chilean volcanoes are very active:

We haven't been able to make an in-depth analysis. We are in a contingency state right now. A volcano every few days will generate a lot of ash, or some night-time incandescence. People can raise a lot of questions, and news. People will begin asking what is happening, why it's happening… (I24 scientist)

The lack of personnel has slowed down the process of undertaking longer-term projects and assessments for the volcanoes, though these are underway and have progressed substantially since the interviews took place.

From the interview data, it was clear that an important complexity in the eruption was the institutional landscape and the differences in institutional structures, remits and relationships between Chile and Argentina. In Chile, institutional remits and responsibilities between SERNAGEOMIN and the National Emergency Office of the Ministry of the Interior (ONEMI, from Spanish “Oficina Nacional de Emergencia del Ministerio del Interior”) were clear:

We have some formal agreement with ONEMI that defines what kind of information we have to provide. It is the technical information, so in terms of the ongoing unrest before or around an eruption, for example and in terms of the hazards, for example, the hazard maps. (I10, scientist)

Prior to the eruption of Cordón Caulle, information about the volcanic unrest had been provided to ONEMI, and the volcanic alert level was raised to red two hours before the onset of eruptive activity. This gave time for evacuation of the settlements closest to the volcano on the Chilean side of the border as noted earlier. A similar situation had arisen prior to the eruption of Chaitén in 2008, although earthquakes were only detected in the 24 hours before the initial explosions:

…We managed to evacuate around 5,000 inhabitants before the destruction of a big part of Chaitén occurred. This was a successful example of early evacuation. It was a big success. Another example: the eruption of Cordón-Caulle in June, 2011. A red alert was declared before the eruption, per se, occurred. This was a success, supported by technical analysis and recommendations given by … the staff of the observatory. (I23 official, referring to the town of Chaitén)

The authorities had the information and the relevant data to act in adequate time, in part because the institutional responsibilities were clear. Furthermore, in Chile, for volcanic eruptions, the protocols required that the national level of civil defence get involved and manage the eruption from the top down:

ONEMI is in charge of civil protection by law… They send alerts to the civilian population and to the system of civil protection. This is the ONEMI protection system: … ambulance, firefighters, and police for first response. The Ministry of Interior has a President, and ONEMI works in the whole country, in the regions, in the provinces and in the communes. (official, I22)

ONEMI recently expanded across Chile, having been based in Santiago prior to 2008. It has had a National Plan for Civil Protection since 2002, based on a Supreme Decree that replaced earlier emergency plans. In its civil activities, it is supported by scientific and technical experts, including SERNAGEOMIN. This means that during the eruption, ONEMI depended on SERNAGEOMIN and OVDAS in particular to assess the hazards – done primarily through hazard mapping and monitoring. A scientist explained the process of assessing the hazard and its limitations:

In general, we don't use numbers for our analysis because we don't have enough information to make that analysis. If you want to make some probabilistic calculations you need a database with more entries; we don't have enough entries to make that kind of analysis (I15, scientist)

A key requirement for future work, this interviewee noted, is a substantial database of volcanic activity. He also noted that settlement and particularly written records in this region are relatively recent, and so there is a great deal of scientific work to be done to constrain past eruptions. While many of the volcanoes are in Chile, there are a number that straddle the border and require collaboration with Argentina – these include Laguna del Maule, Copahue, Planchon-Peteroa and Lanín, among others. The analysis to rank the volcanoes also involves the use of population data, as available, to provide support for the civil defence authorities:

So we made a special analysis, we make the population analysis. It's more than the legal obligation for us … we have to tell them… this situation is more risky than that one, because they don't have the capacity of making that analysis. (I15, scientist)

He further explained some of the complexities involved in communicating the hazard maps within Chile:

As I am a volcanologist, I would very like to see a different shaded map but in this case people in charge of the managing of the emergency, the ONEMI, they have very little capacity to make good interpretations about these kind of maps and at the beginning we start to generate maps with three or four different kinds of polygons, but they are not able to create and make good interpretations of these kind of resources. So we decided to make the decisions easier for this kind of people, produce a more simplified style of maps with only one polygon and one type with only integrated hazards on. (I15, scientist)

This is an important point: scientists at SERNAGEOMIN had to work with ONEMI and accept that their own preferences for hazard maps were not actually useable by the civil protection – and

adjusted their methods accordingly because their role was to support the response by providing technical expertise. This becomes more complex when the local people are involved:

But it's not enough with showing the map, it's not enough to publishing the map and tweeting the map and putting in there, because the people saw a figure with a lot of arms and with a lot of tentacles like an octopus, but the people cannot interpret it properly. (I15, scientist)

During the Villarrica crisis in 2015 (when many of these interviews took place), effort was being made to improve the clarity of the communication protocols between SERNAGEOMIN and OVDAS. This was also partly undertaken to speed up the issuance of warnings "to reduce the anxiety of the people" in an age of instant information.

The number of potentially active volcanoes in Chile also presents a challenge, since many of the volcanoes have been little studied, and so the likely scenarios for future eruptions are difficult to discern.

We are working on hazard and geological maps because you need to do hazard but you need to know…it's necessary to get … the geology of the volcano. Unfortunately, we are not many people working on that, so it takes a long time to publish the geological map and hazard map. (I08, scientist)

In Chile, therefore, there has been a process of learning together and of collaboration between SERNAGEOMIN and ONEMI – particularly after the 2008 eruption of Chaitén. It remains challenged, though, by a lack of personnel.

Institutional organisation in Argentina in 2011-12

In Argentina, at the time of the eruption, the Direccion Nacional de Protección Civil (DNPC), Análisis de Riesgo y Proyectos Especiales (ARPE), part of the Ministry of the Interior, was responsible for managing crisis information. The Civil Protection had an emergency committee at national level, and there were others in municipalities locally. As noted above, Argentina has a federal system (in contrast to the centralised system in Chile) and so management at provincial and municipal levels was important, as well as national level. At a national level, the scientific response included the Meteorological Office (SMN, from Spanish "Servicio Meteorológico Nacional"), which includes the Volcanic Ash Advisory Centre (VAAC) in Buenos Aires; the Space Agency (CONAE, from Spanish "Comisión Nacional de Actividades Espaciales); the geological survey (SEGEMAR), the National Council of Scientific and Technological Research (CONICET), the Agricultural Institution of Argentina (INTA) and the Ministry of Defence Science Laboratory (CITEDEF, from Spanish "Instituto de Investigaciones Científicas y Técnicas para la Defensa"). In the Andes, University volcanologists were also involved. The response was further complicated by the provincial border between Neuquén and Rio Negro, which was close to the volcano. These provinces responded differently and took advice from different scientists.

Historically, various institutions have been responsible for civil defence at national level in Argentina: Dirección Nacional de Emergencias (1972), Sistema Operacional de Emergencias (1988), Sistema Federal de Emergencias (SIFEM; 1999). The Argentinian civil protection at the time of the Cordón Caulle eruption operated within a Federal system (with offices at national, provincial and municipal levels), and interviewees noted that this caused some issues:

It [is for] federal agents to respond but usually they don't have enough information to do it, so we have a gap between the science and the techniques of response of more or less 20 years. (I05, official)

This is in part because information at the national level did not trickle down to the local levels. The differential resourcing (and politics – see below) between national level and local level in Argentina was responsible for quite a number of problems during the response, which was very slow moving. The primary decision-maker in Argentina was the local mayor (although there are mechanisms for declaring emergencies at Provincial or National level), though interviewees noted that efforts are underway to provide a more coherent flow of information from the national civil protection to local responders.

I think the problem in Argentina was the person who makes the decisions is the Mayor… so he's a politician and in the tourist areas they want to keep quiet if the volcano is erupting because they want the money. So the scientists can tell them to evacuate but they're like 'Oh don't worry, because we need the money'. (I08, scientist)

The result of this was differential management of the eruption, with information being slow to emerge. This was especially problematic in areas like Bariloche where the tourist industry was threatened by the eruption but very little was known by the population at the start of the crisis, according to interviewees.

From a scientific point of view, one challenge was that there were relatively few volcanologists in Argentina and they were not connected well to each other or to other institutions at the time of this eruption – significant work on this has occurred since. At a local level, local academics were able to assist local officials during the crisis, while SEGEMAR scientists travelled from Buenos Aires. Indeed, a positive outcome of the eruption was better connections between scientists:

We have this problem that a lot of people, different people are based in different areas and so maybe we do the same and we don't know. So from these protocols and these meetings a good thing happened, we know each other and we can be in contact just in case for the next eruption. (I26, scientist)

This was backed up by Chilean scientists, who noted that they struggled to understand whom they should communicate with in Argentina.

Significant developments have occurred in Argentina since the eruption. In addition to the new volcano observatory, a commission on risks was instituted that eventually, following the 2015 Calbuco eruption, evolved into a network of institutions at a national level for the exchange of information in the face of emergencies (GYRCIT, from Spanish "Red de Organismos Cientifico Técnicos para la Gestión Integral de Riesgo"), under the Ministry of Science, Technology and Innovation. The national plan for disaster risk reduction (PNDRR, from Spanish "Plan Nacional para la Reducción del Riesgo de Desastres") and the national system for integrated disaster risk management (SINAGIR, from Spanish "Sistema Nacional para la Gestión Integral del Riesgo") under the Ministry of Security, were created.

An intensive[2] crisis: Cordón Caulle 2011-12

Cross-border communication

On the Argentinian side of the border, the eruption was much more of a surprise both to locals and to some scientists. While SERNAGEOMIN had informally sent SEGEMAR the reports since 2010 (according to interviewees), and they had been distributed to some informal networks, very little

[2] "Extensive risk is used to describe the risk associated with low-severity, high-frequency events, mainly but not exclusively associated with highly localized hazards. Intensive risk is used to describe the risk associated to high-severity, mid to low-frequency events, mainly associated with major hazards." UNISDR 2015.

was done politically in the towns, and while relationships between scientists and Neuquén province were well developed due to a persistently active volcano further north (Copahue), this was less clearly established in Rio Negro. Local scientists and some local protection officials followed the Chilean alert levels, but did not have clear links with the governments at provincial and municipal levels, who were not receiving the information systematically.

One Chilean scientist described the relationship between Chilean and Argentinian scientific institutions at the time of the eruption:

It's not a permanent cooperation but mostly focusing in some specific projects when funding is around and in terms of the monitoring network there is a national agreement, but the agreement is mostly for making easy the travel to Argentina and the responsibility for the maintenance of the station here and there, things like that. So it's not a real partnership in terms of the data collection and analysis (I10, scientist)

Indeed, Chilean scientists interviewed commented that collaboration with Argentina was challenging because of the policies of the Argentine government, which puts significant restrictions on the import of technology to encourage the use of Argentinian equipment and local procurement. This had led, pre-2011, to a very challenging encounter with Argentinian customs in a previous attempt at collaboration (on Copahue volcano), perhaps because of a lack of awareness of the complex procedures. All of this points to an urgent need for funding of nodal agencies in the region.

There was a very lot of promise, we had a huge truck with all the instruments and all the materials and in Customs, the Argentinians didn't want us to transport our construction materials to Argentina because they have very restrictive inter-nation policies. But we started to explain them we don't want to sell these things, we are going to use it for improve the monitoring and it was very hard, but finally we managed to convince, we managed to get the authorisations. (I08, scientist)

Another Chilean interviewee explained:

There are some ways to authorise, to permit a temporary entrance of the equipment for several months. If a crisis occurs, the equipment can be used and then sent to the volcano but with Argentina it's more difficult to get permissions at the border. (I09 scientist)

He said that it could be challenging to work with Argentina, not because of a poor political relationship between the countries, but because of Argentine bureaucracy around the additional requirements for the import of technology. Thus the economic policies of Argentina presented a challenge to the Chilean scientists. Even where permissions are in place, individual border guards can be difficult to deal with when presented with an unusual cargo – something also noted in other border contexts (Donovan and Oppenheimer 2019).

There was very little communication between Chile and Argentina at the start of the 2011 crisis. Indeed, it was hard for the scientific institutions in Chile to understand the institutional landscape of Argentina, because Chile is a centralised system while Argentina is federal, so while response is centralised in Chile, it is the role of local municipalities in Argentina. There were also some differences between Argentinian Provinces – while Neuquén took some preventative action prior to the crisis, Rio Negro did not. There was a strong sense among interviewees that Chile was better prepared, but some Argentinians felt that Chile should have been more proactive in providing cross-border warnings, since they had the data to do so. In the end, the online reports from Chile were used:

How can it be that in areas where the risk of volcanic eruptions are frequent, we have to find out from the Chilean government and not from our country? (survey respondent)

This was clearly a source of frustration in Argentina. Argentina's institutions had limited awareness that volcanic risk in Argentina is significant, because the majority of the volcanoes are in Chilean territory and also in spite of warnings from Argentinian scientists. The 2011 eruption therefore served as an important wake-up call. This issue was also reproduced at the provincial level: Neuquén province, which was proactive, has a number of active volcanoes, while Rio Negro does not.

Survey respondents were clear that binational approaches were needed both in studying the volcanoes and in providing alerts:

A good way to cover the problem is to carry out detailed geological studies, hopefully binational, contributing to better understand the behavior of the volcano ... It is also necessary to map volcanic hazards, also binational, in which the areas most likely to be affected by volcanic activity of different magnitudes are specified, in addition to well-coordinated evacuation plans and supported by sufficient and timely logistics.

Other respondents were also very keen on having some additional information, rather than having to rely on reports from Chile. Argentina needed time after the eruption to improve its own internal structures for volcanic risk management:

We could improve internal communication, but internally in Argentina, it could be very slow. Going from a federal level to the provinces, it could take days. (I30 scientist)

The issues of communication within Argentina arose repeatedly in the interviews. Since the eruption, there have been positive steps towards some of these collaborations as described above.

An interviewee also noted that the improvements within Chile were themselves relatively recent:

Concepts like critical communication were not implemented in Chile until one or two years ago. The integration with focal points did not exist either. There was not a real communication… That's what has been improved here internally. With Argentina, I believe that there is an important task left to do, which is to create new channels of communication in the critical platform. (I24 scientist)

Within Chile, communication tools are also used to facilitate communication within the scientific community – this interviewee described a WhatsApp group that can make decisions in a crisis in real time, and rapidly communicate with the National Director and ONEMI. However, this becomes more complex communicating beyond Chile to Argentina:

ONEMI must inform, for example, through the Ministry of Interior, but it is a very slow process. They are going to notify it when the ashes are already in Buenos Aires. The faster way is through the technical report. A communication channel must be defined to inform Argentina… It is likely that the fastest way is by OVDAS incorporating SEGEMAR in the distribution list of its reports. Then all it would take is to send a copy of the report. There can be no greater integration than that. (I07 official)

This does require OVDAS to write the report first – this is a much later stage of the process than the taking of decisions within Chile, which occur rapidly. However, the distribution of the activity reports is the simplest route:

The problem is that the intentions are there, but the resources and staff are not enough … Attending the requirements that are sent from Argentina added to the requirements that ONEMI has, and also

*the ones of the communes and provinces and regions, OVDAS collapses. It's too many consultations. It is best to define a single channel of communication. (*I24 scientist)

Thus, as a result of geography, Argentina had to depend on Chile throughout the Cordón Caulle eruption, receiving the reports produced by OVDAS but not having any raw data from ground-based instruments. During this eruption, CONAE, the Argentine National Commission of Space Activities , worked closely with the National Meteorological Office in Buenos Aires to use satellite imagery and dispersion modelling to monitor the plume and also operated within the International Charter "Space and Major Disasters" to support ONEMI and SERNAGEOMIN. Indeed, these institutions had provided significant support via the Charter during the 2008 eruption on Chaitén, again working with Chilean ONEMI and SERNAGEOMIN.

Another major subject that came up across interviews was the fact that the technological and disciplinary strengths of the two countries complement each other:

…we told the provincial authorities that at provincial and national level we should try to negotiate with Chile this cooperation between OVDAS ground based monitoring and satellite-based monitoring and emergency management capabilities but, well, you know… It never worked until probably last year that they finally understood that that's the way to go but I'm not sure they succeeded establishing that kind of agreement or integrated system for mutual assistance or something like that. (I20 scientist)

This was mentioned by interviewees in both countries, but the barrier appeared to be at the government level – partly the very different institutional structures and the Federal vs Unitarian political systems, and partly legal and economic issues associated with data that is owned by individual states. It is particularly interesting that Argentina is able to participate extremely effectively in international programmes such as the Disasters Charter (via its Space Agency, CONAE) and the VAAC system (via the Met Office, SMN), but that working closely between nation-state level institutions is much more challenging. This has been complicated in Argentina by questions about which institutions within the country should be involved – whether universities should be included, for example:

I think that if you're able to take this opportunity to see the big picture and make it something bigger and more open to other universities and institutions I think it can work, but if not I'm afraid that it could be a bad experience that could put us several years in the past. (I22 official)

This interviewee explained some of the institutional challenges within SEGEMAR, too, as a political entity with limited resources. As with many governmental organisational issues around the world, efforts to build a constructive and collaborative scientific agency that can cross multiple kinds of borders are limited by national-level rivalries, bureaucracies and political disputes.

Societal challenges

Interviewees who were not scientists (residents and local officials) described related issues that they faced in their experience of the eruption, particularly on the Argentinian side – because it was more severely impacted. This section initially describes some of the physical and emotional experiences during the eruption, and then relates this to the perceptions of political and economic issues that residents and officials encountered. It draws heavily on qualitative responses from the online survey.

Implications of the challenges for experience on the ground

The problems with ash in Chile were relatively minor – the international road between the countries at the Puyehue pass crossing (Paso Samoré) was closed and buried in a metre and a half of ash and

coarse lapilli, but most of the ash damage was in Argentina. People in Argentina described the eruption as a shock – a cloud approached across the border, and they assumed it was a thunderstorm, until ashfall started. There had been little warning of the eruption in Argentina and the volcano is not visible from the population centres. One survey respondent commented:

During the eruption of Puyehue, here in Bariloche, we were totally uninformed. I was personally climbing a mountain, before the black cloud I thought it was approaching snow; Suddenly there was darkness and sand began to fall from the sky. Our bewilderment was total. Hopefully we are warned against new eruptions.

This is consistent with interviews in Bariloche and Villa La Angostura, where residents expressed the emotional and physical challenges that they faced. At times, the ashfall was so heavy that it was impossible to go outside. Electronics and mechanics were badly affected. Some mentioned challenges with the water supply as well, something also mentioned by survey respondents:

In the eruption in Villa La Angostura one of the main problems was the contamination of the rivers, mallines and lakes by ash, so it is necessary to take measures regarding the potability of the water.

Several survey respondents made similar suggestions for mitigation of future eruptions:

Investing in technology and permanent resources helps to be calmer ... save lives ... and be able to take the necessary measures to alleviate the impact of an eruption.

Others focussed on the need for education:

It is necessary to insist on prevention, campaigns in schools, official institutions and population in general.

The need for a national strategy for large scale hazards was also suggested, with the implication that the border regions were particularly vulnerable:

I live in a country, which I love, but unfortunately is not prepared for an extreme situation, Bariloche is a city that is very close to these volcanoes, and we are not prepared for a natural disaster of great magnitude, it is more I believe that no point of the border cities with Chile is prepared for a large-scale natural disaster.

The lack of education and preparedness was linked also to the wide range of impacts that the eruption had across human life in the region:

The only thing that helps is to be informed and prepared, there should be plans to prepare the population in advance, on how to act, what to do to protect not only lives and homes, but water sanitation and waste management, service management, rationed consumption, how to self-evacuate in an orderly manner and without panic, ways to purify water if necessary, first response how to set up networks of neighbours in action for the common good.

The experience of the eruption was thus very disruptive to life in the border regions around Bariloche and Villa la Angostura. People did not know whether the ash impact on the respiratory system would be dangerous for example – something an owner of a nursery mentioned as particularly concerning.

Political and economic issues

The "otherness" of the volcano across the border (i.e. that it was not well known among the people), and the breakdown of communication, affected the approach of authorities in Argentina:

None of us understood very well why they hid or watered down the information about the volcanic activity. To discredit the people that were working during the eruption, they discredited everyone, from the scientists, to us, who were local. (I13 scientist)

Residents were concerned that the local authorities had tried to cover up the eruption because of pressure from the tourism sector (tourism being the major source of income in the region). They linked this to, in their view, the excessive power of the local mayors and their close ties to the sector. The perception that volcanoes are a threat to local economies was viewed as a key reason for people not being ready for volcanic eruptions in Argentina:

There's a very wrong perception of volcanic risk interfering with the business. I mean most touristic places in the world are either volcanic or exposed to tsunamis or hurricanes and the key is to be able to show some management, but here they didn't think that – so we have this big problem that politicians are often convinced by the people [in] the tourism business that they should keep it quiet, not talk about [the] volcano. (I22 official)

A major problem is therefore that the local level authorities had control of disaster risk reduction:

…they're the first dealing with the impacts and I mean the law indicates that they are the first responders and only if they declare emergency in a bigger scale like provincial or something, the provincial authorities start working and then national. (I22 official)

This also came up in qualitative answers to the survey, in which respondents said they thought "that the seismographs and cameras installed in the eruptive centres should be connected in real time to the internet network, and [government] should not hide information". Another stated:

We must have truthful information about the activity of the volcano – scientific and on behalf of the rulers in the area – and above all, have plans of action and / or evacuation in different areas before the eventuality of a volcanic eruption.

The implication here is that information was not entirely truthful – but also that truthful information should bear the hallmarks of science and be transparent. Ultimately, though, the scientific information should feed into the planning process prior to an eruption.

The impacts of the eruption were severe in Argentina, not least because it occurred at the start of the ski season – a significant source of revenue in the region around the volcano. One survey respondent summed them up:

Interruption of the roads, of terrestrial communication and of telecommunications. Environment. Negative impact on the local economy, Impact on the emotional and psychological health of the population.

Others were particularly concerned about the economic impacts of the eruption, and most mentioned tourism and economics. Others mentioned impacts on regional flora and fauna, especially agriculture (mortality of animals, especially cattle, and also crops):

The rural people lost their flocks for the ash, and we were left without commercial activities due to the lack of tourism, the economic impact was very hard.

This was compounded by the apparent cover-up:

Economic impacts on local activities; lack of confidence in the authorities to hide or minimize risks, discouragement in the population.

The economic impact was thus exacerbated because of uncertainty among the population about whether they could trust the information they were receiving from the authorities.

This was further linked to the mental health and demographics of the population:

The post-eruption impact is sometimes more severe than during. Since the damages are never recovered, the affected person is in a situation of abandonment, the young population migrates and the resilience of those who remain is very complicated.

This is reminiscent of other volcanic crises in which population demographics have been altered – notably Montserrat (Hicks and Few 2015): long-term volcanic activity (even, as here, over less than a full year) can trigger the more mobile (often young and skilled) parts of the population to migrate, leaving those who remain less resilient to further disruption.

Interpreting the eruption

The respondents to the online survey in Argentina were also asked about their views about the nature of volcanic activity. These give some insights into the heuristics they use to interpret the activity, and the imaginaries of the earth that lie behind those interpretations.[3]

I believe that the human being with his arrogance underestimates nature, and in his eagerness for power and domination is altering certain conditions without awareness of how they will turn against humanity ...

There was a strong sense that volcanic activity is part of the natural world, and that science provides some useful information to feed into human interpretation of that world:

To respect our volcanoes is also to accept their natural processes. That the population has religious beliefs is acceptable at one point. The solution comes from science, and if the authorities understand that they are responsible for the welfare of the population. In what happens and in how they perceive these phenomena. The authorities should definitely generate a contingency plan that does not yet exist in our region.

This was also linked to valuing nature rather than damaging it, interestingly:

If we take care of nature, she will give us back. The damage we do permanently affects all aspects!

This sense of humanity as irresponsible stewards of the natural world is interesting because it links the care of the planet to care of humanity itself: volcanism is not necessarily a result of humans not caring for nature, but withstanding volcanic activity might be part of a wider engagement with the environment. A lengthy comment explained in more detail:

I think that the way in which people perceive the phenomena of nature by calling them disasters has to do with impact … It is not about the fact itself: people can evacuate; an eruption, although if(?) it is catastrophic [economically] every 2000 years (approx.) [it] is not a worrying factor either. Those who live at the foot of a volcano have to know what that means… It is not a catastrophe, it is the planet where we are standing which is functioning as we should know that it works, eruptions, earthquakes. The plates move; nothing more. Scientists have enough technology to say: there is likely to be an eruption. people evacuate and period. It's not that bad. once every 2000 years as it would be our case ... it's nothing.

[3] Imaginaries may be defined as shared narratives that enable people to make meaning from the world (e.g. Salazar 2020).

This interpretation perhaps oversimplifies the forecasting of eruptions, but suggests that volcanic risk is something that humans should be able to manage without completely disrupting life.

Cross-border comparisons

Survey respondents and resident interviewees from Argentina were particularly upset that Chile had appeared to know in advance:

When the Puyehue volcano erupted in Chile they were already alerted weeks before, while in Argentina the local government a day before the eruption declared that it was not necessary to be alert. (survey respondent)

This was partly because in Chile, the volcano had been investigated for some time following an earthquake in the region earlier in 2011. However, even when alerted by the Chileans, there were feelings that Argentina was slower to communicate the risk:

Local authorities and civil defense were warned by the volcanologists on the night before, and the next day nobody knew anything, people were on the street with the ashes on the windshields and they had to clean, they did not know what to do, a disaster. I stayed locked up for three days in my house and I had the roof cleaned with 20 cm of ash, horrible, for the next one they let us know so we know what to do. (I19 resident)

Others were watching the alerts in Chile and were concerned about the lack of information from official sources:

The zone of Villa la Angostura and Bariloche and the Linea Sur[4] were very affected and nobody had told us anything – the area was neither on yellow alert nor red. Everything was very hard, everything was new, nobody said anything. Neither the intendancy nor civil defence alerted anything. It was too much!!!!! And we did not have anything to clarify the misinformation. (survey respondent)

This was put down to a lack of interest and awareness on the part of the government:

I am still very concerned about the lack of responsibility that government authorities usually show in emergencies. Not to mention the lack of foresight that they hold. (survey respondent)

During the eruption, many different challenges arose in relation to infrastructure and amenities in Argentina. This was significantly compounded by a lack of confidence in government. The institutions were generally regarded as deeply untrustworthy by survey respondents. This is modelled below.

Extensive risks: Copahue and Villarrica

This section takes a brief look at other key issues on volcanoes close to the international border – focussing on the complexity of longer-term management.

Copahue: inequality of risk

Copahue volcano straddles the border between Chile and Argentina, but there is considerable inequality of risk: Chile has relatively few people living near the volcano, while Argentina has a considerable tourism industry as well as indigenous communities. It also hosts the town of Caviahue, which lies in a breached caldera that contains a lake and is bounded by river valleys. It was cited by many interviewees (hence its mention here), because of its persistent activity and the risk to Caviahue. It was also regarded by survey respondents as a significant threat.

[4] The Linea Sur is the set of small towns that is located along highway 23, which crosses Rio Negro from E to W.

…In the Argentinian side there is a city inside a caldera, the Caviahue caldera, but in the Chilean side of this same volcano there [are] only indigenous communities, very dispersed and not concentrated and they don't have any technology, they don't know what is Twitter or what is Internet … We receive much more feedback from the Argentinian side because they feel…maybe the Chileans also feel but they don't communicate it because they don't have the way to communicate. So from Argentina we receive much more feedback and much more questions and much more concern about the volcano than from the Chilean side. (I03)

This quotation illustrates very effectively the diversity of populations within and between the two countries, and the different challenges for scientists on each side. On the Chilean side, the only communities are indigenous groups, which are not vocal on social media. Communicating with these groups is very different from communicating with settler communities that are vocal on social media – so much of the concern about Copahue that is received in Santiago comes from the Argentine side, where there is a bigger population too.

Villarrica: institutional boundaries[5]

At Villarrica in March 2015, in contrast, Chileans did feel threatened and this created some challenges for scientists in communicating because of the level of understanding in the population. There were also some issues with the communication process between SERNAGEOMIN and the local municipality. On one occasion, the local mayor sounded the warning sirens without consulting the scientists, leading to high levels of public concern, reflected in the media articles from the period. At Villarrica, a major challenge was managing the media and the local officials – there are some interesting comparisons here with Argentina's experience in the Cordón Caulle eruption.

The survey in Chile had a much smaller sample size (25) than that in Argentina (128) and was focussed on civil officials during the Villarrica crisis. This sample size has limited statistical power and higher-order tests were not carried out. However, some relationships are noted here.

	Concern level	Time near volcano	Perceived ease short term forecasting	Perceived ease of long term forecasting	Perceived need to respect the volcano
Material damage	0.56**			-0.45*	
Deaths without evacuation	0.52*				
Perceived need for temporary evacuation					-0.74**
Perceived need for permanent evacuation	0.44*	-0.64*			
If too many warnings are given, people stop taking them seriously			-0.62**		

[5] In this section, U refers to the Mann-Whitney test; H is the Kruskal-Wallis test; R is Pearson's R; r is effect size; rho (ρ) is Spearman's rank correlation co-efficient; t refers to the t-test result; beta refers to the standardised regression coefficients; p is the significance level. All of these are defined in the Methods section. A single asterisk denotes a correlation significant at the 5% level or a one-tailed test; a double asterisk denotes significance at the 1% level or a two-tailed test.

It's always better to be safe than sorry			-0.56**	-0.53**	-0.52*
If one thinks there's any risk at all, the public must be warned			-0.53**	-0.49*	-0.56**
Warnings that turn out to be unnecessary do more harm than good			-0.46**	-0.40*	

Table 2. Selected Spearman's correlations from the Chile dataset. One star indicates that the correlation was significant at the 5% level; two stars indicates it was significant at the 1% level.

Table 2 shows that there are some interesting links between the false alarm and precaution variables and the forecasting variables. There was also a link between the precaution variables and perceived likelihood of deaths without an evacuation (0.55** for both variables). People tended to be in favour of precaution if they also felt that the forecasting was challenging. They also tended to have lower levels of trust in the Chilean institutions than had occurred in the survey in Argentina.

In general, the knowledge and altruism variables tended to show relationship with trust for most groups. Knowledge was a significant predictor of trust for all groups except the Chilean government and friends and family and altruism was significant for all groups except social networks and news media. Accuracy had no relationship to trust in this dataset.

Indigenous communities

Conversations with Atacameños in the vicinity of Láscar volcano in northern Chile (which is persistently active) revealed a further significant dynamic: the relationships between governments and indigenous groups around volcanoes. Particularly striking was the opposition among Atacameños towards Chilean disaster management policy – not only around volcanoes but also around flooding. One Atacameño complained that the government just wanted to send technology and give them lots of modern technological appliances – in contrast with their own desire to live close to nature. In Talabre (a small indigenous town close to Láscar), people live in simple houses, and respect the volcano, viewing it as the source of their water and offering food to it in return for the water. These relationships are not considered in disaster management in Chile, betraying the level of consideration given to indigenous rights in government (Radcliffe and Webb 2016). Interviewees mentioned that these communities lack technology and are dispersed – while the primary focus of efforts to improve communication in Chile is using social media and available technology. Another said that:

They live near the volcano and they have a relationship with the volcano. They want to visit the volcano. They bring food to the volcano. (I13 scientist)

This adds a layer of complexity to the experience of volcanoes in the Andes, and one that is barely considered in current strategies to reduce risk: the cultures that have co-existed with earthly processes for long periods and that have limited engagement with government. Future work will investigate this dimension in more detail.

Cross-border risk perceptions and trust: Argentina

Quantitative results from the survey undertaken in Argentina suggested some interesting patterns between trust and perceived knowledge, accuracy and altruism of different groups. They also demonstrate some variations in the concerns that were held by different groups. Spatially, 70% of

the respondents lived in Bariloche or the area around it; 17% lived in Central Argentina; 3% were from other Andean areas and the rest lived further afield in Argentina.

The survey demographic was skewed in favour of women, with 26% of respondents reporting as male and 74% as female. The mean age was 47, with a range from 18 to 104. Sixty percent of respondents were employed full-time, with 11% housekeepers, 11% students and 11% part-time. Only 3% were unemployed and 5% were retired. While <5% had been affected by most of the volcanic hazards, 92% reported having been affected by volcanic ash, suggesting that ash is by far the most significant hazard affecting the population in Argentina as represented here.

Respondents were asked to explain which volcano(es) they were most concerned about. Puyehue Cordon-Caulle featured very highly, with 71% of residents highlighting it as the single most worrying volcano, and 70% regarding themselves as living close to it. Copahue was the single most worrying volcano for another 11% of respondents. Other volcanoes that were mentioned included Chaiten, Lanin, Villarrica, Osorno, Calbuco and Hudson. Tronador was also mentioned by four respondents.

There were a number of effects from gender on the responses. Women were more likely to be concerned about impacts of ash on skin (U = 1411, p<0.05, r=0.20) and eyes (U=1990, p<0.01, r=0.24). They also tended to be more optimistic about the knowledge of the Chilean government (U=2193, p<0.001, r=0.28) and the Chilean civil protection (U=2001, p<0.01, r=0.25) and the knowledge (U=2037, p<0.05, r=0.22) and accuracy (U=1084, p<0.01, 0.23) of their own friends and family and to trust these groups more (U (gov) = 2025, p<0.0001, r=0.33; U(CP) = 1970, p<0.0001, r=0.36; U(FF) = 1785, p<0.05, r=0.20).

There were also some effects from education level, but these were generally small – the only effect size higher than 0.1 was for trust in social networks, which tended to be higher among those with vocational or secondary qualifications and very low among those with higher degrees (H(5)=15.66, p<0.01, r=0.10). Age had an impact on some of the group variables. As age correlated with time spent living near the volcano, we used partial correlations for these variables to control for the cross-correlation. Older people were less likely to be concerned about false alarms – that warnings can be harmful (R = -0.79, p<0.05). People who had lived close to the volcano for a long time tended to view lahars (R=-0.85**) and debris avalanches (R=-0.93**) as unlikely. They also thought that short-term forecasting was easy (R=-0.815**).

Perceptions of hazards were linked to several other variables, particularly the impact variables. Those who thought that the volcanoes do not erupt frequency tended to be less concerned about severe impacts such as the need for permanent evacuation (ρ=-0.39, p<0.01) and deaths in the event of no evacuation (ρ=-0.39, p<0.01).

There were positive correlations between concern about volcanic risk and perceived likely material damage (ρ=0.24**) and aviation risk (ρ=0.27**).

Responses to questions around trust are closely related both to the perceived knowledge, accuracy and interest of the groups, and to perceived impacts and ease of warning. Four questions were asked about specific groups:

- How much do they know about volcanoes? (knowledge)
- How likely are they to under/overestimate the risk? (accuracy)
- How much are they interested in volcanoes (as opposed to their own interests)? (altruism)
- How much do you trust them to manage volcanoes? (trust)

The overall results are shown in Figure 3. There were some significant correlations here too – anxiety about warnings and false alarms tended to correlate with the view that scientists are not very accurate ($\rho = 0.20$, $p<0.05$) and a lower trust score for scientists ($\rho = -0.18$, $p<0.05$). This went along with a stronger correlation between low view of scientists' accuracy and the perception that unnecessary warnings are harmful ($\rho=0.24$, $p<0.01$). Those who thought it important to be safe rather than sorry also tended to view scientists as knowledgeable ($\rho=0.21$*).

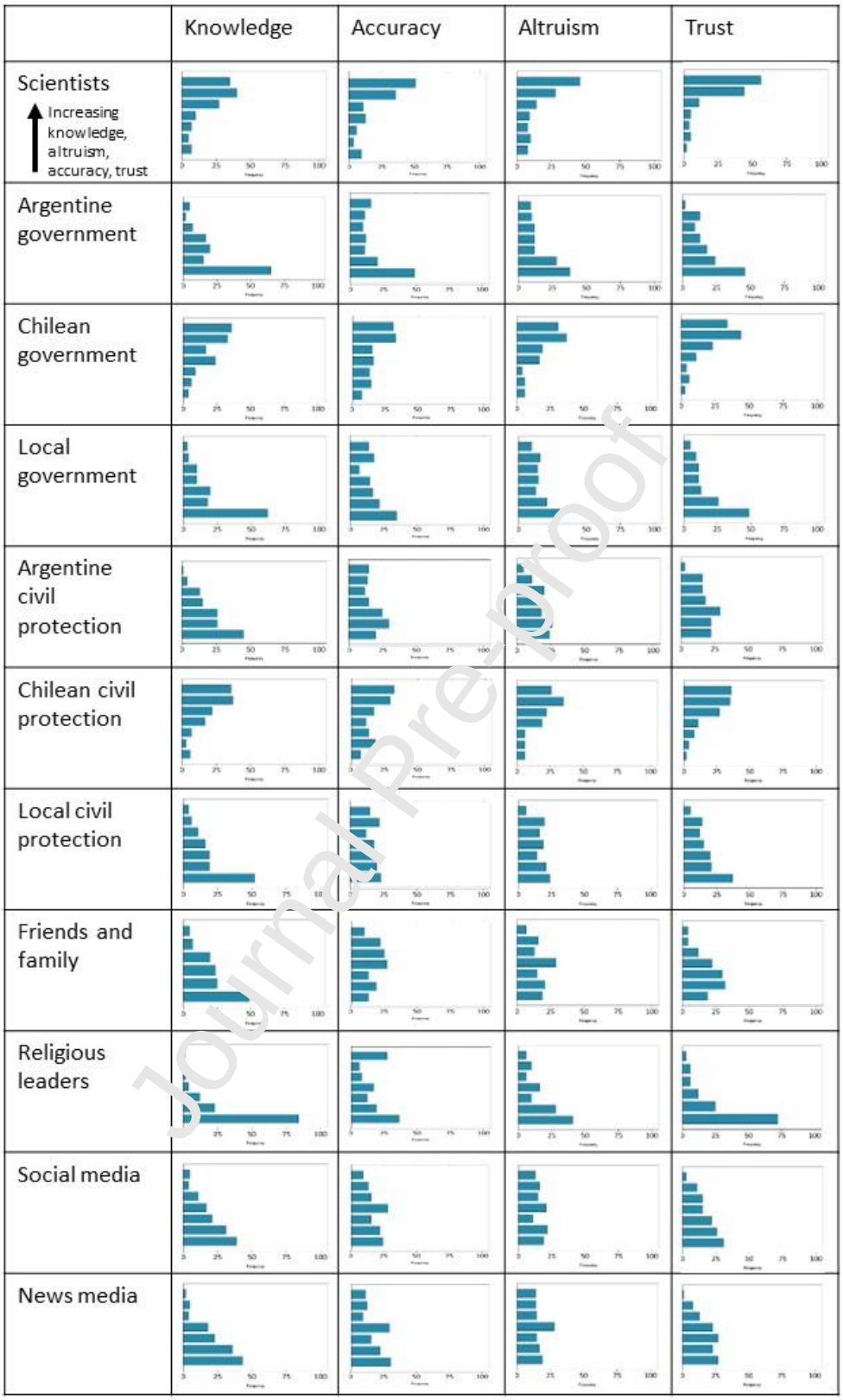

Figure 3. Survey results for perceived knowledge, altruism, accuracy and trust of different groups. The vertical axis is explained at the top of the figure (the top bar of each chart represents a great deal of knowledge, a great deal of altruism, a high level of accuracy and a high level of trust respectively); the horizontal axis represents number of respondents.

There were also some correlations with the impact variables here. People who thought that there would be a lot of damage also thought that the Chilean government was knowledgeable (0.26**) and the same for the Chilean CP (0.23**). These attitudes were also associated with the view that warning and evacuation plans are generally effective, and that these two actors are trustworthy. People who were happy with the warning (0.36**) and evacuation plans (0.37**) also tended to think that the groups were trustworthy in general.

The perceived ease of forecasting eruptions in the short-term was linked to overall accuracy (ρ=0.19, p<0.05) which is largely from the scientists (0.19), Chilean CP (0.19) and friends and family (0.21) groups (all one-tailed). Those who thought that forecasting was easy also thought these groups were accurate. Interestingly, the ease of longer-term forecasting related more to the knowledge and altruism variables. Those who thought that forecasting is easy thought that scientists (-0.24*), the Argentina government (-0.26**), local government (-0.30 **), Argentine CP (-0.31**), local CP (-0.22*) and religious leaders (-0.22*) were knowledgeable. They also tended to think that both the Argentine (0.25*) and local (0.28**) CPs were accurate, and that local government and both Argentine and local CPs were altruistic (all ρ = 0.22*), and tended to trust in the local government (-0.25*), local CP (-0.26*) and religious leaders (-0.21*). This is also reflected in a correlation with all knowledge (-0.23*) and all trust (-0.25*).

The first three of these statements were used to construct a hierarchical stepwise model for the trust statement for each individual group, and then by combining the groups. The results of the regression models are shown by group in Table 3.

Group	Knowledge	Altruism	Accuracy	R^2
Scientists	0.322	0.468	-0.226	0.31
Argentine Government	0.297	0.381	-0.257	0.48
Chile Government	0.395	0.371	-0.189	0.51
Local Government	0.338	0.276	-0.410	0.50
Argentine civil protection	0.380	0.243	n.s.	0.25
Chilean civil protection	0.366	0.256	-0.232	0.38
Local civil protection	0.391	0.317	-0.193	0.48
Friends and family	n.s	0.446	-0.172	0.23
Religious leaders	0.493	0.292	-0.166	0.43
Social networks	0.412	0.324	-0.263	0.47
News media	0.445	n.s.	-0.233	0.29

Table 3. Standardised beta values for the trust models. All are associated with t statistics that were significant at the 1% level in a hierarchical regression model. Positive values for "knowledge" indicate high perceived knowledge; positive values for self-interest suggest a lack of concern for society's interests as opposed to self-interest; positive values for exaggeration suggest a tendency to over/under-estimate risk (i.e. not be very accurate).

The models in Table 3 show the relative importance of these factors in predicting trust – so for scientists, their knowledge is a better predictor than concerns about their self-interest, which is better than concerns about their accuracy. The R^2 value (adjusted) gives a measure of the variance explained by the model. The results suggest that trust is most informed by knowledge for many of these groups, but that their perceived motives are also important, particularly for governments and friends and family, and also for social media – but not at all for news media, where the emphasis is on knowledge and accuracy. Accuracy was also viewed as important in local governments. The knowledge of friends and family was not a factor in whether or not they were trusted: much of the variance was explained by altruism in this group.

Discussion

Transborder volcanic eruptions raise a number of challenges both for scientists and for civil protection organisations. These concerns are different between persistent, low-magnitude extensive activity and intensive, explosive eruptions that generate extensive ashfall. Many of these concerns may also be the result of the border exacerbating an issue that exists in many volcanic crises within a single country, such as communication and monitoring.

Transborder scientific communication

The Cordón Caulle eruption was an important milestone in the evolution of the relationship between the scientific communities in Argentina and Chile, because, building on the experience of the 2008 Chaitén eruption, it confirmed to civil authorities the need for volcano surveillance information in Argentina for volcanoes located in Chile, and also because it accelerated the processes towards better communication between the countries and within them (Outes et al. 2015). Argentina now has a volcano observatory that serves as a central conduit for communication. Resources remain a challenge in both, however, and there has been substantial progress on collaboration between the two countries. In 2019, a hazard map and assessment for Laguna del Maule was published by a team from Argentina, Chile and the USGS, demonstrating the potential for third-party-facilitated collaboration, and a binational map for Lanín volcano was produced in 2020 (SERNAGEOMIN 2019). Additional transborder hazard maps are under preparation. Nevertheless, new protocols for communication during an "intensive" eruption remain to be tested.

The primary difference between the intensive crises like Puyehue Cordón Caulle and the longer-term periodic threats like Copahue is at the social level: the populations have very different levels of experience of living with the volcanoes. This also affects local officials and their experience of managing crises, and the expectations of local businesses. The rare but intense eruptions are more likely to have larger scale impacts and require complex, multiscalar communication across the border. However, in both cases, this is most effective if it is in place before an eruption rather than having to be put in place during a crisis.

Policy and infrastructure

It is often observed by volcanologists that each volcanic eruption produces different hazard scenarios; this is also the case for the societal and institutional impacts and lessons from eruptions. The presence of an international border complicates the management of eruptions not only in terms of communication between nations and scientific institutions but also in understanding the institutional, legal and economic conditions that differ between countries. In the 2011-12 eruption of Cordón Caulle, as at Chaitén, it was difficult for scientists on one side of the border to understand what was going on across the border – and this difficulty was multiplied for citizens. There was a perceptible feeling of frustration among the survey respondents and resident interviewees in Argentina, for example, that they did not feel that their government was acting honestly or with integrity during the eruption, especially at the local level. For many residents of Bariloche and Villa La Angostura, this was an event unlike anything they had previously experienced. It was a total and abrupt interruption to their way of life, and it took a very long time for daily living to return to normal. There was a great deal of cleaning up to do once the ash stopped falling, and many people migrated (Elissondo et al. 2016).

Many of the challenges experienced in this eruption demonstrate the issues that scientific agencies face when working closely with political and economic actors. In Argentina, the level of mistrust of government was coupled with a deep frustration at perceived biases within the political circles (and occasionally imposed onto residents' interpretations of scientists' actions too). These were largely

centred around the view that authorities were trying to "hide" the eruption so that the tourist sector would not suffer – the eruption occurred just as the winter season was starting, and the towns in the Andes depend heavily on tourist income from this time of year. In this case, while the risk to life was relatively minimal in Argentina, the risk to livelihoods was also perceived as discriminatory – there was not enough help for the people in trying to maintain basic infrastructural needs because of the need to protect the rich powerful actors in the ski industry. Communication with the more marginalised residents in particular was almost non-existent, as evidenced in interviewees who described not knowing what was happening in the first hours of the eruption – assuming a thunderstorm was coming, and then finding that it was apparently snowing as they sought to interpret the experience on the basis of other experiences. The lack of communication was the result of a lack of awareness throughout the system at the start of the eruption – the geological survey was only able to send a team out a week or so after the eruption started.

Risk perceptions and trust

While it is not possible to compare the survey samples directly because of different sampling approaches and timeframes, it is nevertheless interesting to note the broad differences between them in two aspects: perceptions of nations and trust. Within the Argentinian survey, of 128 respondents, there were 6 Chileans who had answered and who consistently trusted their own institutions less than the Argentinians trusted Chilean institutions. This is reinforced if the surveys are combined – while Argentinians tended to trust Chilean institutions, Chileans had lower levels of trust in their own institutions. Neither nationality had much trust or confidence in the Argentinian institutions. Certain eruption impacts – particularly health impacts from ash – were also much more concerning to Argentinian respondents. This is consistent with experience in Argentina rather than in Chile.

The prediction of trust from other variables also suggests that there are subtle differences between groups in the importance of perceived knowledge, accuracy and altruism. Some people also seem to be generally more optimistic and trusting than others, and this is backed up in the results for the false alarms and precaution variables, and also in the ease of forecasting variables – in which those who regarded forecasting as easy also tended to trust groups that many other respondents did not trust. These results are consistent with the results of previous studies on trust, but with some local nuances as detailed above (Eiser 2004; Haynes et al. 2007; Eiser et al. 2008, 2015; Paton 2008; Donovan et al. 2018).

Understanding risk across borders

Chile and Argentina have diverse histories, institutional structures, political systems and economic circumstances. Argentina has a federal system of government and its recent history has seen long economic crises. They also have different scientific histories and disaster histories. For example, Chile is closer to the subduction zone fault and has a higher incidence of very large earthquakes and tsunami, while Argentina's civil protection has tended to focus on floods and wildfires (as was detailed by interviewees). Argentina does, however, have significant expertise in satellite remote sensing and atmospheric monitoring, both of which are important in monitoring eruptions.

However, damage mapping and plume monitoring are not very useful for provision of warnings prior to an eruption – this ideally requires ground-based data from seismometers, and since SERNAGEOMIN is part of the Ministry of the Interior, its data cannot be shared in raw format. This is a common problem that affects geological surveys around the world: their links to government means that their data is classified and cannot be shared very easily (Donovan and Oppenheimer 2019). As a Chilean interviewee noted, the research strengths of Argentina in satellite remote

sensing could readily complement the experience of Chilean scientists in ground-based monitoring, but this was not straightforward because of institutional and resource limitations.

Ultimately, an administrative border can act as a confounding factor in the management and communication of volcanic risk. In the case of federal state borders in Argentina, there were some challenges between Villa La Angostura and Bariloche because Neuquen and Rio Negro provinces had divergent approaches to communicating and managing the risk. More broadly, however, the divergent institutional structures of Chile and Argentina made it very difficult for risk information to reach communities quickly – partly because actors on each side of the border were trying to interpret each other and anticipate each other's needs based on their own experience and within the confines of their own legal remits. All of this underlines the need for relationships to be built prior to future crises, so that people on both sides of the border both know who to call on the other side, and know the kinds of information that can be helpfully and legally exchanged.

Conclusions and further work

This paper has discussed some of the challenges in managing eruptions that straddle the Argentine-Chilean border. While some of these issues are case-specific, many of them are likely applicable to other border-regions. Of particular interest are the following issues:

- Border volcanoes present a particular challenge in the management of data, because (i) nation-states may have protective laws about data generated by government agencies and (ii) data types may not be consistent across borders.
- Institutional configurations may be very different across administrative boundaries. While the Unitarian: Federal distinction between Chile and Argentina is particularly stark, perhaps, the different interpersonal relationships between civil and scientific actors within Neuquen and Rio Negro provinces were also mentioned by a number of interviewees. There is a very strong spatial variation in how risk is managed – often affected by the experiences, motivations and friendships of individuals on the ground. This can impact on trust and social perceptions.
- The political histories and structures of different nation-states can also be seen in the contrast here – particularly in Argentinian distrust of elite actors and the centralised, top-down Chilean system. Furthermore, political policy is heavily tied to economics, and the Argentinian policies around import of foreign goods, for example, were cited as causing some challenges for moving equipment between the countries.
- Respondents to the survey suggest that people have a diverse range of imaginaries informing they views of volcanic risk, based on their own interpretations of the earth system. These imaginaries may differ significantly from those of scientists.
- Trust in sources of information is controlled by multiple factors, which may include knowledge and accuracy, but frequently also include perceived motivations (Eiser et al. 2007).
- While intensive eruptions tend to receive the most attention from the international community, extensive eruptions can have significant erosive powers over both scientific and societal resources. The ongoing "chronic" eruptions in Chile during this period – at Copahue, Villarrica and Nevado de Chillán – absorb resources from OVDAS, particularly in terms of personnel. At the same time, the hazards are rarely significant enough to attract new resources – and the risk is open to misinterpretation by laypeople, including those in government. Furthermore, the nature of the activity means that people become accustomed to it, and obtaining new resources is increasingly difficult. Intensive eruptions are much more effective catalysts for significant change – both nationally and internationally.

- Chaitén's eruption in 2008 had led to major advancements in the monitoring programme in Chile (Amigo, 2021), but had limited impact on transborder eruption management.
- The Cordón Caulle eruption led to significant reforms in the institutions of Argentina in particular, both in volcano monitoring with the establishment of the new Observatorio (OAVV), and in civil protection. Ultimately, this eruption and that of Calbuco in 2015 fed into new institutional structures, improved communication procedures in both countries, and renewed efforts to collaborate.

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Author statement

AD designed and carried out the research, analysed the data, wrote the paper; GT helped in the design and in the fieldwork and reviewed/edited the paper; AA, GV, GOL, ER provided assistance in the field and reviewed/edited the paper.

Declaration of interests

☐The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Highlights

- We present new social data concerning the 2011-12 eruption of Puyehue Cordon Caulle on the Chile-Argentinian border.
- We show that the eruption was significant in the evolution of institutions and agreements between the countries.
- We show that at the local level, there was deep dissatisfaction with risk communication in Argentina (which was worse affected).
- We argue that the scientific institutions complement each other well in terms of their expertise but need more resourcing from government.