

Volcano monitoring and hazard assessments in Chile

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ABSTRACT

Volcanism in Chile occurs in a variety of tectonic settings but mostly in the context of oceanic-continental plate collision, including 92 potentially active volcanoes. There have been more than 30 documented eruptions in the last few centuries. The *Servicio Nacional de Geología y Minería* (SERNAGEOMIN) is a statutory agency of the Government of Chile responsible for volcano monitoring and hazard assessments across the country. After the impacts derived from volcanic activity at the end of the 20th century, SERNAGEOMIN created the Volcano Hazards Program and the *Observatorio Volcanológico de Los Andes del Sur* (OVDAS). Despite this effort, most volcanoes in Chile remained unmonitored. In 2008, the aftermath of the eruption of Chaitén led to a nationwide program in order to improve eruption forecasting, development of early warning capabilities and our state of readiness for volcanic impacts through hazard assessments. In the last decade responses to volcanic crises have been indubitably successful providing technical advice before and during volcanic eruptions.

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1 INTRODUCTION

Chile is located along the south-western edge of South America. The subduction process of the Nazca and Antarctic oceanic plates along the Chilean margin is characterised by countless earthquakes, including the largest seismic event ever recorded (Mw 9.5 in 1960), and large-scale tectonic structures related to plate convergence, such as the Andean mountain chain that runs along the eastern side of the country, along the border with Perú, Bolivia and Argentina. Coincident with the Andes, the volcanic arc forms three distinct groups defined as Central (CVZ), Southern (SVZ) and Austral Volcanic Zones (AVZ) (Figure 1). These volcanic zones are separated by segments (at ~2–15° S and 27–33° S) in which volcanism has been absent since the Miocene, due to shallow subduction [Stern 2004]. Volcanism in Chile therefore spans a wide latitudinal range along which subduction, crustal parameters and magmatic composition vary systematically. In addition, further subdivision of the volcanic arc has been made based upon upper crustal structures and the distribution, chemistry and magmatic composition of its products [Stern 2004]. Aside from the Andes, volcanism is also present at intraoceanic volcanic islands within the Nazca plate at the SE Pacific. The subduction of the spreading Chile Ridge underneath the South American plate, which generates asthenospheric windows under the continental crust and around the Antarctic Peninsula related to the Bransfield and Larsen rift spreading centers, are both part of the Chilean Antarctic Territorial claim.

1.1 Active volcanoes in Chile

According to the *Servicio Nacional de Geología y Minería* (SERNAGEOMIN), 92 volcanoes are considered active in the Chilean territory (i.e., with a documented or probable activity during the Holocene). Most of these volcanoes are stratovolcanoes, volcanic complexes and monogenetic fields located along the Andes chain between 17–56° S and 75–67° W. Non-Andean volcanoes include Rapa Nui island (also called Isla de Pascua or Easter Island 27.1° S; 109.1° W) located on the easter hotspot ~350 km of the East Pacific Rise; the Pali Aike volcanic field (52.1° S; 69.7° W) corresponding to backarc plateau of Holocene basalts in southernmost Patagonia; and Deception Island (62.9° S; 60.3° W), a sea-filled caldera at south-western end of the Southern Shetland Islands in the Bransfield basin, Antarctica.

The volcanoes of Northern Chile belong to the CVZ, which extends into neighbouring southern Peru, western Bolivia and northwestern Argentina (Figure 1A). Volcanoes in the Chilean segment of the CVZ span more than 1000 km from 17.7 to 27.1° S, where the most active center is Láscar volcano (23.36° S; 67.73° W) east of the Atacama basin, where several explosive and dome-forming eruptive cycles have occurred since the 20th century. In this region, volcanoes are built on top of the Altiplano-Puna plateau and therefore several volcanoes are higher than 6000 m a.s.l., including Ojos del Salado, which is the highest volcanic summit in the world (27.1° S; 68.5° W; 6887 m a.s.l.).

Separated by ~700 km from the CVZ, the SVZ begins at Tupungatito volcano (33.4° S; 69.8° W) at the approximate latitude of Santiago city, and ends with the subduction of the spreading Chile Ridge, at the

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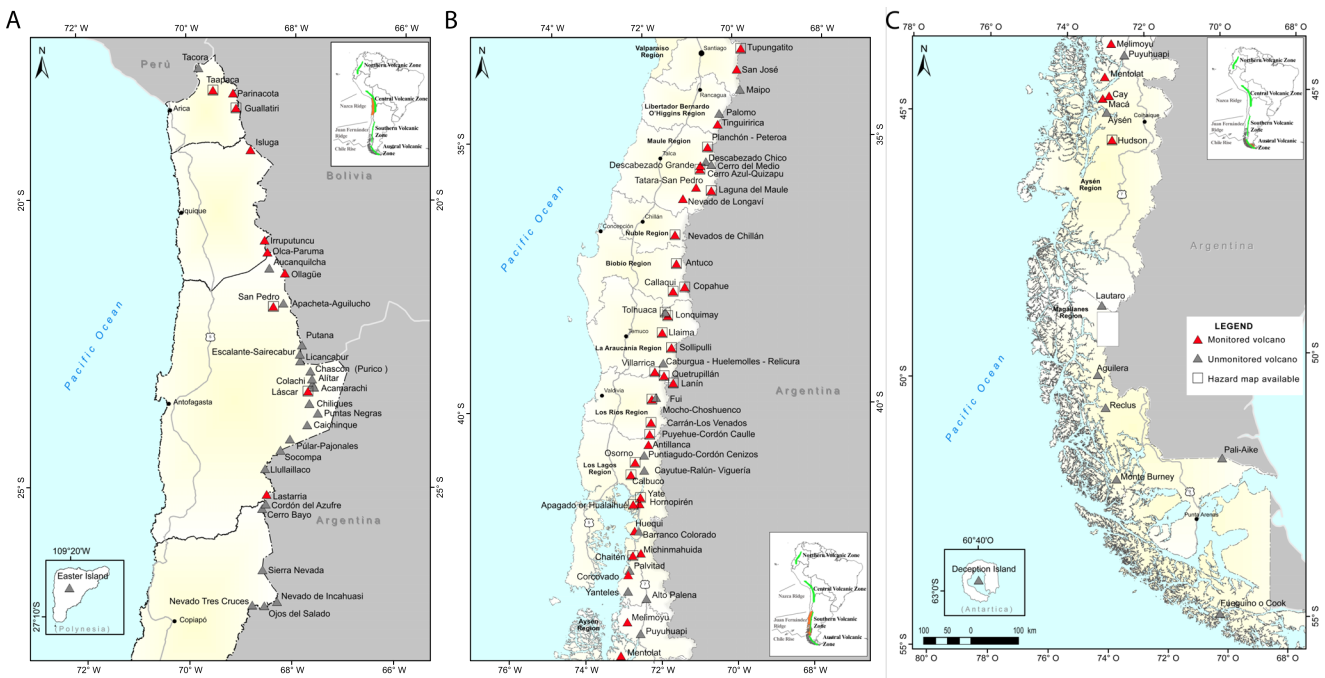


Figure 1: Active volcanoes in Chile considering Andean volcanism divided in three distinct groups: Central (CVZ), Southern (SVZ) and Austral Volcanic Zones (AVZ), Eastern Island (SE Pacific) and Deception Island (Antarctica). Red triangles indicated volcanoes currently monitored. Squares indicated where volcanic hazard maps are published. Administrative regions of Chile and regional capitals are also shown. White rectangle indicates where the Chile-Argentina border is still pending definition: “Agreement between the Republic of Chile and the Argentine Republic to specify the route of the limit from Mount Fitz Roy to Cerro Daudet” (Buenos Aires, Dec. 16th, 1998).

Nazca-Antarctic-South America triple junction, south of Hudson volcano (45.9° S; 72.9° W). The SVZ forms a continuous arc segment over 1400 km in length (Figure 1B–C). Most of the active volcanic front of the SVZ lies at the western edge of the Andean mountain chain, which spans the Chile-Argentina border, and therefore the majority of the SVZ active volcanoes lie wholly or partly in Chile. In the southern SVZ, volcanoes show a close spatial association with the regional-scale Liquiñe-Ofqui fault zone [Cembrano and Lara 2009]. The most active centers in the SVZ are the Villarica and Llaima volcanoes, located in the Araucanía region. In addition, the largest Plinian eruptions recorded the last century in Chile have occurred in the SVZ in 1932 at Quizapu volcano (35.6° S; 70.7° W) and in 1991 at Hudson volcano [Hildreth and Drake 1992; Naranjo and Stern 1998], and several moderate-size explosive eruptions have occurred in the last decades at Chaitén (2008–09), Puyehue-Cordón Caulle (2011–12), Villarica (2015) and Calbuco (2015) volcanoes.

The southernmost group of volcanoes in the Andes forms the AVZ, which are derived from the subduction of the Antarctic plate beneath southernmost Chile, between 49 – 55° S. Only five volcanoes have been recognized in this region, although some additional volcanic centers might be hidden under the southern Patagonian ice-cap (Figure 1C). Although no eruptions have been documented in the AVZ in the last decades, Lautaro

(49.0° S; 73.5° W) seems to be the most active volcano, with explosive activity documented since the 19th century [Martinic 2008]. The presence of few active centers over six degrees of latitude and the relatively small number of known eruptions, suggest lower magma production rates for the AVZ than for the SVZ.

In summary, 35 volcanoes have documented activity since the 16th century and more than 400 volcanic events have occurred [Petit-Breuilh 2004]. A compilation of volcanic events that have occurred in Chilean territory since the 19th century is depicted in Figure 1.

1.2 Population exposed to volcanic activity

Roughly 5 % of the continental territory of Chile is directly threatened by volcanic processes such as lahars and pyroclastic density currents (PDCs), and up to 35 % could be affected by ash fall [Lara et al. 2011]. The latter implies around 10 % of the population is exposed to at least one volcanic hazard. Only a small population lives within 10 km of an active volcano; however, 60 % of the population live within 100 km of an active volcano. At least 15 eruptions since the 19th century have resulted in loss of life, at Lonquimay, Llaima, Villarica, Mocho-Choshuenco, Carrán-Los Venados and Hudson volcanoes. Nevertheless, this number might be much higher considering activity in the past centuries and the scarcity of reports.

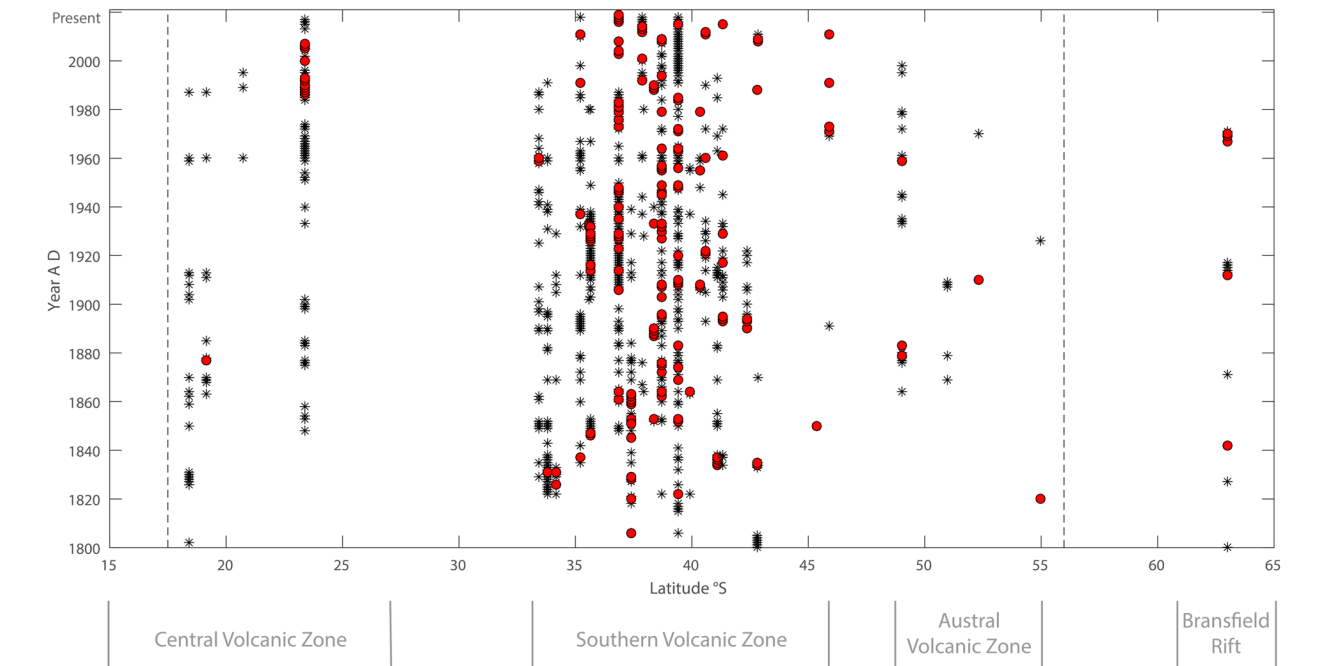


Figure 2: Volcanic eruptions occurred since the 19th according latitude in Chile, including Deception Island in Antarctica. Grey crosses indicate all the reported events from different sources. However, during this period only 150 events have been established as confirmed eruptions, represented by red dots (this work). Note that SVZ is much more active than other regions in Chile.

In northern Chile, most of the volcanoes are in remote areas, except for Taapaca volcanic complex (18.11° S; 69.50° W), close to Putre one of the main populated towns of the Chilean Altiplano [Clavero et al. 2004]. Due to the prevailing atmospheric circulation, ash derived from explosive volcanism affects southern Bolivia and north-western Argentina, as has occurred during historical times (e.g., Láscaer eruption in 1993). However, during the austral summer months, westward dispersal of ash is favoured and could affect populated regions in Chile.

The SVZ is the most active volcanic segment in Chile and a probability >90 % for at least one VEI ≥ 3 eruption within a decade has been estimated [Dzierma and Wehrmann 2012]. On the other hand, over 70 % of the Chilean population live in the Central Valley region between the cities of Santiago and Puerto Montt, lying within <100 km of active volcanoes of the SVZ. Lahars, PDCs, lava flows and ash fall have been the main volcanic hazards during historical times and around 500 casualties have occurred in the last few centuries, mostly due to lahars.

South of 42° S, although the volcanoes are remote, the Chilean population is located downwind from the volcanoes, and therefore large explosive eruptions could produce significant tephra fall impacts on both people and livestock, such as occurred during the eruptions of Hudson (1991) and Chaitén (2008–09) volca-

noes.

2 CHRONOLOGY OF VOLCANO MONITORING AND HAZARD ASSESSMENTS

SERNAGEOMIN is the official institution that monitors the volcanic activity and develops hazard assessments in Chile. In 1991 the Volcano Hazards Program was created in order to conduct geological mapping and the volcanological research. Later, in 1996, the *Observatorio Volcanológico de Los Andes del Sur* (OVDAS) was created to monitor the most hazardous volcanoes in the SVZ, near the city of Temuco. Despite this effort, OVDAS was a small group of people in charge of monitoring just a few volcanoes. On May 1, 2008, there was little warning before the start of a large eruption of Chaitén volcano (42.83° S; 72.65° W), located in northern Patagonia. At that time little was known about the geological evolution and hazards related to the volcano and owing to the lack of monitoring, the authorities believed that Michinmahuida, the neighbour volcano, was showing unrest. With no seismic stations, earthquakes directly felt by residents of Chaitén town (10 km downstream from the volcano) provided the first warning of the impending eruption, which started about 24 hours later. The initial eruption was highly explosive and lasted for 10 days. About 5,000 at-risk residents in the town could not evacuate by road because of heavy tephra fall, so

an evacuation by sea was organized and completed by May 6th. Heavy rains from May 11th washed a large volume of volcanic debris and generated floods and hyper-concentrated flows [Pierson et al. 2013]. Flooding and burial destroyed ~80 % of the town and the Chilean government declared the town unsuitable for habitation in late May 2008. However, as volcanic activity decreased in late 2008, hundreds of former residents returned and rebuilt the town. Finally, in 2012 the government reversed the exclusion order and town was declared habitable again [Major and Lara 2013].

Prompted by the impacts of the Chaitén eruption, the Chilean Government created a new, well-funded volcano-monitoring and hazard assessments program called *Red Nacional de Vigilancia Volcánica* (RNVV) in 2009, which includes OVDAS (which was therefore reinforced) and a new program to conduct geological research and hazard assessments.

2.1 Volcanoes monitored by SERNAGEOMIN

The approach applied in Chile to define which volcanoes are monitored is based on the National Volcano Early Warning System (NVEWS) study for the U.S.A. [Ewert et al. 2005], which has been used to broadly assess the risk associated with each volcano, by combining hazard and exposure factors. This system has been modified and adapted during the last decade to better suit the national volcanic context, however, a direct measure of vulnerability has not been done yet. A methodological update was carried out with the aim of reducing gaps due to lack of information and to enhance the representation of the volcanic activity according to the experience gained since the RNVV era. In particular, to quantifying the weights of several parameters analytic hierarchy process techniques were introduced as well as expert interviews and focus group. Results from the 2017 national census are also included, which is the most recent demographic compilation in Chile, as well as public and private infrastructure around the volcanoes.

As NVEWS stated, the relative volcano threat is the sum of the hazard multiplied by the sum of the exposure. Accordingly, volcanoes are ordered using a threat ranking which allows us to allocate more resources to those volcanoes that pose higher risk, since it is difficult to provide monitoring for all the active volcanoes in the country. In summary, volcanoes have been grouped in five categories according to their score: very high (14), high (16), moderate (20), low (23) and very low (19) risk. All very high- and high-risk volcanoes are currently monitored, and at least some minimal monitoring networks have been deployed for some moderate- and low-risk volcanoes in order to establish baseline levels of activity. By 2020, 45 volcanoes are monitored in real-time, which are located from northernmost Chile up to the Aysén region, ~3000 km-long arc segment (Figure 1). In addition, efforts have been made

to provide the first seismic reconnaissance at Burney (52.32° S; 73.38° W) and Fuegoino (54.97° S; 70.27° W), two AVZ volcanoes in the Magallanes region.

3 HOW VOLCANOES ARE MONITORED

The RNVV addresses two main topics: 1) real-time monitoring and 2) hazard assessments, which includes geological mapping and numerical modelling. While the working group responsible for the first task is based in the Southern Andes Volcano Observatory (OVDAS) located in Temuco, Southern Chile, the group in charge of hazard assessment is based in the headquarters at Santiago. In total 60 people work at the RNVV department, whose expertise are described in (Table 1). In addition, OVDAS is responsible for maintaining the equipment at multiple sites and ensuring the flow of data from volcanoes to the observatory in order to provide volcanic alert levels, and to advise Civil Protection (hereafter named ONEMI, *Oficina Nacional de Emergencias*) when actions should take place before and during a volcanic crisis.

Cutting edge research is also carried out on understanding volcanic processes [e.g. Bertin et al. 2015; Cardona et al. 2018; Franco et al. 2019], and because Chilean volcanoes provide a natural laboratory for the study of volcanism, collaborative research relationships have been established worldwide which have improved significantly the understanding of the volcanic and magmatic processes magmatic [e.g. Singer et al. 2014; Delgado et al. 2016; Aiuppa et al. 2017; Moussallam et al. 2018].

Volcano monitoring comprises the systematic collection of geological, geochemical and geophysical data at the monitored volcanoes from ground-based sensors. In Chile these typically include collecting ash during short-lived explosions; sampling and analysing gases and water that are emitted from active vents and on the flanks of the volcanoes; remote measurements of SO₂ gas flux; measurement of volcanic CO₂/SO₂ gas ratios at high temporal resolution; the location and type of seismic activity; measuring acoustic waves in the atmosphere; surveying deformation of the ground surface; and observing surface activity using webcams and thermal imagery (Table 2). Most of the measurements are performed in real-time, but the staff also undertake campaigns to collect data on a regular basis (monthly to annually). To manage the information derived from the monitoring network, the scientific staff is supported by a team of analysts in charge of data reduction and responsible for the real-time surveillance for all volcanoes. Supervision of monitoring is done by senior seismologists on a regular basis, who can issue reports to civil protection in case of unrest. Although seismology is the most important monitoring tool used in Chile, the integration of seismic data with results from the other described methods is far more powerful. Available data

Table 1: Staff in charge of volcano monitoring and hazard assessments in Chile.

Area	Staff							Administrative Officers
	Researchers			Engineers and Technicians				
	Geology/Geography	Seismology	Geodesy	Geochemistry	Electronic/Electrical	Informatic	Field assistants	
Monitoring and early warning	4	9	3	2	12	8		
Geological mapping and hazard assessments	8	-	-	-	-	-	3	10

are gathered, analysed, and discussed during evaluation meetings twice a month followed by the alert level definition for each volcano done by the scientific committee. Satellite data are also analysed, at different temporal, spatial and spectral scales. High-resolution visible imagery inspection is carried out regularly (daily to monthly) which includes tracking color changes in crater lakes, ice melting on ice-capped volcanoes and mapping deposits and morphological changes around active vents. Synthetic aperture radar interferometry is also done by the scientific staff. On the other hand, thermal detection of hotspots and ultraviolet absorption due to SO₂ emission into the atmosphere are taken from available platforms.

In order to ensure enough human resources to develop and maintain monitoring and hazard assessments expertise, SERNAGEOMIN has been injecting resources sustainably, so both tasks can be maintained even during periods of little volcanic activity. Data acquisition is performed in real time, by different techniques such as satellite technology, optical fiber and internet connectivity. The acquisition of data from various disciplines deployed in the monitoring stations is performed by configuring specific software for each discipline, some of them developed at OVDAS and others taken from the scientific community. Once data are acquired in real-time from the stations, they are stored in a relational database and the information is available for processing by the monitoring staff. Currently, only few monitoring data are available through SERNAGEOMIN's website and only for the highest risk volcanoes. However, a periodic summary of information is published for each monitored volcano. Memorandums of Understanding between SERNAGEOMIN and both academic and public institutions can be signed to provide access to all available information, such as reduced or raw data. In this case, all proposals are evaluated by an internal scientific committee. Finally, all public information of the Government of Chile is under the Transparency Law, which allows any person to request information

on-line*.

4 VOLCANO HAZARD MANAGEMENT

The responsibility for generating hazard maps of active or potentially active volcanoes lies with SERNAGEOMIN, but studies from the academic community in order to better understand volcanic processes are also used. Volcanic hazard maps communicate information about several volcanic phenomena such as tephra/ash fallout, ballistic pyroclasts, lava flows, PDCs, lahars, debris avalanches and susceptibility of new vents in monogenetic fields. In order to establish long-term eruption forecasting, historical and geological data are used to obtain eruption frequencies, magnitudes and styles, and therefore extensive fieldwork is carried out for sampling as well as mapping the extension of deposits related to specific types of past events. Deposits are analysed and dated to establish magnitude-recurrence patterns. As the geological record might be biased by preferentially deposits from larger events, numerical modelling is used as a complementary tool, typically involving scenario-based assessments of a single hazard type. Finally, all available information is combined, resulting in a simple display of qualitatively hazard zones. These maps have shown to be more effective for communication with authorities and stakeholders and are built from a combination of geological and modelling sources. In the case of tephra/ash fallout hazards, these are estimated using stochastic application of computer simulations, where the input parameters such as column height, erupted mass and grain-size distribution are defined by the user and wind fields representative for the region are taken from global datasets [e.g. Amigo 2013]. The output is shown as probabilities to reach a certain threshold (e.g. thickness in cm) for a given eruptive scenario. One problem of this approach is that such maps are sometimes complex to interpret and communicate.

*http://www.sernageomin.cl/gobiernotransparente/solicitud_informacion.html

Table 2: Summary of monitoring techniques and number of instruments for volcanoes currently monitored. Volcanoes are grouped according the categories based on the new threat ranking (high to low risk as I to IV, respectively).

Instruments	Volcanoes				Total
	I (13)	II (16)	III (10)	IV (6)	
<i>Ground vibration</i>					
Seismic	77	64	19	15	175
Accelerometers	4	-	-	-	4
<i>Deformation</i>					
GNSS	33	16	-	-	49
Tiltmeters	9	7	-	-	16
Geodesic sites	4	1	-	-	5
<i>Fluids detection and sampling</i>					
SO ₂ (DOAS + IR camera)	7	4	-	1	12
CO ₂ /SO ₂ (MultiGAS)	1	-	-	-	1
On-site surveys	2	3	-	-	5
<i>Atmospheric waves</i>					
Infrasound	3	3	-	-	6
<i>Cameras</i>					
Webcams	28	17	7	4	56
Thermal	2	1	-	-	3
<i>Ash collection</i>					
Ashmeters	5	3	-	-	8
<i>Satellite coverage</i>					
High-res imagery	14	14	10	14	52
SAR analysis	9	1	-	-	10

In Chile hazard maps are published by SERNAGEOMIN, which includes a peer-review process as well as geospatial and geodatabase standards. Maps are created at different scales, such as national (1:2000000), regional (1:250000) and for single-volcanoes (1:75000–1:50000). Since 2009, 28 maps have been published focused in the most active centres (Figure 1) and currently two new maps are planned to be published every year until 2023, for a total of 34 hazard maps for individual volcanoes. Hazard maps are freely available on

the website*.

Currently, a new approach is under development in order to evaluate only the highest risk zone of active volcanoes, but at a higher scale (e.g. 1:25000). For this, much more detailed fieldwork is necessary as well as better constrained numerical simulations and high-resolution digital elevation models. This new generation of maps is thought to be more appropriate for land planning needs and for the better determination of meeting-points within hazard zones, which are used during eruption simulations and constantly communicated to exposed communities (Figure 3), and therefore increase the effectiveness of hazard mitigation plans.

5 INFORMATION DISSEMINATION AND OUT-REACH

In Chile the short-term eruption forecasting is achieved through a system of volcanic alert levels, providing information on the state of unrest, based on the observation of precursors, for each monitored volcano. The alert levels range from green (background level), yellow (minor to moderate unrest), orange (moderate to heightened volcanic unrest or minor volcanic eruption) and red (impeding major volcanic eruption or eruption in process). The volcanic alert levels are assigned by SERNAGEOMIN based on the level of volcanic activity, whether the activity will likely result in an eruption, and the potential impact of the expected event. The goal of this work is to guide the appropriate response of the authorities and ONEMI.

Currently, the volcanic activity is disseminated as follows: a summary of the volcanic activity (*Reporte de Actividad Volcánica*, RAV) is reported monthly for all volcanoes in green alert level, biweekly for those in yellow alert level and daily for volcanoes in orange and/or red alert levels. Daily reports also include a hazard map depicting potential areas to be impacted by the current state of activity. In addition, when unusual events occur, such as large magnitude volcano-tectonic or long-period seismic events, seismic swarms, thermal anomalies, explosions or significant changes at the surface of active vents, a special report is issued promptly (*Reporte Especial de Actividad Volcánica*, REAV), independent of the volcano alert level. Finally, if activity is detected or reported for unmonitored volcanoes, a statement is issued that includes all the available information and suggestions for the collection of new data in order to better assess the phenomenon (*Minuta Excepcional Volcánica*, MEV).

Reports issued during 2019 comprise 132 monthly reports for all volcanoes with a green alert level. In this case, volcanoes are grouped into 11 administrative regions and therefore one single report includes several centers. Together with the three volcanoes with a yellow alert level, 25 biweekly reports along with 379

*<http://portalgeominbeta.sernageomin.cl/>



Figure 3: Example of a map indicating meeting-points within a high hazard zone during the ongoing eruption of Nevados de Chillán volcanic complex. The map is made and released by the technical institution (SERNAGEOMIN) and Civil Protection (ONEMI) coordinated.

daily reports were issued for the three volcanoes with an orange alert level, specifically during the Nevados de Chillán, Copahue and Villarrica crises. Finally, 194 special reports were issued and just one report for one unmonitored volcano.

Reports are sent to ONEMI following a formal response protocol, who coordinate the emergency response and use its own civil protection alert system. In some cases, ONEMI issues a citation to the operative emergency committee, which is comprised of political authorities and other response organisations. During

these meetings, decisions such as restriction areas and eventually evacuation of people are made and details of the government's response to the crisis and actions to be taken are announced. When significant emission of ash into the atmosphere occurs (eruptive columns higher than 2 km above the vents), a Volcano Observatory Notice for Aviation (VONA) is sent to the civil aviation authority.

All RAV and REAV reports are published on SERNAGEOMIN's website and are stored and made freely available. In addition to publication on the website*,

social media such as Twitter (@Sernageomin) has become the primary source for rapid dissemination of information about new volcanic reports and hazard zones during volcanic crises.

The RNVV is often involved in outreach activities across the country, not only during volcanic unrest or crisis, but also in times of volcanic repose. Our outreach programs allow both authorities and communities to better understand the potential risk from their volcanoes. Exercises simulating volcanic unrest and eruptions are coordinated by ONEMI involving exposed communities in order to test responses and planning for future eruptions. During the last years, volcanic outreach fairs have been organized twice per year. Up to 2019, eight events have been organized at different towns throughout the country that have gathered more than 5,000 people, mostly children. The aim of these events is to raise awareness of communities exposed to volcanic hazards. Fairs have different modules where rocks and minerals, maps and hazard zones in 3D models are displayed as well as information on the eruptive history of the volcanoes in the area. In many cases field trips and workshops for risk prevention and mitigation are organized. In addition to information delivering, local knowledge based on community experiences with volcanic processes are collected. Fairs have been multidisciplinary and involve collaborative work with universities, civil protection and regional governments, and have shown to be very effective.

6 NEEDS, CHALLENGES, AND FUTURE PERSPECTIVES

After one decade of the RNVV creation in Chile, several challenges arise for the next years, which are summarized as follows:

- Continuous sustainable growth of the monitoring network, improving the network where it is less developed.
- Distribution of field instrumentation based on the new threat ranking, evaluating volcanoes currently monitored as well as including others not monitored previously, such as those in southernmost Chile (Magallanes) and on Easter Island.
- Strengthen the relationship with academic institutions focused on multiparametric analysis of the volcanic activity.
- Develop the capacity for operational models using Big Data techniques such as semi-supervised machine learning methods.
- Application of effective methods for risk and hazard assessment involving exposed communities.

- Using social media as a two-way dialogue to communicate and receive information directly from the public and other sources.

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DATA AVAILABILITY

The data presented in this article are available on request to the corresponding author.

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*<http://www.sernageomin.cl/red-nacional-de-vigilancia-volcanica/>

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