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PERSPECTIVES

# Advances in scientific understanding of the Central Volcanic Zone of the Andes: a review of contributing factors

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**Abstract**
The Central Volcanic Zone of the Andes (CVZA) has been the focus of volcanological research for decades, becoming a very important site to understand a number of volcanic processes. Despite most of the research in the CVZA being carried out by foreign scientists, the last two decades have seen a significant increase in contributions by regional researchers. This surge has been facilitated by the creation of new volcanic observatories, improvement of the monitoring networks, creation of postgraduate programs where new local volcanologists are trained, creation of specialized research nuclei or groups, and increasing investment in research. This article presents a review of the evolution of the contributions of the regional volcanological community to the knowledge of the CVZA in the last 20 years (2000–2019), both from research and monitoring institutions in Peru, Bolivia, Argentina, and Chile. Based on updates made by the regional groups, a new list of active/potentially active volcanoes of the CVZA is presented, as is a complete database for article published on the CVZA. We find that a significant motivator has been regional volcanic unrest that has triggered new investment. Perú is the country with the highest investment in monitoring and research and is the best instrumented, Argentina is the country with the highest number of local participation in published papers in the domain of volcanology and magmatic systems, and Chilean volcanoes are the focus of the highest number of articles published. The current situation and general projections for the next decade (2020–2030) are also presented for each country, where we believe that the over the next 10 years, will be increased the monitoring and research capabilities, improved the scientific knowledge with more participation of regional institutions, and strengthen the collaboration and integrated work between CVZA countries, especially in border volcanoes.

**Keywords** Regional volcanology · Monitoring networks · Volcanological research

**Resumen**
La Zona Volcánica Central de los Andes (ZVCA) ha sido uno de los focos principales de la investigación en volcanología, transformándose en un sitio muy importante para entender una gran diversidad de procesos volcánicos. Aunque la mayoría de la investigación que se ha realizado en la ZVCA ha sido llevada a cabo por investigadores extranjeros, en las últimas dos décadas se ha observado un significativo incremento en las contribuciones realizadas por investigadores locales. Lo anterior ha sido consecuencia de la creación de nuevos observatorios volcanológicos, mejoramiento de las redes de monitoreo, creación de programas de postgrado donde nuevos volcanólogos locales han sido formados, creación de núcleos y grupos de investigación, y por el incremento de la inversión en investigación. Este artículo presenta una revisión de la evolución de las

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contribuciones de la comunidad volcanológica local al conocimiento de la ZVCA en los últimos 20 años (2000–2019), tanto desde las instituciones de investigación como de monitoreo en Perú, Bolivia, Argentina y Chile. En base a las actualizaciones realizadas por grupos regionales, se presenta una nueva lista de volcanes activos y potencialmente activos de la ZVCA, además de una completa base de datos de artículos publicados acerca de la ZVCA. Algunas de las razones más importantes que han motivado una mayor inversión en volcanología a nivel regional han sido algunos episodios de perturbaciones y erupciones volcánicas. Perú es el país con la mayor inversión en monitoreo e investigación, además de ser el país mejor instrumentado, Argentina es el país que cuenta con el mayor número de participantes locales en artículos publicados en el área de volcanología y sistemas magmáticos, y los volcanes chilenos son el foco del mayor número de artículos publicados. También presentamos la situación actual y las proyecciones para la siguiente década (2020-2030) en cada país de la ZVCA, donde creemos que en los siguientes 10 años, se incrementarán las capacidades de monitoreo e investigación, se mejorará el conocimiento científico con mayor participación de instituciones regionales, y se reforzará la colaboración y el trabajo integrado entre los países de la ZVCA, especialmente en el caso de los volcanes fronterizos.

## Introduction

The occurrence of major eruptions, especially catastrophic events, has triggered the creation and/or improvement of volcanic surveillance networks, increasing the investment in instrumentation, human resources, and the interest in volcanological research (Tilling 2009). Some examples of volcanic eruptions that have produced profound changes in volcanology research are as follows:

(1) *Hibok-Hibok volcano, Philippines*: In 1952, after the 1951 eruption that killed ~3000 people, the former Commission on Volcanology (COMVOL), corresponding to the current Philippine Institute of Volcanology and Seismology (PHIVOLCS), was created (McCall et al. 1992).
(2) *Mount St. Helens Volcano, USA*: The May 1980 eruption killed 57 people and produced US $1.1 billion in economic losses (Lipman and Mullineaux 1982; Tilling et al. 1990), thus changing the study of modern volcanology at a global level. At a local-to-regional scale it also favored the creation of the Cascades Volcano Observatory and the expansion of the USGS Volcanic Hazards Program (Tilling and Bailey 1985; Driedger et al. 2020).
(3) *Nevado del Ruiz Volcano, Colombia*: The lahars of 1985 killed at least 25,000 people, thus becoming the worst volcanic tragedy in South American history (Naranjo et al. 1986; Tilling 2009). After the eruption, the Colombian government created three volcano observatories, and whereas the US government formed the Volcanic Disaster Assistance Program (VDAP), and agency with the aim of assisting countries and local scientists into responding to volcanic crises (Tilling 2009; www.volcano.gov/vdap).

One of the major volcanic areas in the world corresponds to the Andean Range, which hosts four active volcanic areas (the Northern, Central, Southern, and Austral volcanic zones). In the Central Volcanic Zone of the Andes (CVZA), 44 active and potentially active stratovolcanoes have been identified (de Silva and Francis 1991). These are distributed between southern Perú, western Bolivia, northwestern Argentina, and northern Chile. Although research on the CVZA has been carried out by a combination of foreign and regional researchers, the recent improvement of regional capabilities has substantially increased the knowledge of this area. Here, we present a short summary of the evolution in the state of knowledge for the volcanic processes in the CVZA over the past two decades (2000–2019), describe the main volcanic events that prompted installation of new monitoring capabilities and resulted in increased research investment, and use this to provide a projection of how volcanology in this area will evolve during the coming decade (2020–2030). To support this, details of investment, equipment acquisition, personnel incorporation and/or training, monitoring networks, and ISI/WoS (Institute of Scientific Information/Web of Sciences) publications in, across, and about the CVZA, as completed by institutions and agencies in Perú, Bolivia, Argentina, and Chile between 2000 and 2021, are collated extensively as Online Resources (Online resources 1 and 2). A detailed list of references relating to the following sections is also presented in Online resource 3. Finally, we present an update of the active/potentially active volcanoes in CVZA based on recent advances in local volcanological research (Fig. 1; Online resource 4).

## Volcanology in the CVZA: the past 20 years (2000–2019)

### Perú

Volcanological research in Peru began in the 1990s with studies about the eruptive chronology of potentially active volcanoes, which represents the first step of any volcanic hazard initiative. Several studies were conducted after the

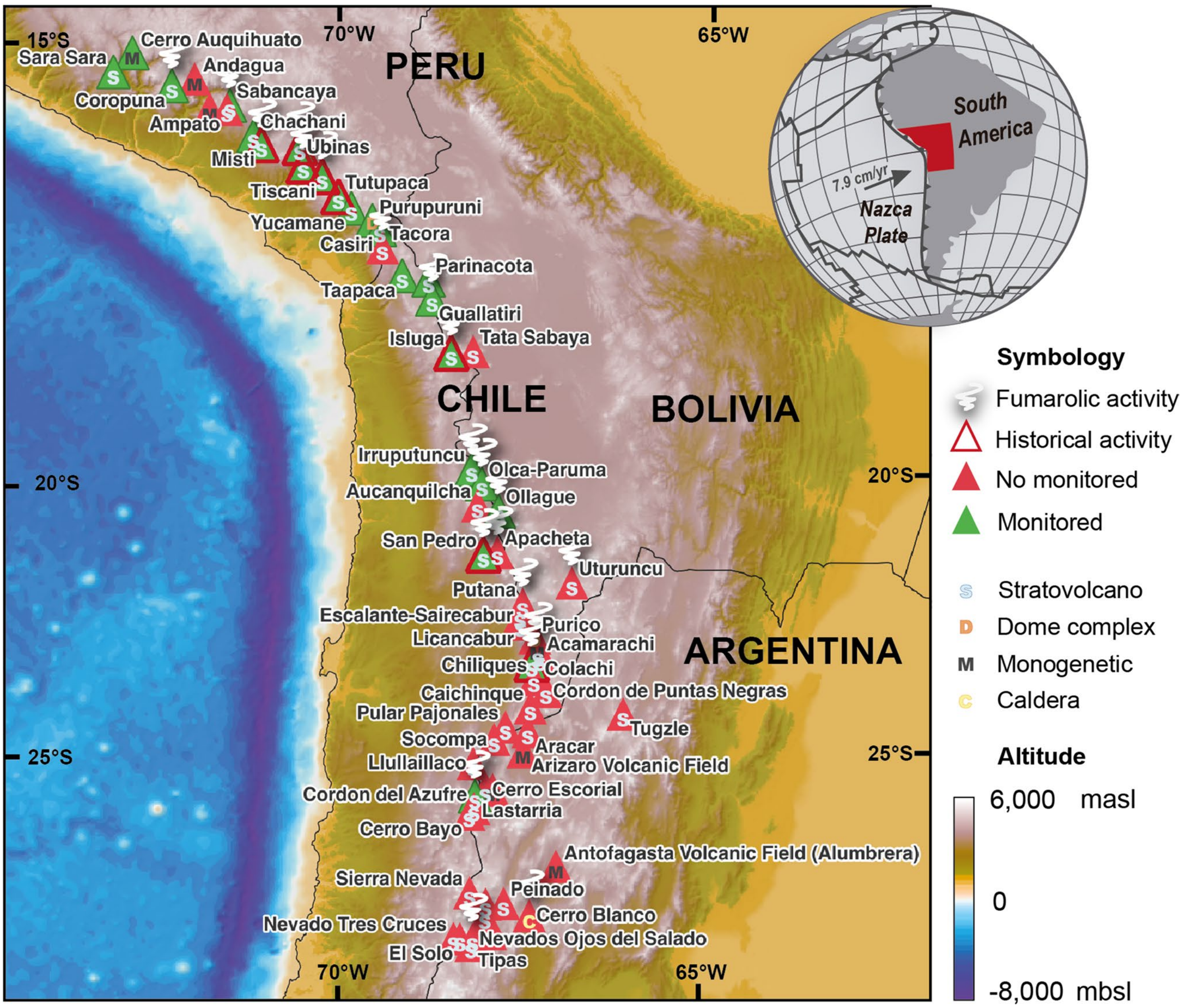


**Fig. 1** Location map of the Central Volcanic Zone of the Andes (CVZA) where active/potentially active volcanoes are shown, after updates carried out in the period 2000–2019. Details about volcanoes with permanent fumarolic emission, with historical eruptive records, monitored and not monitored volcanoes, and the type of volcanoes are also shown

frequent vulcanian eruptive activity from 1988 to 1997 at Sabancaya volcano (Fig. 1). Over the following two decades, studies were undertaken as follows:

(1) to understand of processes that triggered Sabancaya's unrest during the period 1988–1997
(2) to determine the eruptive chronology of some Peruvian volcanoes, such as El Misti, Ubinas, Ampato-Sabancaya, Yucamane, and Tutupaca (Fig. 1)
(3) to assess the hazards of Misti volcano, highlighting their effects in the city of Arequipa
(4) to evaluate the size and effects of the plinian (VEI 6) eruption of Huaynaputina volcano (1600 CE), an eruption considered as the largest eruption during historical times in the Central Andes
(5) to understand the last eruption of Tutupaca volcano, which is associated with the youngest debris avalanche in the Andes (218 ± 14 aBP)
(6) to analyze the evolution and petrology related to the products emitted from several monogenetic fields across Peru, including Huambo, Andahua-Orcopampa, among others.

In addition, the eruptive episodes of Ubinas volcano between 2006 and 2017 have promoted research in the following:

(1) Mechanisms that triggered its recent eruptions.
(2) Seismology studies for precursor signals and identification of the sources of explosions.
(3) Crisis management.
(4) Characteristics of its hydrothermal system.
(5) Detection of thermal anomalies.

Similarly, after the detection of the 1992–1997 deformation episode at Hualca-Hualca (Fig. 1), and especially after the 2016–2020 unrest of Sabancaya, several studies have focused on the deformation, and their implications for the various eruptive episodes.

As detailed in Online resource 1, during the early 2000s, only a few Peruvian volcanoes (e.g., Misti and Ubinas) were monitored, albeit partially, by both Instituto Geológico, Minero y Metalúrgico (INGEMMET) and Instituto Geofísico del Perú (IGP). These networks were inherited from the first efforts to install monitoring capabilities during Sabacaya's 1988–1997 volcano eruption in the previous years. The first major eruptive crisis in the 2000s occurred at Ubinas volcano during 2006, forcing IGP and INGEMMET to respond to the crisis, and giving the chance to improve their monitoring networks. In 2013, the INGEMMET Volcanic Observatory (OVI) was created, and the unrest at Ubinas between 2013 and 2017 reinforced government investment. During 2016, Sabancaya started a new eruptive cycle, providing a new chance to improve volcanic surveillance and research at this site also. During 2017, high levels of investment in equipment and infrastructure allowed IGP to install new instrumentation at several volcanoes, including Coropuna, Sara Sara, Auquihuato, Chachani, Huaynaputina, Tutupaca, and Casiri. As a consequence, in 2019, IGP created the National Volcanological Center (CENVUL).

## Bolivia

The volcanic region of the Bolivian Western Cordillera remained poorly known into the twentieth century. In 1995, a report of a phreatomagmatic eruption at Irruputuncu volcano (Fig. 1) called to attention the volcanic risks in this region. In the following years, the Geological Survey of Bolivia began a program of regional mapping with international assistance from the Swedish Board for Investment and Technical Support (BITS), the Canadian International Development Agency (CIDA), and the Institute de la Recherche pour le Développment (IRD, France). At the beginning of the 2000s, extensive areas of the Western Cordillera and Altiplano were mapped (Fig. 1). Two major findings resulted from this work as collated in Online resource 3 were (1) the wide variety of volcanic centers (from large calderas and stratovolcanoes to smaller monogenetic centers) and (2) the wide distribution of young volcanism scattered across the Altiplano, as well as the Western and Eastern Cordillera. Some other investigations over the last two decades have identified (see references in Online Resource 3):

(1) Foundering (delamination or dripping) of the lithosphere to trigger peraluminous to metaluminous magmatism in the Eastern Cordillera and Altiplano.
(2) The occurrence of at least two ignimbrite flare ups, one in the Early Miocene (25–17 Ma) that extended from southern Perú to northern Chile and western Bolivia, and one in the middle Miocene to Quaternary (10–0.7 Ma), which developed in the northern Chile and Argentina, and western Bolivia.

However, the most notable volcanological progress corresponds to identification of the ground deformation of Uturuncu volcano (Fig. 1), which resulted in the collaborative project PLUTONS. As part of this project, several universities and institutes from the UK, USA, Bolivia, Chile, and Argentina studied the volcano in detail, using a wide spectrum of geological and geophysical techniques (see references in Online Resource 3). Despite this renewed interest in Bolivian volcanoes, and a subtle increase in the number of publications after the PLUTONS contributions, no volcanic surveillance has been performed in Bolivia between 2000 and 2019, and the low level of interest from local government has been reflected in a limited budget for local research institutions, which has limited their contributions to the knowledge of the area (see references in Online Resource 3).

## Argentina

Although some sparse research on the Argentine CVZA existed before the 1980s, it was during the late 1980s and into the 1990s that knowledge on the volcanism of this region increased substantially for the first time (see references in Online Resource 3). The most significant milestones that motivated this initial development were the discovery of the Cerro Galán caldera and the "ultra-plinian" Ramadas eruption, along with the identification of the Puna region (a hinterland plateau east of the main volcanic arc) as a key location to understand geodynamic processes such as lithospheric delamination and erosion by subduction. This increase in knowledge was driven, at least in part, by the advent of Landsat satellite images that allowed extensive "exploration" of this remote region. The topics addressed in this initial phase conditioned the two main research subjects followed in the 2000–2019 period:

(1) collapse calderas (and associated ignimbrites)
(2) back-arc mafic monogenetic centers, both of which are found throughout the Puna region

Conversely, studies on Argentine stratovolcanoes have been comparatively scarce. During the past two decades, however, a significant advance in the knowledge of the Argentine CVZA was achieved. Traditionally, research on the Argentine CVZA has been predominantly petrological (see references in Online Resource 3), focusing on the geodynamic implications of the spatio-temporal variations of volcanism throughout the region. Instead, in recent years, other topics such as physical volcanology, volcano-tectonic interplay, and volcano morphometry have increased markedly, providing a more complete view of the region's volcanism (see references in Online Resource 3). Furthermore, a growing body of research (as collated in Online resource 3) has focused on geophysical imaging of structures and magma bodies below the Puna region. On the other hand, the increase in availability of absolute and young ages, and/or inferences of Holocene volcanic activity, is currently changing the way the scientific community approaches this region in terms of volcanic hazard and risk.

Unlike Chile, Peru, and Bolivia, there has not been any confirmed historical eruption of northern Argentine volcanoes, and hence, no direct link between volcanism and a change or increase in research and/or monitoring can be made. However, ground deformation detected at Cerro Blanco caldera (Fig. 1) sparked subsequent research which demonstrated that Cerro Blanco produced one of the largest, possibly VEI 7, Holocene eruptions on Earth, becoming a "key site" towards understanding the activity of potentially active calderas. On the other hand, as a consequence of several eruptions that occurred in the last decade in the Southern Volcanic Zone of the Andes (e.g., Cordón Caulle, Copahue, Calbuco), the Argentinian Observatory of Volcanic Surveillance (OAVV) was created by the Argentinian Geological Survey (SEGEMAR) in 2019. However, to date there has been no installed permanent volcanic monitoring on northern Argentine volcanoes. However, the Volcanic Ash Advisory Center (VAAC) located in Buenos Aires provides permanent satellite surveillance to detect and track volcanic plumes for all volcanoes of the CVZA and associated air space.

### Chile

Volcanology research in northern Chile became more frequent during 1970s, and especially during the 1980s. This research was focused on the petrogenesis of eruptive products at regional and local scale, and the geochronology and stratigraphy of ignimbrites (see references in Online Resource 3). However, during the 1990s research expanded to other topics including tectonic evolution of the CVZA, basement geochemistry and its influence on the magma evolution, and especially, understanding the evolution and eruptive activity of Lascar volcano (Fig. 1), which entered a dome growth-and-collapse cycle between 1986 and 1994. In the period 2000–2019 research was expanded further to several topics which included the following:

(1) evolution, stratigraphy and geochronology of calderas and their related ignimbrites
(2) tectonic evolution of the volcanic arc
(3) geological evolution and petrogenesis of stratovolcanoes
(4) monogenetic volcanism
(5) understanding the dynamics of Lascar volcano and its eruptive activity
(6) the origin of magnetite deposits of El Laco volcano

However, two key events have been the focused the research on Chilean volcanoes in this period:

(1) The discovery of ground deformation at Lastarria-Cordón del Azufre (Lazufre; Fig. 1), which produced a series of ground deformation and seismological studies, including the execution of the PLUTONS project mentioned above.
(2) The installation of capabilities to develop fluid geochemistry surveys, so as to determine the origin and nature of fumarolic fluids from persistently degassing volcanoes.

During 2000–2009, no permanent volcanic monitoring was carried out at northern Chilean volcanoes. However, after the Chaitén eruption in May 2008, the Chilean government created the National Volcanic Surveillance Network (RNVV) and increased the Volcanic Observatory of the Southern Andes (OVDAS) budget, taking charge of the volcanic surveillance along all of the Chilean territory (Amigo 2021). Northern Chilean volcanoes started to be monitored permanently in 2010, and 10 volcanoes have been monitored since 2013 (www.sernageomin.cl/gobiernotransparente). In 2018, the Nucleus on Volcanic Risk Research (Ckelar Volcanes) at Universidad Católica del Norte (UCN) was formed, initially with the objective of performing research at the northern Chile volcanoes with a focus on fluid geochemistry, volcanic mapping, volcanic seismology, and monogenetic volcanism (see references in Online Resource 3).

## Volcanology in the CVZA: updates, present and future work (2020–2030)

### Updates in the inventory of active/potentially active volcanoes

The first attempts to provide an official list of active volcanoes in the CVZA were carried out by Casertano (1963) and Hantke and Parodi (1966) for Chilean and Peruvian volcanoes, respectively. Further work dedicated to collating a list of all active volcanoes at a global scale was completed by IAVCEI (1973) and Siebert et al (2011), and in which the CVZA was also included. However, the first work to identify exclusively potentially active volcanoes of the CVZA was carried out by de Silva and Francis (1991) who, using and applying a combination of Landsat satellite images, field observations, and morphological criteria, identified 44 potentially active stratovolcanoes. This work has been valid for almost 30 years but has now been updated in Chile in 2011 (Lara et al 2011), followed by Argentina in the same year (Elissondo and Villegas 2011), and Perú in 2019 (Bromley et al 2019), with there being a second update for Chile in 2019 (SERNAGEOMIN 2019). In the case of Bolivia, the work of de Silva and Francis (1991) remains valid; although after Sparks et al. (2008), Uturuncu volcano was added to the potentially active volcanoes list. Following these most recent updates that resulted from new research carried out between 2000 and 2019, 62 volcanoes are currently considered as active/potentially active volcanoes in the CVZA (Fig. 1, Online Resource 4), of 52 correspond to stratovolcanoes (this being eight more than those listed in the de Silva and Francis (1991) inventory), seven monogenetic volcanoes or fields, two dome complexes, and one caldera.

### Present and future work (2020–2030)

In the case of Peru, two volcano observatories are currently active, CENVUL-IGP and OVI-INGEMMET, which work in coordination with the National Institute of Civil Protection (INDECI). The continuous activity of Sabancaya volcano, episodic explosions of Ubinas, and hazard/risk assessment and crisis management (especially in the city of Arequipa) has been the main research focus during 2020–2021. In the coming years, the priorities will be the following:

(1) to improve monitoring capabilities and networks (and to increase the number of volcanoes monitored)
(2) to determine the internal structures of Sabancaya, Misti, and Ubinas volcanoes (by use of combined geophysical methods)
(3) to assess pre-eruptive conditions prior to Ubinas' 2019 eruption and Sabancaya's 2016–2020 unrest.
(4) to study the evolution of Yucumane, Sara Sara, and Casiri volcanoes
(5) to assemble the eruptive chronology of Yura and Andahua monogenetic fields

The Bolivian government has no plan to install a volcano observatory to monitor volcanoes for the next few years, due to the lack of interest from the local government regarding the volcanic risk. However, UMSA is currently studying two major explosive eruptions (Turaquiri and Lauca-Perez ignimbrites), which could affect the local climate, and is planning to acquire instrumentation (seismometers, GPS, total stations, and drones) to carry out independent research. The first attempts to perform a formal collaboration between Bolivian and Chilean universities started in 2021, with the aim of producing collaborative efforts on border volcanoes, mainly to improve and/or produce new geological maps, and to determine the evolution of those volcanoes.

Until 2021, no monitoring networks had been actively deployed on north Argentina volcanoes. However, the OAVV-SEGEMAR plans to extend monitoring to northern Argentina in the coming decade (2020–2030), although there is no information about the starting date, and budget involved (García and Badi 2021).

Although OVDAS-SERNAGEOMIN currently monitors 10 volcanoes in northern Chile, no improvement plans have been declared in order to increase the number of volcanoes monitored and improve the current monitoring network. On the other hand, during 2020, the Nucleus on Volcanic Risk Research (Ckelar Volcanes) was officially recognized by the UCN as a formal research group, which have focused their efforts in the volcanism of northern Chile in order:

(1) to understand the distribution and evolution of monogenetic volcanism
(2) to establish the geological evolution of stratovolcanoes
(3) to determine the origin, nature, and evolution of fumarolic fluids from persistent degassing volcanoes
(4) to establish the relationship between tectonics and the distribution of the volcanism
(5) to understand the seismic behavior of active volcanoes
(6) to assess volcanic hazards and risks
(7) to provide an effective action plan between the volcanological community, authorities and the local community, in order to improve the crisis management in the case of future eruptions. Additionally, Ckelar Volcanes has increased the investment in instrumentation with the objective to provide more capabilities for monitoring in real-time

## Conclusions

Although during the early 2000s, most of the research in the CVZA was carried out by foreign researchers, and the investment from CVZA countries was very limited (Fig. 2), eruptive episodes at Sabancaya and Ubinas volcanoes encouraged the creation of two observatories in Peru. Instead, observatories in Chile and Argentina were installed after several eruptions at volcanoes along the southern Chile/Argentina bordering volcanoes. Additionally, detection of deformation

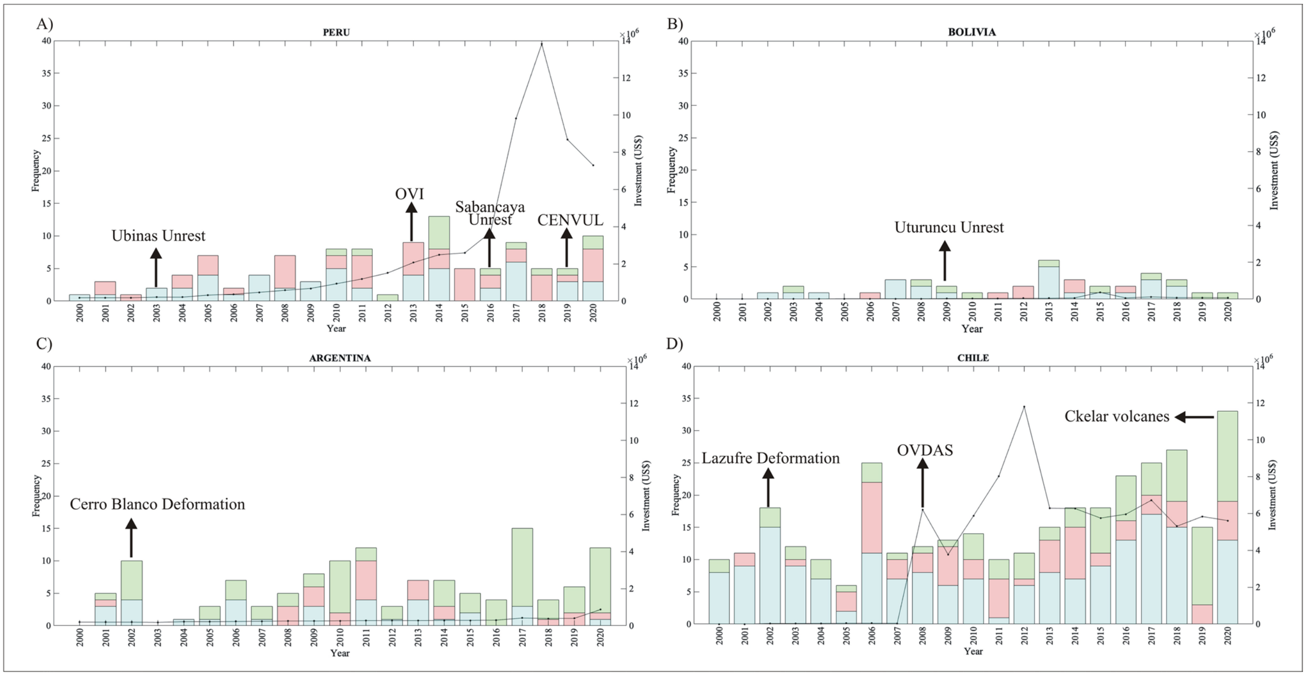


**Fig. 2** Histograms of ISI/WoS articles published per year related to each CVZA countries. Light blue: only foreign authors; light red: participation of local researchers; light green: local researcher first author. The black line shows the investment in research and monitoring of each country. Most relevant volcanic events or creation of new institutions are also indicated

on Hualca-Hualca, Uturuncu, Cerro Blanco, and Lazufre volcanoes (Pritchard and Simons 2002) promoted regional research by creation of research initiatives such as PLUTONS and Ckelar Volcanes, and new research projects from institutes and universities in Argentina (Fig. 2). These initiatives have allowed improvement of monitoring networks, generation of new knowledge on previously unknown volcanic systems, and updates and constraints on ages and extents of eruptions. Although promising research plans in most of the CVZA countries are projected for the following years, the remote location of the volcanic areas, low population density, and lack of infrastructure close to the volcanoes, as well as the relatively low eruptive frequency in the CVZA, have been used as arguments by local authorities to not promote or provide investment in monitoring and research. This attitude to funding is especially critical in the cases of Bolivia and Argentina, and partially in Chile.

The most important lesson learned in the period reviewed has been the improvement of the collaborative work between CVZA countries by signing of formal agreements, which have been facilitated by the integrative network created by the Latin American Volcanological Association (ALVO), created in 2010. In 2018, the agreement between SEGEMAR and SERNAGEOMIN promoted development of integrated maps for bordering volcanoes and integration of monitoring networks. This initiative, although started for only the southern Chile/Argentina volcanoes, is expected to be expanded to the north in the future. Agreements between IGP-UCN and INGEMMET-UCN were signed in 2019 and 2021, respectively, provide technical and scientific support, technology and data transfer, training of new volcanologists, hazard and risks assessment, and outreach. An "old" UNSA-UCN agreement which dates from the late 1980s has allowed the development of an International School of Volcanology in the Central Andes which has covered Argentinian and Chilean volcanoes. Finally, the first Symposium on the Central Volcanic Zone of the Andes was carried out in a virtual mode during July 2021, as organized by INGEMMET, IGP, UNSA, Fundación Miguel Lillo, and UCN. This was a first attempt to integrate the CVZA countries for a further collaborative research. All of these collaborations and integrated work, which will be expanded in the following years, have the aim of increasing the regional research capabilities and knowledge of the CVZA in the future.

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