REPORT VOLCANICA

Hazard assessment studies and multiparametric volcano monitoring developed by the *Instituto Geológico, Minero y Metalúrgico* in Peru

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Abstract

Urban development in the areas surrounding active volcanoes has led to increasing risks in southern Peru. In order to evaluate the hazard, the *Instituto Geológico, Minero y Metalúrgico* (INGEMMET) created a Volcano Observatory (OVI) to carry out detailed geological investigations to understand eruption histories and provide volcanic hazard maps. The generation of geological information on volcanoes has allowed the identification of scenarios and zoning of potentially impacted areas. This information has also allowed OVI to implement surveillance networks giving priority to the volcanoes that pose the greatest risk to the population, infrastructure, and economic activities. Since 2006, OVI has been running volcanic monitoring networks with a multidisciplinary approach, improving real-time transmission, and making timely forecasts. Based on geological information and the risk posed by the volcanoes, the greatest efforts have been made to monitor Sabancaya, Misti, Ubinas, and Ticsani volcanoes. Following the order of priorities, monitoring of Coropuna, Huaynaputina, Tutupaca and, Yucamane volcanoes has also been developed. In addition, OVI carries out routine education activities and diffusion of information that serve to manage volcanic risk in Peru.

Este artículo está disponible en español: `https://doi.org/10.30909/vol.04.S1.7392` [PDF ES].

1 Introduction

The Peruvian active volcanic arc is located in the southern part of the country. It is part of the Andean Central Volcanic Zone (CVZ), which results from the subduction of the oceanic Nazca Plate beneath the continental South American plate. Active volcanoes are emplaced in an NW–SE direction, parallel to the Peru-Chile Trench, and on top of the Mio-Pliocene plateau, which is composed of ignimbritic and volcano-sedimentary deposits [Paquereau Lebti et al. 2006; Mamani et al. 2009; Thouret et al. 2016].

The *Instituto Geológico, Minero y Metalúrgico* (INGEMMET) Volcano Observatory (OVI) is an interdisciplinary centre for the study and surveillance of volcanoes, whose purpose is to determine the nature and probability of volcanic eruptions through systematic, permanent and real-time monitoring. Furthermore, OVI's staff evaluate the types of volcanic hazards based on geological studies and provide timely alerts to society about unrest episodes and/or imminent volcanic eruptions. The observatory has four main areas: (a) geology and hazard assessment; (b) volcano monitoring; (c) education and outreach; and (d) electronics, telemetry, and informatics. The results of OVI's study and surveillance of volcanoes have been documented in technical reports, bulletins, geological maps, volcanic hazard maps and on websites with real-time information (panel view), which have been used by authorities and decision makers for disaster risk management. Specifically, such information has proven useful during the eruption crises of Sabancaya (2016–present), and Ubinas (2006–2009, 2013–2017, and 2019).

OVI's most important function is to generate information for the management of the volcanic risk in Peru. For this, it necessary to establish a practical criterion to judge whether a volcano is active or potentially active. At OVI, a volcano is considered 'active' if it erupted at least once during the Holocene (e.g. Smithsonian Global Volcanism Program*, while it is considered 'potentially active' if eruptive activity during the Holocene has not been evidenced but the probability for unrest episodes is not zero. This classification of volcanoes in Peru has allowed OVI to provide a means to assess volcanic hazards and prioritize the development of monitoring networks at individual volcanoes. Ten active eruptive centres in southern Peru are identified: (1) Coropuna [Bromley et al. 2019; Mariño et al. 2020], (2) Sabancaya [Samaniego et al. 2015] (3) Misti [Thouret et al. 2001; Harpel et al. 2011; Cobeñas et al. 2014; Rivera et al. 2017], (4) Ubinas [Thouret et al. 2005; Rivera et al. 2017], (5) Huaynaputina [Thouret et al. 1999; Prival et al. 2019], (6) Ticsani, (7) Tutupaca [Samaniego et al. 2015; Manrique et al. 2019], (8) Yucamane [Rivera et al. 2020], (9) Purupuruni [Bromley et al. 2019], and (10) Casiri [Bromley et al. 2019]. These consist of volcanic

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*`http://volcano.si.edu/search_volcano.cfm`

clusters, stratocones and dome clusters. Additionally, the monogenetic field of the Andagua–Huambo–Orcopampa zone, which is composed of small scoria cones associated with blocky lava flows [e.g. Delacour et al. 2006] can also be considered as an active volcanic field (Figure 1).

1.1 Populations exposed to volcanic activity

The number of people exposed to volcanic activity in Peru is dependent on the eruptive dynamics and magnitude of the potential eruptions. As of today, the population living within 30 of one active volcano is approximately 1.5 million [INEI 2018]. However, even for small-to-moderate eruptions, such as that which occurred at Ubinas volcano in 2019 (VEI 2), ash fallout was reported up to 200 from the vent. During larger eruptions such as the one that occurred at Huaynaputina volcano in 1600 CE (VEI 6) [Thouret et al. 1999; Prival et al. 2019], the affected area was much larger with ash deposits that reached up to a distance of 1000 from the crater. Therefore, there could be around 3 million people [INEI 2018] exposed to volcanic activity during large-scale eruptions, mainly located in the regions of Arequipa, Moquegua, Tacna, and Puno.

1.2 Brief history of the Volcano Observatory of INGEMMET (OVI)

INGEMMET is the geological and mining survey of Peru. Part of its function is to identify, study, and monitor the hazards associated with volcanic activity. Volcanological studies carried out by INGEMMET began in 1997 with the publication of the inventory of volcanoes in Peru [Fídel Smoll et al. 1997]. Since then, geological study, volcanic hazard assessment, and multidisciplinary monitoring have provided a comprehensive understanding of volcanic activity and the identification of probable eruptive scenarios.

To respond to the 1990–1998 eruptive activity of Sabancaya volcano [Gerbe and Thouret 2004], temporary seismic stations were deployed by the *Instituto Geofísico del Perú* (IGP) during 1990–1993. Subsequently, during 1993 and July–December 1995, IGP registered seismic information with three telemetered stations between 1420 around the volcano obtaining one of the first database for Sabancaya's activity [Antayhua et al. 2001]. At Ubinas volcano, adequate monitoring did not exist until 2006, although IGP had deployed some temporary seismic stations during five weeks in 1996 [Rivera et al. 2010]. In 2006, when Ubinas volcano entered an unrest phase, "regional and national authorities did not have any emergency plans" [Rivera et al. 2010]. Consequently, in March 2006 a scientific committee including INGEMMET, IGP, and the *Universidad Nacional de San Agustín* (UNSA) was created to install equipment to monitor Ubinas volcano. This committee collaborated in data processing and issued volcanic bulletins and reports until the beginning of 2019; unfortunately, this is not the case now.

In order to manage the eruptive crisis at Ubinas volcano, in 2006 INGEMMET started to develop a multiparametric surveillance network. It was the beginning of the institution's efforts to implement instrumental monitoring of the country's volcanoes using a multidisciplinary approach including techniques such as geodesy, remote sensing, gas chemistry, hydrochemistry, volcanic seismology, and the geological analysis of recent volcanic products. During the same period, detailed studies on volcanoes started in order to constrain the eruptive chronology, identify the main volcanic phenomena and assessment hazards. The first official volcanic hazard map of Peru provided by INGEMMET was published in 2007 for Misti volcano [Mariño et al. 2007].

Having strengthened the volcanology program, OVI was officially created on March 15, 2013 in the city of Arequipa, as part of the *Dirección de Geología Ambiental y Riesgo Geológico* of INGEMMET. Throughout this time, OVI has always sought to improve its work by enhancing research, expanding monitoring networks, and seeking collaboration with other institutions, in addition to actively participating in the various platforms created by governments at different levels for the management of volcanic disaster risk.

1.3 Which volcanoes are monitored?

OVI prioritizes the monitoring of high risk-level volcanoes in Peru, based on geological studies, hazard assessments, their ongoing activity and proximity to large urban areas such as Arequipa. OVI focuses on the monitoring of Sabancaya, Misti, Ubinas, and Ticsani volcanoes, which have real-time multi-parameter surveillance networks. Other active volcanoes such as Coropuna, Huaynaputina, Tutupaca, and Yucamane have campaign stations.

Currently, eight active volcanoes are monitored, four of which are monitored in real-time (Sabancaya, Ubinas, Misti, Ticsani) with permanent stations and the remaining four volcanoes (Coropuna, Tutupaca, Yucamane, and Huaynaputina) are monitored through punctual data acquisition field campaigns. Real-time monitoring data from the permanent stations installed on the volcanoes are transmitted through a telemetry system to the observatory. At the other volcanoes, the data are downloaded from the sensors and direct measurements are also made during the field campaigns (in average once per month). Many of these instruments (seismometers, thermometers, GPS) remain installed for long periods of time (month or years) and therefore establish the baseline parameters for these volcanoes. In addition, this allows us to characterize the area for installation of future permanent volcanic monitoring stations. The instrumentation and analy-

 4(S1): 73 – 82. doi: 10.30909/vol.04.S1.7392

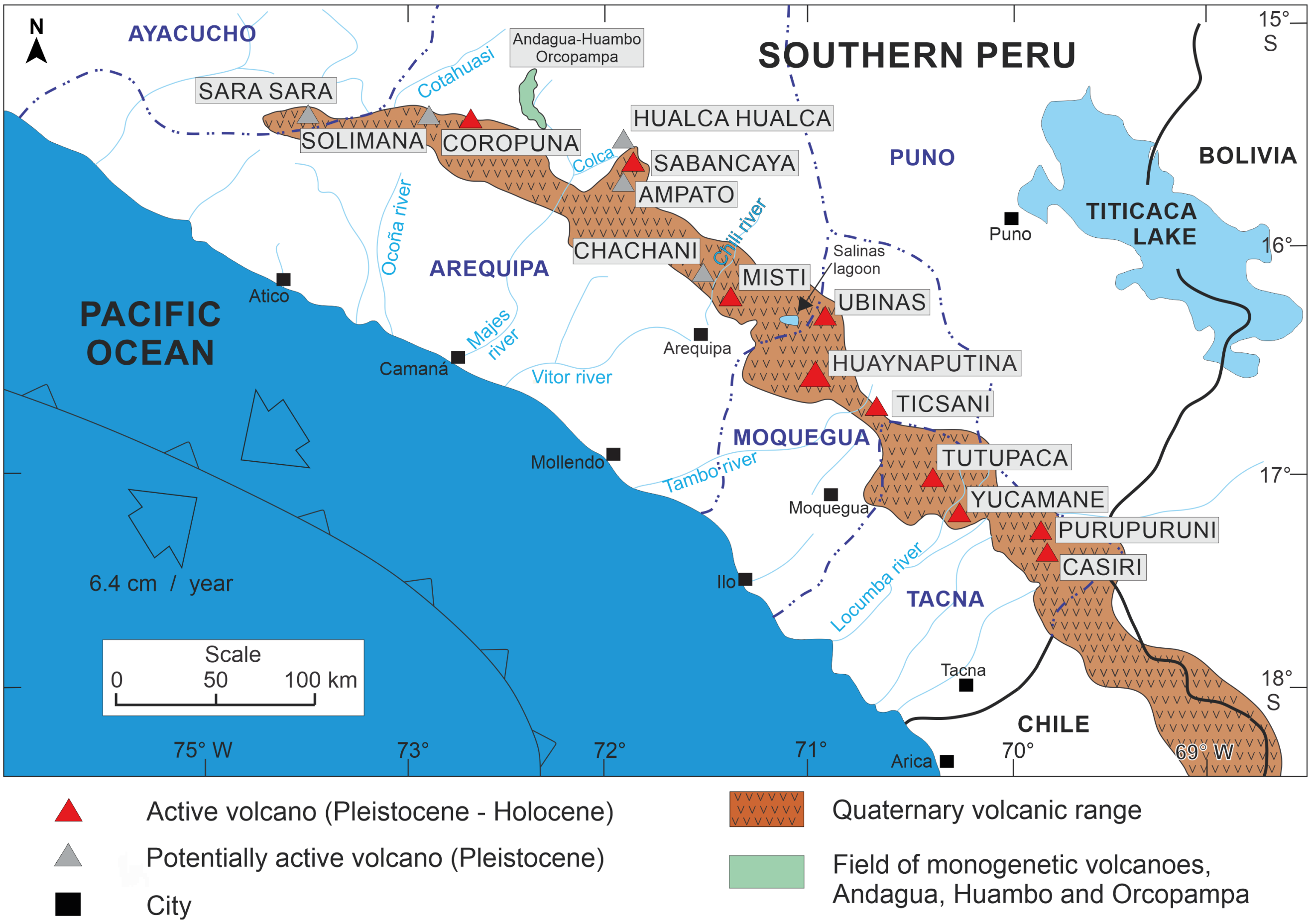

Figure 1: Map of southern Peru with the location of active and potentially active volcanoes.

sis methodology are grouped into five disciplines: seismology, volcanic deformation, fluid and gas chemistry, remote sensing, and geology. The volcano monitoring networks in Peru are operated by INGEMMET and IGP, whose stations are installed in different locations allow a broader record.

2 Geological studies and volcano monitoring

OVI has a team composed of geologists dedicated to the study of volcanic activity. This team performs detailed field and laboratory work to reconstruct the eruptive history of volcanoes. Various tools including cartography, stratigraphy, petrography, geochemistry, and geochronology are used to understand the processes that generated the eruptions and determine future eruptive scenarios. This information enables us to develop geological maps and hazard assessments.

The volcano monitoring performed by OVI consists of a multiparameter approach that includes seismometers, GPS, tiltmeters, volcanic gas sensors, optical and thermal cameras, thermometers, meteorological stations, geoelectric sensors, satellite imagery, ash collectors, and petrologic analysis of emitted products (Figure 2).

INGEMMET started volcano monitoring in 2006 using seismology, chemistry, geodesy, and geology which has been improved with time. Since 2013, OVI increased the seismic monitoring network with broadband triaxial seismometers (0.033100) GURALP 6TD and 40TD, and SILICON AUDIO (0.0051500) sensors with MINIMUS recorders.

Gas monitoring started in 2005 first at Sabancaya, Misti, and Ubinas volcanoes through direct SO_2 measurement using flyspec field equipment. The first DOAS station to measure volcanic SO_2 flux in real-time station was installed in the municipality of Ubinas in 2013 (6 SE). This was after completed with another DOAS sensor (~4 S). They have been implemented through the NOVAC (Network for the Observation of Volcanic and Atmospheric Change) international cooperation project. In 2017, the first real-time MultiGAS sensor was installed at ~2.5 of Sabancaya through the DECADE (Deep Earth Carbon Degassing) project; the gas monitoring network have been completed with three DOAS sensors installed to 48 around the vent. In-situ measurements with DOAS and UV cameras are also performed at Misti, Ticsani, Tutupaca, and Yucamane volcanoes.

To monitor volcanic deformation, OVI uses GNSS

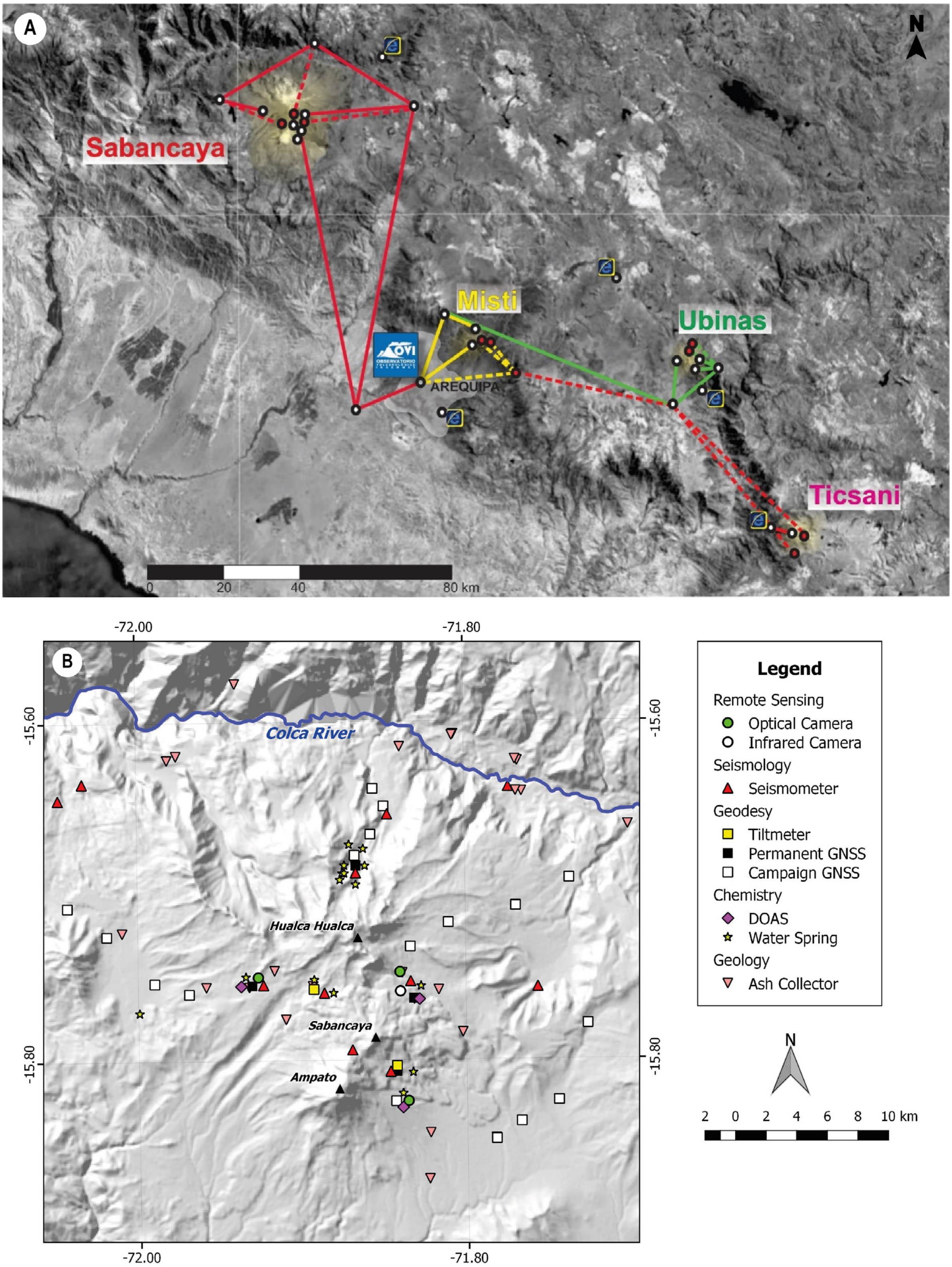

Figure 2: [A] Satellite image showing the real-time monitoring networks operated by OVI. These volcanoes present the highest activity and risk in Peru. Color lines are used to differentiate the network of each volcano. White dots represent multiparametric stations and repeaters; red dots represent the stations in process of physical infrastructure improvement (concrete towers, protection fence). Stations with internet transmission are represented by "e". [B] Monitoring network of Sabancaya volcano. The five seismometers installed in the northern zone (near to Colca river) are used for monitoring landslides and active faults; however, they can also record distal seismicity of Sabancaya.

receptors with real-time stations at Sabancaya, Misti, Ubinas, and Ticsani volcanoes. Networks of ash collectors are also installed around Sabancaya and Ubinas volcanoes to identify the composition of eruptive products, measure the thickness of the deposits, and make isopach and isomass maps. The number of real-time and field campaign measurement stations are detailed in Table 1.

Optical cameras allow proper recording during the day and in optimal weather conditions (visibility), when conditions are not favourable, thermal cameras can record activity in poor visibility conditions.

Additionally, geological studies and hazard assessment developed by OVI has been strengthened over time through international collaboration. Several institutions such as the *Institut de Recherche pour le Développement* (IRD, France) have allowed us to carry out very important geological research projects and at the same time have allowed the training of personnel. The Volcano Disaster Assistance Program (VDAP, USGS) has contributed enormously in the improvement of monitoring networks, training, and routine advice for the processing and interpretation of geological and monitoring data. OVI is always willing to develop collaborative projects with national and international institutions.

2.1 OVI staff and multidisciplinary expertise

OVI has a staff of 32 professionals from different disciplines (Table 2). The Geology and hazard assessment team and the Volcano monitoring team comprises 11 and 14 scientists, respectively. Additionally, there are three engineers for technical support and four administrative staff.

Education and outreach activities are carried out by the geology and volcano monitoring teams in parallel to hazard assessment and volcano monitoring work. In addition, OVI receives laboratory (sample preparation, analytical chemistry, petrography, remote sensing), communications, and logistics support from the main INGEMMET office in Lima.

2.2 Data storage and access to generated information

The information from the different sensors installed on the volcanoes are telemetered in real-time to the data centre in two ways: direct telemetry using UHF radio links and by internet. These methods allow us to transfer data automatically to OVI. Likewise, there are data, such as chemical samples of hot springs and direct field measurements (seismology, geodesy, geology) that are download directly to removable disks.

All the information (transferred by telemetry and collected in the field) are systematically stored on NAS servers. Then, each specialist can access the database through ports on the local network. Additionally, ports

Table 1: Permanent monitoring sensors at Peruvian volcanoes installed and operated by OVI. All stations are telemetered except those with an asterisk.

Volcano	Seismometer	GPS	EDM	Tiltmeter	DOAS	Hydro-chemistry	Multi-gas	Camera	Infrasound	Thermometry	Total
Coropuna		4*				12*				4*	20
Sabancaya	11	4	2*	2	3	9*	1*	6	3*	6*	47
Misti	1	1	4*			8*	1*	1		3*	19
Ubinas	6	4	3*	1	3	8*	1	4		3*	33
Huaynaputina	2*					6*				4*	12
Ticsani	2	2	1*			18*	1*	1		5*	30
Tutupaca	1	6*				12*	1*			4*	24
Yucamane						8*	1*			3*	12

* data collected in field.

Table 2: Detail of OVI staff.

1. Geology and hazard assessment	10 geologists 1 geophysicist
2. Volcano monitoring	5 seismologists 4 geodesists 2 chemists 2 geologists 1 specialist in remote sensing
3. Technical support	2 electronics engineers 1 computer engineer
4. Administrative support	2 administrative assistants 2 drivers—field assistants

are enabled for external access using FTP and SSH protocols, which allows data processing outside of the office.

The information generated by OVI is owned by the Peruvian state and as such is available to those who require it, subject to prior authorization and coordination with the institution, which is obtained by email to the executive president of INGEMMET. In case of agreements for research work or inter-institutional cooperation activities, access to information is free for all team members.

3 Volcano Hazard management

The recent eruptions of Ubinas (2006–2009, 2013–2017, 2019) and Sabancaya (2016–present) volcanoes have reminded political authorities, Civil Defense, and scientists of the weaknesses and limitations in emergency response and the protection of citizens. Disaster risk management and emergency response capacity is highly dependent on preparedness and the available tools and technology. The use of management tools such as hazard maps is important before, during, and after an eruptive crisis because they can identify scenarios and possible affected areas. OVI officially makes the volcano hazard maps in Peru and has published such maps for Sara Sara [Rivera et al. 2020], Ampato-Sabancaya [Mariño et al. 2012], Misti [Mariño et al. 2007], Ubinas [Rivera et al. 2011], Ticsani [Mariño and Soncco 2018], Tutupaca [Mariño et al. 2019], and Yucamane [Rivera et al. 2018] volcanoes. Currently, work is underway to complete the hazard maps for Coropuna, and Chachani volcanic clusters. Additionally, a project started in 2020, is underway to make the second version for Misti volcano by using DEMs with horizontal resolutions of 10 and 2. For an individual volcano, OVI carries out a ~3-year research project which includes geological mapping, stratigraphy, different type of samples analysis, reconstruction of its eruptive history, hazard assessment, identification of scenarios and modelling. As result of the projects, we publish a geological-and-hazard assessment bulletin, geological map, and hazard maps (proximal hazards, tephra fallout, and lahars). These maps and bulletins are published on the INGEMMET website and are freely accessible. Also, 3D maps have been generated, allowing dynamic interaction for users*. The first map published in this format was that of the Misti volcano in 2018 (Figure 3).

The information included in the bulletins and maps constitutes the basis for emergency planning, as happened with the recent eruptions of Ubinas and Sabancaya volcanoes and has also served as an essential input in the preparation of contingency plans and evacuation drills carried out in the city of Arequipa.

Depending on a volcano's history of activity, OVI uses monitoring and geological data to construct probabilistic event trees for the examination of possible outcomes of volcanic behaviours. The results of event trees have helped us to structure the monitoring information and geological data to prioritize efforts, make decisions to maintain or change of alert levels, and give recommendations to the authorities. Considering that disaster risk management is a complex process, the use of different tools and coordinated participation of all the stakeholders of the Civil Defence platforms is essential.

4 Information dissemination and outreach

Communication and dissemination of volcanic monitoring information is carried out through summary reports of volcanic activity and technical reports. The characteristics of these products will depend on the target audience and the frequency with which they are issued. Volcanic activity reports are short and understandable. They are meant for local authorities and those that are part of the disaster risk management system, and also the local population. The frequency with which they are released will depend on the level of volcanic activity and can be daily, weekly, monthly, or annual. Technical reports are documents with technical-scientific information that seek to objectively inform the authorities and technical institutions that are part of the national disaster management system about volcanic hazards. Likewise, there is a space in the website that contains real-time information about volcanic activity where the general public can watch images from the cameras, access daily reports, view gas flux histograms, and so on.†

4.1 Dissemination of information

Civil authorities incorporated the hazard-zone map for Misti volcano into the land management and urban

*https://data-ingemmet-peru.opendata.arcgis.com/pages/volcanes

†http://ovi.ingemmet.gob.pe/panelview/index.html

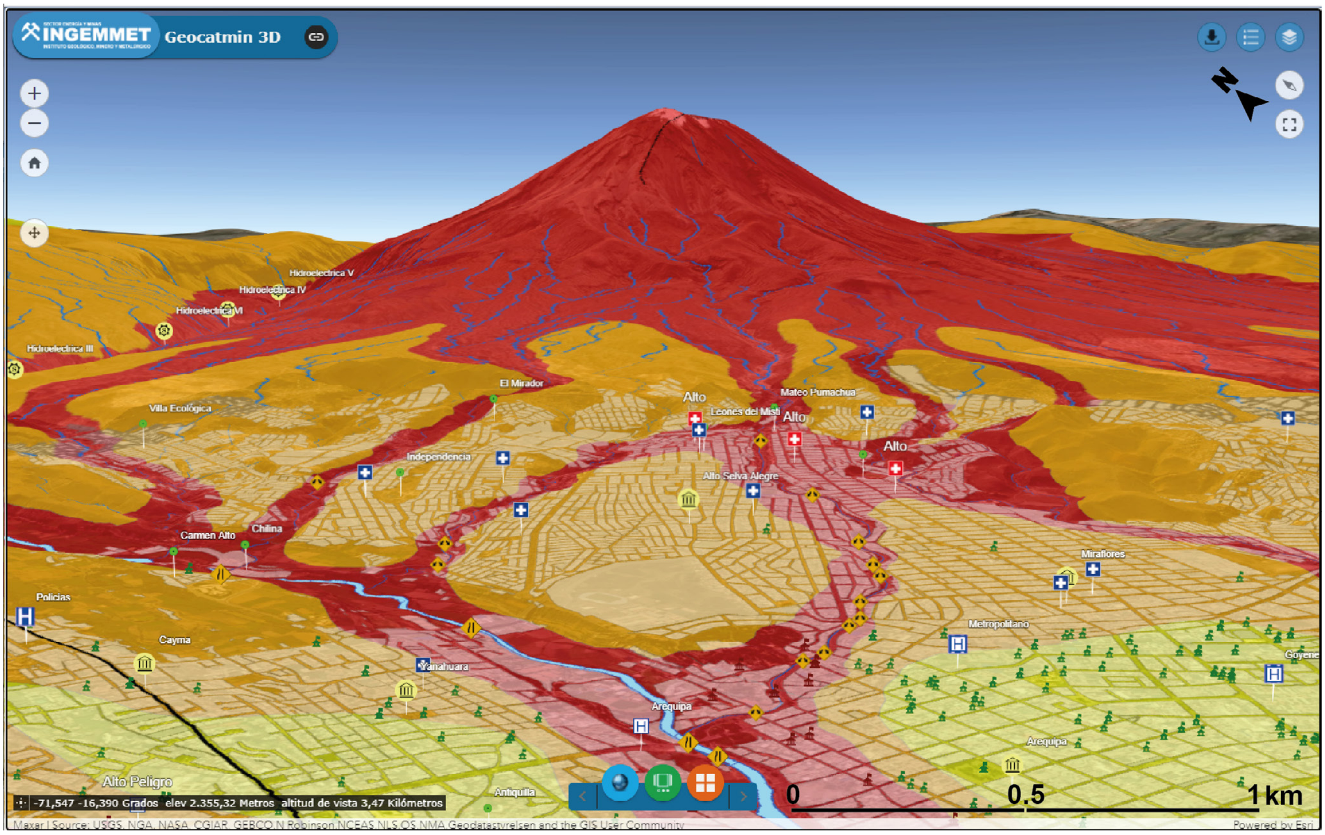

Figure 3: Screenshot of 3D-hazard map of Misti volcano combined with urban area and critical infrastructure of Arequipa [modified from Thouret et al. 1995].

planning for the city of Arequipa. Because of the proximity of houses (within 9) to the summit of Misti, INGEMMET has designed and implemented an expanded program for disseminating the hazard-zone map and increasing awareness of its implications.

Since 2006, hazard maps have been printed for mass distributed through coordination with local authorities, local institutions, private enterprises, and NGOs. Additionally, a training program targeting teachers from educational institutions has also been expanded [Macedo et al. 2008]. An example of the significant efforts made by INGEMMET with other institutions is the *Centro de Sensibilización para la Gestión de Riesgos* created in Arequipa together with the *Instituto Nacional de Defensa Civil* (INDECI) and the NGO Volcan-Explor-Action (France), inaugurated in February 2011. This centre has displays to explain in a simple way the origin of volcanoes, types of volcanic hazards, and monitoring methods, as well as the Misti volcano hazard map.

In addition to monitoring reports, OVI publishes bulletins and technical reports on geology and volcanic hazards assessment with a target audience of public, scientific, academic, and technical civil defence communities. This information is used for planning emergency responses, such as for identifying the location of shelters to resettle affected populations.

OVI also generates educational information in the form of brochures, leaflets, and flyers directed towards the authorities and public. Technical data is translated in these publications into simple information for education and awareness. During the year, a program of guided tours at the observatory is provided to authorities and primary, secondary, and university students. During the tours, visitors can "touch" volcanic samples, watch videos, interact with the staff, and see how volcanoes are monitored.

Workshops, educational public exposition fairs, and routine talks are provided to journalists, health care professionals, army personnel, tour guides, and other organizations in order to educate and disseminate the information to the community. Additionally, to create a space for thought, discussion, and exchange of experience in volcanic risk management, INGEMMET has organized eight international forums on volcanic risk and two meetings for the volcano observatories of Latin America.

4.2 Interaction with public institutions

Due to the recent eruptions of Ubinas (Moquegua region) and Sabancaya (Arequipa region) volcanoes, scientific committees were created to assist during volcanic emergencies. These committees include INGEMMET-OVI, IGP, the *Servicio Nacional de Meteorología e Hidrología del Perú* (SENAMHI), and UNSA.

These committees participate in the Civil Defence platforms providing information and advising on volcanic risk management. However, the collaboration between the various institutions has been difficult in the last two years (2019–2020); currently, there are efforts to achieve a better understanding and institutional collaboration on a higher level, which we hope will be carried out promptly.

Within the framework of the national disaster risk management system, OVI routinely coordinates with local and regional authorities, national institutions such as *Centro de Operaciones de Emergencias Nacional* (COEN), *Centro de Operaciones de Emergencia Regional* (COER), INDECI, *Centro Nacional para la Estimación, Prevención y Reducción del Riesgo de Desastres* (CENEPRED), *Comisión Nacional de Investigación y Desarrollo Aeroespacial* (CONIDA), and local municipalities. In addition, to promote the study of volcanoes and volcano monitoring, OVI develops research projects related to geology, volcano hazards, and applied investigations in cooperation with national and international scientific institutions and researchers from geological surveys, volcano observatories, and universities.

5 Needs, challenges, and future perspectives

OVI has been developing a comprehensive program to progressively implement real-time, multiparameter monitoring of all the active volcanoes in Peru. The amount of instrumentation required and monitoring priority for each volcano was planned according to the study: "Assessment of volcanic threats and monitoring capabilities in Peru" developed by IGP, INGEMMET, and UNSA [Macedo et al. 2016]. This project has been developed with investment from the Peruvian government through equipment purchases and training of personnel. The progress made by OVI so far has been possible in large part due to the "young" team that has put all its effort into improving the work. However, the support of foreign institutions such as USGS–VDAP, IRD, Laboratoire Magmas et Volcans from Université Clermont Auvergne (France), and many other institutions, through technical advice and equipment donations have allowed the strengthening of our capacities; therefore, we hope to continue and strengthen the cooperation.

With the perspective of continuing that improvement, it is necessary to continuously train young volcanologists through national and international cooperation.

Finally, it is essential to strengthen the collaboration between the participating institutions of the scientific committees in order to generate unified information necessary for an adequate management of volcanic risk in Peru.

Acknowledgements

The authors would like to thank the editors, especially to O. Chevrel for all the coordination necessary for the publication of this article, C. Chacaltana, C. Benavente and L. Fidel for administrative support, and our colleagues at the Observatorio Vulcanológico of INGEMMET in Arequipa for continuous support and discussions. C. Harpel is also acknowledged for the English improvement of a previous version of the text. Thoughtful reviews by two anonymous reviewers improved the manuscript.

Author contributions

R.A. wrote the manuscript, E.T., Y.A., M.O., F.A., and L.C. wrote the volcano monitoring and challenges and future perspective. All authors reviewed the final manuscript.

Data availability

The data described in this article are openly available via the institutional repository of the INGEMMET. Bulletins (https://repositorio.ingemmet.gob.pe), maps (https://geocatmin.ingemmet.gob.pe/geocatmin), reports and real-time monitoring (http://ovi.ingemmet.gob.pe).

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References

Antayhua, Y., H. Tavera, and I. I. Bernal (2001). "Análisis de la actividad sísmica en la región del volcán Sabancaya (Arequipa)". *Boletín de la Sociedad Geológica del Perú* 92, pp. 79–88.

Bromley, G. R. M., J.-C. Thouret, I. Schimmelpfennig, J. Mariño, D. Valdivia, K. Rademaker, S. del Pilar Vivanco Lopez, ASTER Team, G. Aumaître, D. Bourlès, and K. Keddadouche (2019). "In situ cosmogenic ^{3}He and ^{36}Cl and radiocarbon dating of volcanic deposits refine the Pleistocene and Holocene eruption chronology of SW Peru". *Bulletin of Volcanology* 81 (11). doi: 10.1007/s00445-019-1325-6.

Cobeñas, G., J.-C. Thouret, C. Bonadonna, and P. Boivin (2014). "Reply to comment on: "Cobeñas, G., Thouret, J.-C., Bonadonna, C., Boivin, P., 2012.

The c. 2030 yr BP Plinian eruption of El Misti volcano, Peru: Eruption dynamics and hazard implications. Journal of Volcanology and Geothermal Research 241–242, 105–120." by Harpel et al., JVGR 2013". *Journal of Volcanology and Geothermal Research* 275, pp. 103–113. DOI: 10.1016/j.jvolgeores.2014.02.014.

Delacour, A., M.-C. Gerbe, J.-C. Thouret, G. Wörner, and P. Paquereau-Lebti (2006). "Magma evolution of Quaternary minor volcanic centres in southern Peru, Central Andes". *Bulletin of Volcanology* 69 (6), pp. 581–608. DOI: 10.1007/s00445-006-0096-z.

Fídel Smoll, L., W. Morche, and S. Núñez Juárez (1997). *Inventario de volcanes del Perú. Proyecto: Album de mapas de riesgos volcánicos de las principales ciudades del Suroeste del Perú*. Boletín Ingemmet. Serie C: Geodinámica e Ingeniería Geológica. Instituto Geológico, Minero y Metalúrgico—INGEMMET.

Gerbe, M.-C. and J.-C. Thouret (2004). "Role of magma mixing in the petrogenesis of tephra erupted during the 1990–98 explosive activity of Nevado Sabancaya, southern Peru". *Bulletin of Volcanology* 66 (6), pp. 541–561. DOI: 10.1007/s00445-004-0340-3.

Harpel, C. J., S. de Silva, and G. Salas (2011). "The 2 ka Eruption of Misti Volcano, Southern Peru—The Most Recent Plinian Eruption of Arequipa's Iconic Volcano". Geological Society of America. DOI: 10.1130/2011.2484.

INEI (2018). *Censos Nacionales XII de Población y VII de Vivienda, 22 de octubre del 2017, Perú: Resultados Definitivos*. Lima, Peru.

Macedo, L., L. Fidel, F. Muñoz, R. Amache, H. Pareja, and J. Vásquez (2008). "Mitigación de riesgos volcánicos en la ciudad de Arequipa." XIII Congreso Latinoamericano de Geología—XIV Congreso Peruano de Geología. Sociedad Geológica del Perú, p. 5.

Macedo, O. et al. (2016). *Evaluación del riesgo volcánico en el sur del Perú, situación de la vigilancia actual y requerimientos de monitoreo en el futuro*.

Mamani, M., G. Worner, and T. Sempere (2009). "Geochemical variations in igneous rocks of the Central Andean orocline (13 S to 18 S): Tracing crustal thickening and magma generation through time and space". *Geological Society of America Bulletin* 122 (1–2), pp. 162–182. DOI: 10.1130/b26538.1.

Manrique, N., P. Samaniego, E. Médard, F. Schiavi, J. Mariño, and C. Liorzou (2019). "Pre-eruptive magmatic processes associated with the historical (218 ± 14 aBP) explosive eruption of Tutupaca volcano (southern Peru)". *Bulletin of Volcanology* 82 (1). DOI: 10.1007/s00445-019-1335-4.

Mariño, J., M. Rivera, L. Cacya, J.-C. Thouret, L. Macedo, G. Salas, R. I. Tilling, M. Sheridan, C. Siebe, and S. Zuñiga (2007). *Mapa de Peligros del Volcán Misti*. Lima, Peru: Instituto Geológico Minero y Metalúrgico.

Mariño, J., P. Samaniego, N. Manrique, P. Valderrama, and M. L. (2019). *Geología y mapa de peligros del complejo volcánico Tutupaca*. INGEMMET, Boletín Serie C: Geodinámica e Ingeniería Geológica. Instituto Geológico, Minero y Metalúrgico—INGEMMET.

Mariño, J. and Y. Soncco (2018). *Mapa de Peligros del Volcán Ticsani*. Lima, Peru: Instituto Geológico Minero y Metalúrgico.

Mariño, J., J.-C. Thouret, M. Cabrera, R. Aguilar, N. Manrique, B. Edwards, and W. Kochtitzky (2020). Boletín Geológico. Lima, Peru: INGEMMET.

Mariño, J., P. Samaniego, M. Rivera, N. Bellot, N. Manrique, and R. Delgado (2012). "Mapa de peligros del complejo volcánico Ampato-Sabancaya". Congreso Peruano de Geología XVI (Lima, Peru). Sociedad Geológica del Perú.

Paquereau Lebti, P., J.-C. Thouret, G. Wörner, and M. Fornari (2006). "Neogene and Quaternary ignimbrites in the area of Arequipa, Southern Peru: Stratigraphical and petrological correlations". *Journal of Volcanology and Geothermal Research* 154 (3-4), pp. 251–275. DOI: 10.1016/j.jvolgeores.2006.02.014.

Prival, J.-M., J.-C. Thouret, S. Japura, L. Gurioli, C. Bonadonna, J. Mariño, and K. Cueva (2019). "New insights into eruption source parameters of the 1600 CE Huaynaputina Plinian eruption, Peru". *Bulletin of Volcanology* 82 (1). DOI: 10.1007/s00445-019-1340-7.

Rivera, M., J. Mariño, J.-C. Thouret, and P. Samaniego (2011). *Mapa de Peligros del Volcán Ubinas*. Lima, Peru: Instituto Geológico Minero y Metalúrgico.

Rivera, M., P. Samaniego, J. Vela, and J.-L. Le Pennec (2018). *Geología y evaluación de peligros del Complejo Volcánico Yucamane - Calientes (Candarave - Tacna)*. INGEMMET, Boletín Serie C: Geodinámica e Ingeniería Geológica. Instituto Geológico, Minero y Metalúrgico—INGEMMET.

Rivera, M., H. Martin, J.-L. Le Pennec, J.-C. Thouret, A. Gourgaud, and M.-C. Gerbe (2017). "Petro-geochemical constraints on the source and evolution of magmas at El Misti volcano (Peru)". *Lithos* 268-271, pp. 240–259. DOI: 10.1016/j.lithos.2016.11.009.

Rivera, M., P. Samaniego, J. Vela, J.-L. Le Pennec, H. Guillou, J.-L. Paquette, and C. Liorzou (2020). "The eruptive chronology of the Yucamane-Calientes compound volcano: A potentially active edifice of the Central Andes (southern Peru)". *Journal of Volcanology and Geothermal Research* 393, p. 106787. DOI: 10.1016/j.jvolgeores.2020.106787.

Rivera, M., J.-C. Thouret, J. Mariño, R. Berolatti, and J. Fuentes (2010). "Characteristics and management of the 2006–2008 volcanic crisis at the Ubinas volcano (Peru)". *Journal of Volcanology and Geothermal Research* 198 (1-2), pp. 19–34. DOI: 10.1016/j.jvolgeores.2010.07.020.

Samaniego, P., P. Valderrama, J. Mariño, B. van Wyk de Vries, O. Roche, N. Manrique, C. Chédeville, C. Liorzou, L. Fidel, and J. Malnati (2015). "The historical (218 ± 14 aBP) explosive eruption of Tutupaca volcano (Southern Peru)". *Bulletin of Volcanology* 77 (6). doi: 10.1007/s00445-015-0937-8.

Thouret, J.-C., F. Legros, A. Gourgaud, G. Salas, E. Juvigne, E. Gilot, and A. Rodriguez (1995). "Recent Eruptive Activity At El-Misti Volcano (south Peru)—Implications for Hazard Assessment in Arequipa Area". *Comptes rendus de l'Académie des sciences—Séries IIB—Mécanique, Physique, chimie, astronomie* 320 (10), pp. 923–929.

Thouret, J.-C., J. Davila, and J.-P. Eissen (1999). "Largest explosive eruption in historical times in the Andes at Huaynaputina volcano, A.D. 1600, southern Peru". *Geology* 27 (5), p. 435. doi: 10.1130/0091-7613(1999)027<0435:leeiht>2.3.co;2.

Thouret, J.-C., A. Finizola, M. Fornari, A. Legeley-Padovani, J. Suni, and M. Frechen (2001). "Geology of El Misti volcano near the city of Arequipa, Peru". *Geological Society of America Bulletin* 113 (12), pp. 1593–1610. doi: 10.1130/0016-7606(2001)113<1593:goemvn>2.0.co;2.

Thouret, J.-C., B. R. Jicha, J.-L. Paquette, and E. H. Cubukcu (2016). "A 25 myr chronostratigraphy of ignimbrites in south Peru: implications for the volcanic history of the Central Andes". *Journal of the Geological Society* 173 (5), pp. 734–756. doi: 10.1144/jgs2015-162.

Thouret, J.-C., M. Rivera, G. Wörner, M.-C. Gerbe, A. Finizola, M. Fornari, and K. Gonzales (2005). "Ubinas: the evolution of the historically most active volcano in southern Peru". *Bulletin of Volcanology* 67 (6), pp. 557–589. doi: 10.1007/s00445-004-0396-0.