Andean Geology 51 (2): 379-412. May, 2024
doi: 10.5027/andgeoV51n2-3681

Andean Geology
www.andeangeology.cl

REVIEW ARTICLE

The Andean Southern Volcanic Zone: a review on the legacy of the latest volcanic eruptions

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ABSTRACT. The Andean Southern Volcanic Zone (SVZ) concentrates many of the most active volcanoes of the Andean continental arc, as well as the region's most recent and impactful volcanic eruptions. In this contribution, we briefly revise the general characteristics of the SVZ volcanism and provide a synthesis of the scientific findings related to the latest volcanic eruptions (<35 years) in this arc segment. These eruptions alone have inspired >430 peer-reviewed publications with over 9,000 citations, with large-magnitude (VEI 4-5) eruptions being the most studied. Our study shows that SVZ research has been primarily focused on environmental and atmospheric impacts (29%), eruption descriptions and physical volcanology (20%), volcanic hazard and risk assessments (15%), and other investigations complementary to volcanology. Whereas the least silicic eruptions (*e.g.*, Llaima 2008-2009 and Villarrica 2015) shed light on magma replenishment and degassing dynamics controlling eruption styles, intermediate eruptions (andesitic-dacitic) offered clues on either rapid or slow eruption initiation, with relevant findings on phreatic-to-magmatic style transitions and eruption triggering mechanisms. On the other hand, silicic (*i.e.,* rhyolite-rhyodacite) eruptions provided unique observations on rapid magma ascent, high-rate magma extrusion, rheology, fragmentation processes, and style transitions. These recent eruptions have also inspired a new generation of tephrochronological, tephrostratigraphical, and physical volcanology studies, aimed at assessing the long-term (kyr-scale) evolution of the volcanic systems and their associated hazards. We debate how the knowledge gained from research and the long-term human coexistence with volcanoes are relevant to reducing volcanic risk in the SVZ. Finally, we discuss how challenges and opportunities emerging from other disciplines can complement our understanding of volcanism in this active region.

Keywords: Volcanic eruptions, Volcano monitoring, Volcanic ris, Southern Andes, Chile, Argentina.

RESUMEN. La Zona Volcánica Sur de los Andes: una revisión sobre el legado de las últimas erupciones volcánicas. La Zona Volcánica Sur de los Andes (ZVS) concentra muchos de los volcanes más activos del arco continental andino, así como las erupciones volcánicas más recientes y disruptivas de la región. En esta contribución se revisan brevemente las características generales del volcanismo de la ZVS y se provee una síntesis de los hallazgos científicos referentes a las últimas (<35 años) erupciones volcánicas en este segmento. Estos eventos han inspirado al menos 430 publicaciones revisadas por pares que suman más de 9 mil citas, donde aquellas con índice de explosividad volcánica (IEV) 4-5 han sido las más estudiadas. Investigaciones científicas en la ZVS han estado enfocadas en los impactos ambientales y atmosféricos (29%), descripciones de erupciones y estudios de volcanología física (20%), peligros y riesgos volcánicos

(15%), y estudios enmarcados dentro de otras disciplinas complementarias a la volcanología. Trabajos sobre las erupciones más máficas en la región (*e.g.,* Llaima 2008-2009 y Villarrica 2015) han permitido profundizar acerca del control que las recargas magmáticas y las dinámicas de desgasificación ejercen en los estilos eruptivos. Estudios en erupciones de composiciones intermedias (*i.e.,* andesíticas-dacíticas) han provisto antecedentes sobre el inicio rápido o lento de estas, con hallazgos relevantes acerca de las transiciones de estilo eruptivo freático a magmático y sus mecanismos desencadenantes. Investigaciones enfocadas en erupciones silíceas (*i.e.,* riodacíticas-riolíticas) han proporcionado observaciones únicas en el mundo sobre elevadas tasas de ascenso y extrusión magmática, características reológicas, procesos de fragmentación magmática y transiciones de estilo eruptivo. Estas erupciones recientes han también inspirado nuevos estudios tefrocronológicos, tefroestratigráficos y de volcanología física enfocados en la evolución de los sistemas volcánicos en el largo plazo (del orden de miles años) y sus peligros asociados. Se provee también una discusión acerca de cómo el conocimiento adquirido a partir de la investigación y la coexistencia de las comunidades con los sistemas volcánicos es clave en la reducción del riesgo volcánico en la ZVS. Finalmente, se discuten cómo los desafíos y las oportunidades surgidas desde otras disciplinas pueden ayudar a complementar el entendimiento del volcanismo en esta región.

Palabras clave: Erupciones volcánicas, Monitoreo volcánico, Riesgo volcánico, Andes del Sur, Chile, Argentina.

1. Introduction

The Andes is an ~8,000 km-long, continuous mountain range formed by the subduction of the Nazca, Antarctic, and Scotia oceanic plates beneath the continental lithosphere of South America. During the last ~25 Myr, the spreading rate across the Pacific-Nazca plate boundary has been among the fastest on Earth, reaching 145±4 mm/yr around 30° S (DeMets *et al.*, 2010). This has driven an oblique convergence of the Nazca Plate at rates >66 mm/yr between ~7 and 46° S (Angermann *et al.*, 1999; DeMets *et al.*, 2010), that ultimately controls the dehydration of the subducting slab and mantle metasomatism to produce partial melts. The resulting Andean volcanic arc has been conceptually divided into four Quaternary active segments, all separated by regions that lack modern volcanic activity. These segments are the Northern (NVZ; 5°N-2°S), Central (CVZ; 13-27° S), Southern (SVZ; 33-46° S), and Austral (AVZ; 49°-55° S) volcanic zones (Stern, 2004) (Fig. 1).

The northernmost SVZ is part of a prominent orogen (<7,000 m a.s.l. at ~33° S) that decreases in altitude towards the south (<2,000 m a.s.l. at ~40°S), from where volcanoes stand out from the rest of the mountains. Compared to the CVZ and the AVZ, the SVZ concentrates the largest volcanic edifices, the highest number of reported eruptions since the European colonisation (mid-16th Century), and the largest eruptions in Holocene times (Simkin and Siebert, 1994; Stern, 2004; Stern *et al.,* 2007). The SVZ hosts a total of 57 active volcanoes, primarily located along the western flank of the Andean range (Amigo, 2021; García and Badi, 2021) (Fig. 1). Here, the term "active volcano" includes all the volcanoes with Holocene eruptive activity or instrumentally recorded signs of unrest, such as active degassing, seismicity, or surface deformation (Szakács, 1994; Lara *et al.*, 2021). Of the 57 SVZ volcanoes, 41 are based in Chile, 9 in Argentina, and 7 are on the international border between these two countries. The SVZ comprises 55 and 42% of the Chilean and Argentinian active volcanoes, respectively.

Several reviews focused on SVZ volcanism have been written in the last decades (*e.g.*, Stern, 2004; Stern *et al.*, 2007; Tilling, 2009). However, particularly in the last ~15 years, volcanic eruptions in this arc segment have been systematically studied by the volcanological community, producing mounting evidence stored in a wide variety of formats. As these studies have provided new insights and ideas about volcanic processes and their associated impacts, some with worldwide implications, a holistic review for an up-to-date understanding of the SVZ volcanism is deemed necessary. In this contribution we therefore briefly revise the main characteristics of the SVZ, including their tectonic setting, arc segmentation, and petrogenesis. Our main goal is to assess the influence of recent (<35 years) SVZ eruptions on scientific production and their legacy for a deeper understanding of SVZ volcanism, specifically regarding to eruption mechanisms, dynamics, and impacts. We also provide a local retrospect on the progress of volcanology, volcano monitoring, and exposure and social vulnerability to critically discuss possible further steps for disaster risk reduction. Our review finally deals with aspects of the SVZ that are yet understudied, and which could offer valuable insights to a broader understanding of volcanism. While this work does not intend to be an exhaustive review of all existing SVZ literature it does provide

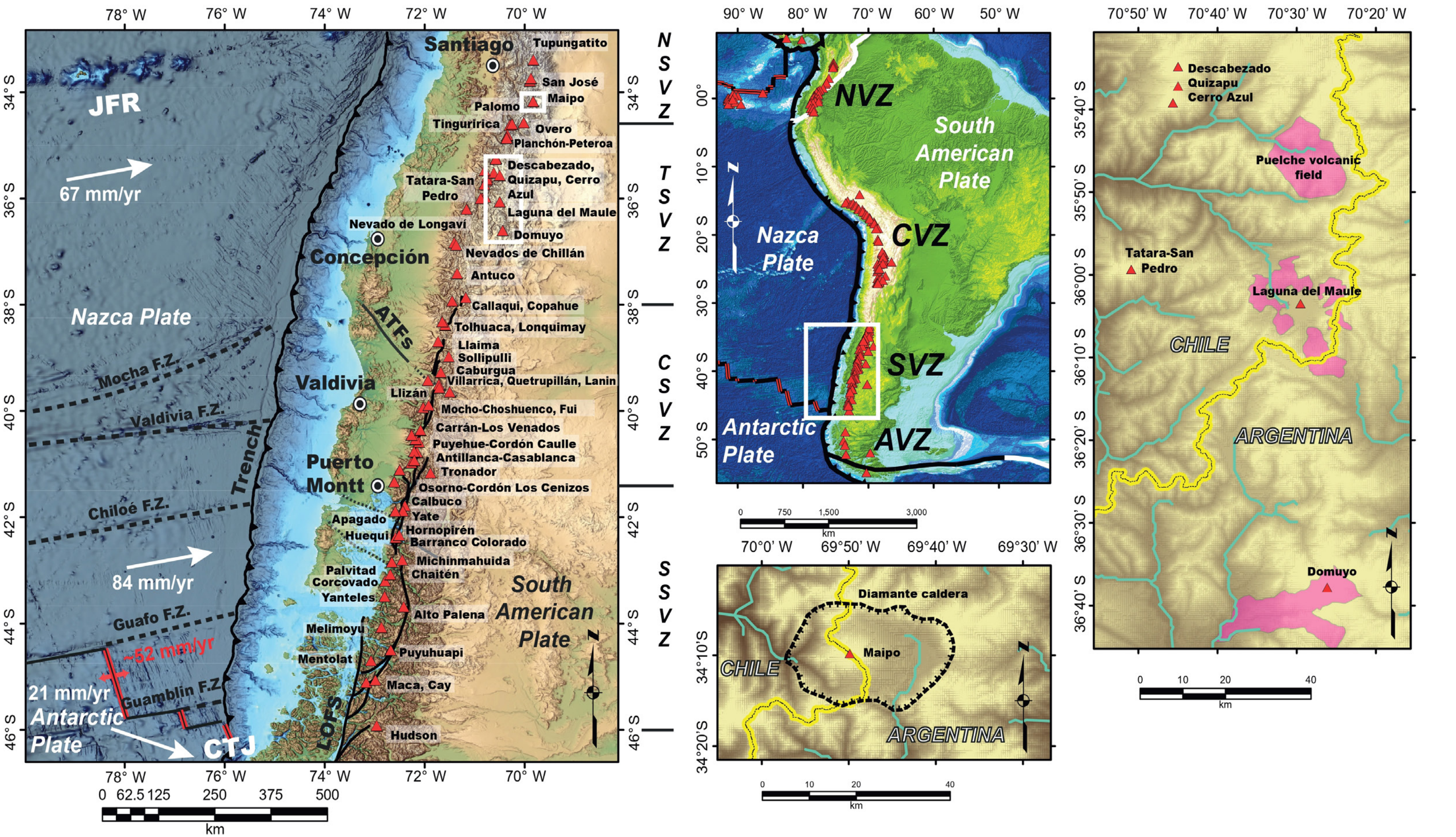

FIG. 1. Tectonic setting of the SVZ. **A.** Map of the SVZ, its active stratovolcanoes and volcanic complexes (red triangles). SVZ segmentation after Hickey-Vargas *et al.* (2016). The Liquiñe Ofqui Fault System (LOFS) and the major Andean Transversal Faults (ATFs) are also indicated. Thick black dotted solid lines in the Nazca plate represent fracture zones (Weller and Stern, 2018). Plate motion rates and azimuths (arrows) from Kendrick *et al.* (2003), DeMets *et al.* (2010), and Jia and Wei (2021). Base topography from ETOPO Global Relief Model-Bedrock 30 arcsecond hillshade (NOAA National Centers for Environmental Information, 2022)[1]. **B.** Close up of the Diamante caldera and Maipo volcano. **C.** Distribution of rhyolite-dominated volcanoes in the Transitional Southern Volcanic Zone, based in Hildreth *et al.* (1999, 2010) and Silva-Fragoso *et al.* (2021). The central, unlabelled map in the figure offers background tectonic information of the Andean volcanic arc and its active segments (Northern, NVZ; Central, CVZ; Southern, SVZ; and Austral, AVZ).

[1] NOAA National Centers for Environmental Information. 2022: ETOPO 2022 15 Arc-Second Global Relief Model. NOAA National Centers for Environmental Information. https://doi: 10.25921/fd45-gt74. Accessed on 10/05/2023.

a refreshed compendium of peer-reviewed sources and the learnings arisen from SVZ recent eruptions based on 328 contributions cited in this work.

2. The Andean Southern Volcanic Zone

2.1. Tectonic setting

The SVZ is limited to the north (~33° S) by the Pampean flat slab segment, traditionally associated with the subduction of the Juan Fernández Ridge (JFR), an oceanic hotspot track (Fig. 1A) that represents a thicker oceanic lithosphere with increased buoyancy (Espurt *et al.*, 2008; Porter *et al.*, 2012; Pilger, 2024). At the other end (~46° S), the southern limit of the SVZ is marked by the Chile Triple Junction, a place where the Nazca-Antarctica active Chile Ridge meets the western margin of South America (Fig. 1A). While north of 33° S, the oceanic slab subducts at an angle of 30° near the trench and then flattens to <10° at slab depths of 100-150 km for several hundred kilometres east, between 33 and 36° S the slab subducts at an angle of 25-30° (Cahill and Isacks, 1992; Anderson *et al.*, 2007) and 30-33° further to the south (Lange *et al.*, 2007). Along the SVZ segment (33-46° S), the Nazca plate subducts at a rate of ~67-84 mm/yr (Fig. 1A; Kendrick *et al.*, 2003; Jia and Wei, 2021).

The oceanic crust is pervasively fractured by bending-related normal faults and fracture zones that facilitate fluid percolation to mantle depths, weakening the oceanic lithosphere prior subduction (Fig. 1; Ranero *et al.*, 2005). In the continent, two regional fault arrangements accommodate the strain partitioning due to oblique convergence: the Liquiñe-Ofqui Fault System (LOFS), and the Andean Transverse Faults (ATFs). The LOFS is a NS- to NNE-striking intra-arc fault system of continental scale (~1,200 km long) with dextral and dextral-reverse kinematics, and minor NE- to ENE-striking secondary faults with dextral, dextral-reverse, and dextral-normal kinematics (Cembrano *et al.*, 1996, 2000; Arancibia *et al.*, 1999; Lavenu and Cembrano, 1999; Lange *et al.*, 2008; Roquer *et al.*, 2022). The ATFs are NW-SE faults striking 30 to 60° away from the main trend of the arc (Stanton-Yonge *et al.,* 2016). Altogether, these regional fault systems are first-order factors controlling most of the distribution and nature of the SVZ volcanism (Cembrano and Lara, 2009). While the NE- and ENE-trending volcanic structures are associated with tension fractures, extensional-shear fractures, or tail cracks, along with more primitive magmas erupted, the NW-trending, ATF-related volcanic structures can serve as transient magma pathways allowing the eruption of more evolved magmas (López-Escobar *et al.*, 1995; Cembrano *et al.*, 1996; Cembrano and Lara, 2009; Stanton-Yonge *et al.*, 2016). The intersection of ATFs structures with LOFS structures are considered high-permeability and structural damage zones that may facilitate the emplacement of volcanic centres, hydrothermal systems, intrusive bodies, and Cu-Mo-Au ore deposits (Roquer *et al.*, 2017; Piquer *et al.*, 2019; Pearce *et al.*, 2020; Vigide *et al.*, 2020; Pérez-Estay *et al.*, 2023). According to Lara *et al.* (2008), LOFS master faults with visible vertical offsets display numerous small eruptive centres on top, probably formed after transient vertical adjustments, either by isostatic rebound or transpressional-induced uplift. In these areas, monogenetic cones exhibit ~NE-SW elongated bases, a direction that coincides with the maximum regional stress direction (Lara *et al.*, 2008). Analogous modelling has shown that transpressional deformation is distributed between 34 and 42° S in the SVZ, as indicated by margin-parallel dextral oblique-slip thrust faults and sinistral oblique-slip reverse faults (Eisermann *et al.*, 2021). This observation defies the hypothesis of kinematic partitioning and deformation localised in a few margin-parallel faults, particularly along the LOFS (*e.g.*, Arancibia *et al.*, 1999; Cembrano *et al.*, 1996), and prescinds from margin-oblique, pre-Andean crustal structures behind the emplacement of volcanic chains.

In the region, the occurrence of megathrust earthquakes recorded since ~1550 CE has temporarily increased the number of eruptions in volcanoes located up to 500 km from the limits of their rupture zones (Watt *et al.*, 2009a), most likely by inducing static stress changes in volcanoes with shallow magma chambers under unclamping or very weak clamping conditions (Bonali *et al.*, 2013). One of the most famous examples of the relationship between megathrust earthquakes and volcanic eruptions is the 1960 Puyehue-Cordón Caulle Volcanic Complex (PCCVC) eruption, which took place ~38 h after the M_w 9.5 Valdivia earthquake (Lara *et al.*, 2004). Additionally, ground deformation and increased degassing have been observed at active SVZ volcanoes after megathrust earthquakes (*e.g.*, Tinguiririca, Planchón-Peteroa, Cerro Azul, and Nevados de Chillán; Pritchard *et al.*, 2013). Complementary studies have shown that the state of the volcano before the main shock, the geometry of the volcano's fault system, and the incidence angle of the incoming seismic energy are relevant factors controlling the volcanic response after large-magnitude earthquakes (Farías *et al.*, 2014; Bonali *et al.*, 2015; Farías and Basualto, 2020). NW-striking faults (*i.e.,* ATFs) can be affected by transient stress changes induced by megathrust earthquakes, affecting magma ascent and eruption (*e.g.,* Lupi *et al.,* 2020; Franco-Marín *et al.*, 2023).

2.2. Volcanic arc segmentation

Several studies have recognised and characterised along-arc geochemical variations in the SVZ. Initially, Moreno (1975, 1976) proposed a segmentation of the SVZ into Northern (33-37° S) and Southern (37-46° S) based on petrographic characteristics and magma compositions. Since then, more detailed segmentations have been postulated based on geochemical, petrological, and tectonic criteria (Hickey *et al.*, 1984, 1986; Stern *et al.*, 1984; Hildreth and Moorbath, 1988; Stern, 1991; Tormey *et al.*, 1991; López-Escobar, 1993, 1995; Dungan *et al.*, 2001; Naranjo and Stern, 2004). Along-arc geochemical variability has been explained by lower-crust differentiation (*e.g.*, Hildreth and Moorbath, 1988), source-region contamination by terrigenous±pelagic sediments and intra-crustal contamination (Stern *et al.*, 1984; Stern, 1991), and different degrees of mantle melting or chemical variations in the mantle column (*e.g.*, Tormey *et al.*, 1991). Recently, Hickey-Vargas *et al.* (2016) suggested that the main controlling factors behind this geochemical variability are the thickness of the continental crust and mantle lithosphere, and the heterogeneities of the subducting Nazca plate and overlying asthenosphere (for example, an enriched or depleted mantle asthenosphere). Based on the observed along-strike REE and isotope geochemical variations, and considering also the role of the LOFS in the control of volcanism, Hickey-Vargas *et al.* (2016) proposed a new segmentation for the SVZ: Northern (NSVZ; 33-34.5° S), Transitional (TSVZ; 34.5-38° S), Central (CSVZ; 38-41.5° S) and Southern (SSVZ: 41.5-46° S) (Fig. 1A). The Moho becomes shallower from north to south (average depth of ~50 km under the NSVZ to ~40 km under the SSVZ), as does the depth of the intracrustal discontinuity (from ~10 to 5 km; Tassara and Echaurren, 2012). Interestingly, magma storage depths for the main stratovolcanoes become increasingly deeper towards the south (Bechon *et al.*, 2022).

The age of the subducting plate, which decreases southwards, does not significantly influence magma extrusion rates, and presumably, the hottest slab segments are not necessarily the more magmatically productive (Völker *et al.*, 2011). For example, in the Hickey-Vargas *et al.* (2016) SVZ segmentation scheme, the TSVZ volcanoes show the lowest magma production rates because of protracted asthenosphere melt interaction with the mantle lithosphere.

2.3. Petrogenesis

The wide range of magma compositions erupted in the SVZ -from basalts to rhyolites- has been explained by fractional crystallisation of basaltic magmas, upper-crustal assimilation, and/or mixing between basaltic and rhyolitic magmas (Hickey *et al.*, 1984, 1986; López-Escobar, 1984, 1993; Rudnick, 1995; Singer *et al.*, 2008; Hickey-Vargas *et al.*, 2016).

The basaltic magmas erupted in the SVZ contain signatures from the subducted oceanic lithosphere, subarc mantle, and continental crust (Hickey *et al.*, 1986). Regionally, the asthenospheric mantle wedge contains mobile elements (*i.e.,* $^{10}Be/^{9}Be$ and U-series isotopes; Hickey-Vargas *et al.*, 2002; Kilian and Behrmann, 2003) transferred from subducted pelagic sediments over diverse timescales (10^4-10^7 years). Hickey-Vargas *et al.* (2016) distinguished two types of SVZ basalts: Type 1, voluminous, subduction-related magmas fed by inputs from the subducted oceanic plate and asthenospheric melting; and Type 2, small-volume batches of magma produced by partial melting of aged, subduction-related pyroxenite in the subarc mantle. Their occurrence depends on the relative degree of fluid contribution from the subducting slab to the overlying asthenospheric wedge, or the interaction between asthenosphere-derived magmas with the continental lithosphere during ascent, the latter enhanced by the higher permeability around the LOFS.

At large, long-lived stratovolcanoes, mafic rocks can be either produced by water-poor (~1 wt.%) tholeiitic magmas, as in Osorno or Antuco (Martínez *et al.*, 2018; Bechon *et al.*, 2022), or by highly water-saturated magmas, as in Nevado de Longaví, Calbuco, Huequi, and Mentolat, which are probably the only ones whose products document hornblende and garnet fractionation from mafic magmas (Watt *et al.*, 2011; Hickey-Vargas *et al.*, 2016; Weller and Stern, 2018; Sellés *et al.*, 2022). The presence of hydrous minerals indicates relatively high-water contents in the subarc mantle, probably due to the subduction of a locally fractured oceanic crust (Weller and Stern, 2018; Sellés *et al.*, 2022). At stratovolcanoes, mixing between different magma batches has influenced the evolution of their magma suites (*e.g.*, Mella, 2009; Schindlbeck *et al.* 2014; Boschetty *et al.*, 2022). In contrast, magmas erupted at isolated clusters of small eruptive centres (*e.g.*, Caburgua-Huelemolle, Carrán-Los Venados, and Fui) have undergone variable crustal contamination prior to olivine crystallisation, and show evidence of more extensive partial melting at their source regions followed by a rapid ascent, possibly due to a high fluid input from the subducting slab (Hickey-Vargas *et al.*, 2002; Bucchi *et al.*, 2015; Morgado *et al.*, 2015; McGee *et al.* 2017; Mallea-Lillo *et al.*, 2022). These clusters are associated with shallow transient magma reservoirs whose eruptibility depends on magma input rates (Morgado *et al.*, 2017). Rawson *et al.* (2016a) recognised that small eruptive centres around the Mocho-Choshuenco composite stratovolcano become more mafic with distance from it because of fractional crystallisation processes. In addition, small eruptive centres lying east of the main volcanic arc front are enriched in incompatible elements, probably due to unmixed primitive melts arising through relatively peripheral reactive channels in the mantle wedge (Rawson *et al.*, 2016a).

Although most mafic products have erupted as lavas, with relatively low production of tephra, mafic ignimbrites are recognised at Llaima and Villarrica volcanoes (*e.g.*, Naranjo and Moreno, 1991; Clavero y Moreno, 1994; Lohmar *et al.*, 2007, 2012; Silva Parejas *et al.*, 2010; Marshall *et al.*, 2022; Valdivia *et al.*, 2022). Rapid magma ascent, magma mixing events, and magma-water interaction have been invoked to explain the exceptionally explosive nature of those mafic eruptions (*e.g.*, Lohmar *et al.*, 2012; Pioli *et al.*, 2015; Valdivia *et al.*, 2022).

In the region, the formation of andesitic magmas has been attributed to the mixing of primitive magmas and lower crustal components, either during magma ascent or at the mantle source region by subduction processes (Stern *et al.*, 1984; Hildreth and Moorbath, 1988). Other studies argue that andesitic and dacitic magmas are produced by polybaric fractional crystallisation of initially mafic magmas (for example at Nevado de Longaví, Nevados de Chillán, and Descabezado-Quizapu; López-Escobar *et al.*, 1997; Rodríguez *et al.*, 2007; Ruprecht *et al.*, 2012; Oyarzún *et al.*, 2022). The existing magmatic reservoirs can be affected by occasional mafic recharge events, which can sometimes drive Plinian eruptions, as in the Quizapu (Ruprecht, *et al.*, 2012) and Mocho-Choshuenco (Feignon *et al.*, 2022) volcanoes via "recharge filtering", a model usually applied to arc settings (Kent *et al.*, 2010; Kent, 2014). The fractionation of parent magmas, assimilation of crustal rocks, and mixing processes within multiple shallow crustal reservoirs can also produce andesites and dacites, as in the Tatara-San Pedro (Davidson *et al.*, 1987, 1988; Dungan *et al.,* 2001; Ferguson *et al.*, 1992; Singer *et al.*, 1997) and Lonquimay (Gilbert *et al.*, 2014) volcanoes. Despite the thinning of the continental crust towards the south, crustal assimilation, particularly at lower crustal depths, is still a relevant mechanism for intermediate magma production (*e.g.*, Hildreth and Moorbath, 1988; McMillan *et al.*, 1989). Calbuco volcano represents an unusual case, as it presents a stationary storage zone at intracrustal discontinuity depths (after Tassara and Echaurren, 2012), where the primary basaltic magmas fractionate to form andesites and eventually dacites prior to volatile saturation and eruption (Vander Auwera *et al.*, 2021).

The most evolved magmas from the SVZ, rhyodacites to rhyolites, have been recognized at the Diamante Caldera and at the Descabezado-Quizapu, Laguna del Maule, Puelche, Domuyo, PCCVC, Chaitén, and Yate volcanoes (see Fig. 1 for locations). Trace element and isotopic compositions of the Pudahuel/Diamante Ignimbrite pumices (132±2 ka; Klug *et al.,* 2022) suggest a strong crustal component combined with extensive crystal fractionation (Stern *et al.,* 1984; Futa and Stern, 1988; Sruoga *et al.*, 2005, 2012; Holm *et al.*, 2011; Pineda *et al.*, 2021). At Laguna del Maule, parental basaltic magmas mixed with lower crustal components, forming a rhyolitic suite via mingling, mixing, hybridization, and fractional crystallisation in the upper crust (Andersen *et al.*, 2017). On the other hand, the rhyolites from the Puelche volcanic field fractionated from a hybrid parent rather than continuously from basaltic magmas (Hildreth *et al.*, 1999). These TSVZ rhyolites show higher crustal contributions than their southernmost SVZ counterparts (Hildreth *et al.*, 2010). In fact, the PCCVC and Chaitén silicic magmas formed by melt extraction from mafic crystal mushes, in some cases during a single-step differentiation at upper crustal depths (Singer *et al.*, 2008; Pallister *et al.*, 2013; Seropian *et al.*, 2021; Winslow *et al.*, 2022).

3. The SVZ as a knowledge hub for the volcanology community

3.1. The influence of the recent SVZ eruptions in the volcanological literature

We carried out a bibliometric analysis to provide a snapshot of the contributions of recent SVZ eruptions to the volcanological knowledge for the period 1989-2020. On 13 March, 2023, we searched in the Scopus database (https://www.scopus.com/search/form.uri?display=basic#basic) by entering the name of the volcano, adding "eruption" (or "erupción" to include results in Spanish), and filtering peer-reviewed contents related to confirmed eruptions according to the Global Volcanism Program catalogue (https://volcano.si.edu/search_eruption.cfm). We dismissed all publications focused on topics other than on these recent eruptions.

Nearly 430 peer-reviewed contributions have been published in scientific journals, accounting for >9,000 citations (see Supplementary Table 1 for a detailed description of each paper). These contributions show the widespread impact of SVZ eruptions in the scientific community. The most studied eruptions correspond, in decreasing order of publications, to the VEI 4-5 PCCVC (2011-2012), Chaitén (2008-2009), Calbuco (2015), and Hudson (1991) eruptions (Fig. 2A). Notably, scientific publications about Chaitén are the most cited (>2,700), followed by PCCVC (>2,000), and Hudson (>1,350). In comparison, the largest SVZ eruption of the 20th Century, the VEI >5 1932 Quizapu eruption, remains barely studied and poorly cited (Fig. 2A). On the other hand, modest (VEI ≤3) eruptions such as those at Lonquimay (1988-1990), Llaima (2008-2009), Planchón-Peteroa (2010-2011, 2018-2019), Villarrica (2015), and Nevados de Chillán (2016-2022) have been scarcely studied (<15 contributions each), despite their comparatively longer eruptive cycles. Of these, the only exception is the Copahue 2012-2021 eruptive cycle, with over 32 publications. All these VEI ≤3 eruption contributions show a similar number of citations (≤300). Paradoxically, while Villarrica ranks highest in the Chilean volcanic threat ranking (https://rnvv.sernageomin.cl/que-es-ranking-de-riesgo), scientific literature about its 2015 eruption remains limited and, in part, available as non-peer-reviewed contributions written in Spanish, which were not systematically considered in this article.

The journals that have hosted most of the revised contributions are the Journal of Volcanology and Geothermal Research (46), the Bulletin of Volcanology (29), and the Journal of Geophysical Research (23) (Fig. 2B). These journals are also the most cited regarding articles about recent eruptions. South American-specific journals, such as the Journal of South American Earth Sciences and Andean Geology are within the top 10 in the ranking of total contributions and citations (Fig. 2B), particularly because of special issue publications (*e.g.*, Agusto *et al.*, 2022). In general, papers about recent and impactful SVZ eruptions are published and cited within the first eight years after the event. Afterwards, these metrics show a more modest growth trend (Fig. 2C).

The SVZ eruptions have inspired works on a wide range of topics and fields, such as environmental and atmospheric impacts (29%), eruption descriptions and physical volcanology (20%), volcanic hazard and risk assessments (15%), remote sensing (15%), petrology and geochemistry (12%), and geophysics and structural geology (9%) (Fig. 3A). Figure 3B shows that the eruption descriptions and physical volcanology articles are the most cited with 34%, while environmental and hazard/risk-related studies together represent 36%. These numbers indicate that publications about recent SVZ eruptions with a focus on eruptive mechanisms, dynamics, and impacts (deepened in sections 3.2 and 3.3) are attractive to the volcanological community. Recent studies have also contributed to the understanding of the social dimensions of volcanic risk, such as territorial vulnerabilities, knowledge gaps, capacity-building, disaster policy, decision-making, volcanic risk perceptions, conflicts, and political tensions, among others (Radovich, 2013; Larenas, 2014; Espinoza, 2015; Romero and Romero, 2015; Sandoval *et al.*, 2015; Petit-Breuilh, 2016; Forte *et al.*, 2022, 2024; Alegría and Vergara-Pinto, 2024).

3.2. New perspectives on eruption mechanisms and dynamics

In the SVZ, recent mafic eruptions (*i.e.,* basaltic to basaltic andesite) brought a renewed understanding of magmatic systems feeding mildly explosive events. Direct observations provided chronologic descriptions of their development, eruptive phases, products, and hazards (*e.g.*, Moreno and Fuentealba, 1994; Romero *et al.*, 2014, 2018; Franco *et al.*, 2019). The 2008-2009

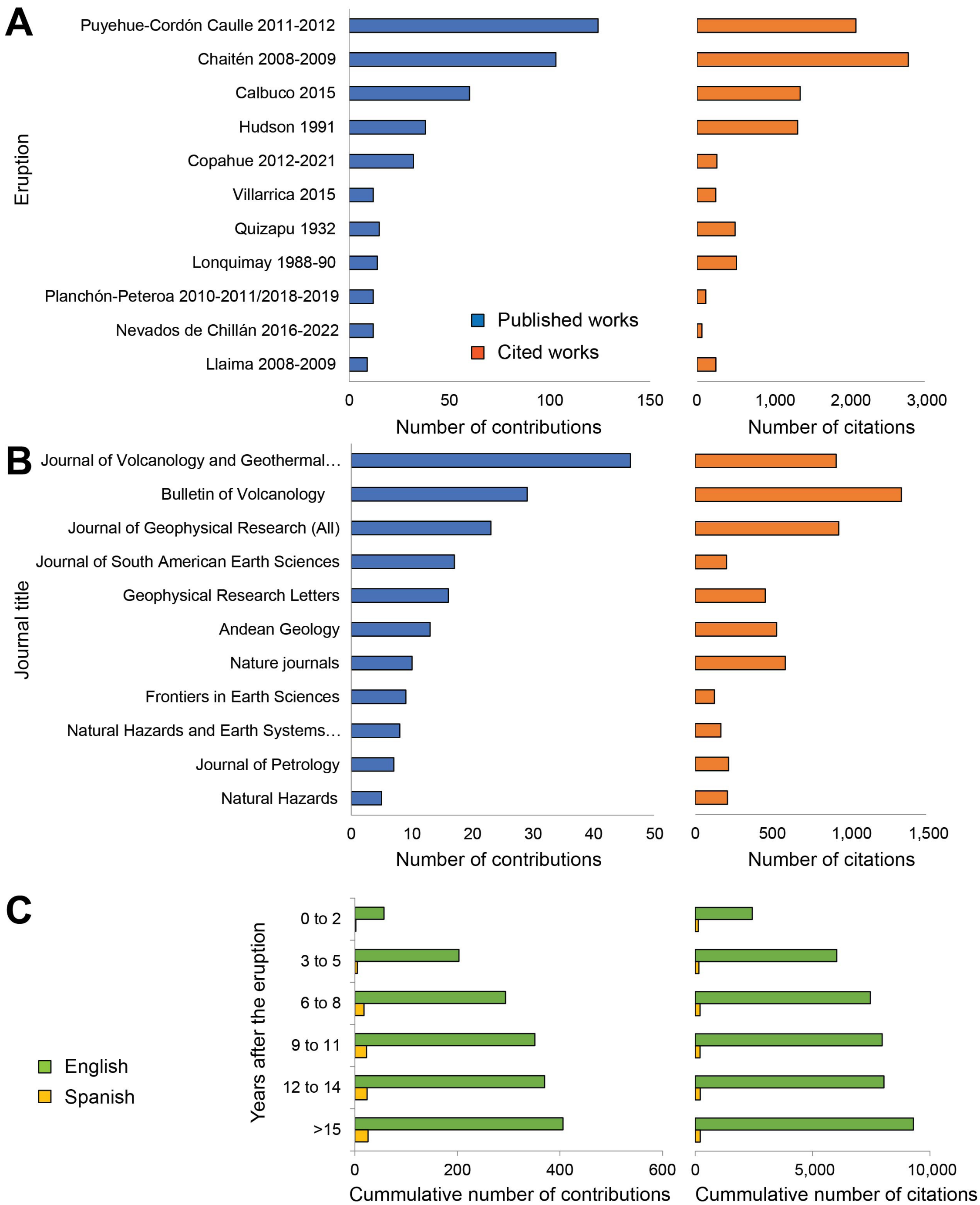

FIG. 2. Peer-reviewed publications related to recent volcanic eruptions in the SVZ (1932 Quizapu eruption is also included for comparison). **A.** Number of contributions and citations by eruptive event. **B.** Number of contributions and citations by journal. **C.** Trends of productivity and citations by language. Data acquired from Scopus on 13 March 2023.

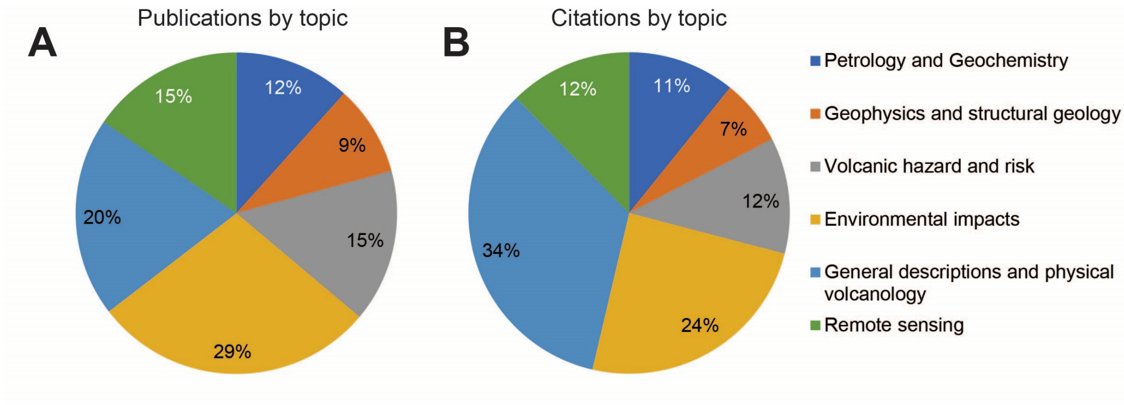

FIG. 3. Pie charts on the most published **(A)** and cited **(B)** topics for peer-reviewed articles on recent SVZ eruptions. Data acquired from Scopus on 13 March 2023.

Llaima volcano eruptions, and some of its previous eruptive cycles (Fig. 4A), involved a magmatic system that replenished regularly (Bouvet de Maisonneuve *et al.*, 2012); although in 2008-2009 the most explosive eruptive pulses occurred through extensive recharge events that remobilised the magma mush and the gas accumulated in the reservoir (Ruth *et al.*, 2016). A similar model was invoked for the 1921, 1948, and 1971 Villarrica eruptions (Pizarro *et al.*, 2019). These mechanisms imply that changes in the degassing system, and not necessarily rapid magma ascent rates, might control explosivity at open-vent volcanic systems (Ruth *et al.*, 2016; Aiuppa *et al.*, 2017; González-Vidal, 2022; Romero *et al.*, 2022). For instance, the rising of large gas slugs sourced an unsteady lava fountain at Llaima in 2008 (Ruth and Calder, 2014), whereas the steady, 1.5 km-high lava fountain of Villarrica in 2015 (Fig. 4B) likely resulted from a foamy magma flow in the conduit (Romero *et al.*, 2018). Such pre-eruptive changes can be long-term (months to years) and involve geophysical and surface precursory signals when reaching the shallow crust (*e.g.*, Aiuppa *et al.*, 2017; Ruth *et al.*, 2018; Franco *et al.*, 2019). Furthermore, lava lake samples from the 2015 Villarrica eruption were used by Moussallam *et al.* (2023) to set up a basaltic andesite geothermometer that can be applied to similar open-vent systems at anhydrous conditions.

Other mafic eruptive cycles, such as the 2000 and 2012-2021 at Copahue (Fig. 4C), the 1991, 2010-2011 and 2018-2019 at Planchón-Peteroa (Fig. 4D), or the 2011 short-lived eruption at Hudson, provided excellent natural examples of phreatic-to-magmatic eruptive transitions and a valuable opportunity to track them using volcanic ash sampling, petrology, remote sensing, and geophysics (*e.g.*, Naranjo and Haller, 2002; Naranjo and Lara, 2004; Naranjo and Polanco, 2004; Delgado *et al.*, 2014; Petrinovic *et al.*, 2014; Aguilera *et al.*, 2016; Caselli *et al.*, 2016; Daga *et al.*, 2017; Romero *et al.*, 2020a).

The mesosilicic (*i.e.,* andesite-dacite) SVZ eruptive products have also provided insights into magma storage, ascent, and eruption. For example, the sub-Plinian eruption of Calbuco in 2015 (Fig. 4E) which lacked clear precursors, involved rapid reservoir overpressuring either by a second boiling event driven by SO_2 and CO_2 exsolution (Pardini *et al.*, 2018; Arzilli *et al.*, 2019) or underplating of the magma chamber by a possibly mafic and hotter magma (Morgado *et al.,* 2019a, b). A combined model was also deemed plausible (Namur *et al.*, 2020). Similarly, the dacitic effusive eruption at Nevados de Chillán in 2008 lacked any relevant precursors (Coppola *et al.*, 2016). In contrast, the 2004 and 2016-2022 eruptions at this same volcano (Fig. 4F) offered great advantage to track a complete eruptive cycle, from its precursory signals and first surface manifestations of volcanic activity, through the progression of magmatic activity (lava extrusion and collapse), to its final waning stages (Moussallam *et al.*, 2018, 2021; Benet *et al.*, 2021; Cardona *et al.*, 2021; Astort *et al.*, 2022).

Scientists had not witnessed a rhyolite eruption before the 2008 Chaitén (Fig. 4G) and 2011-2012 PCCVC (Fig. 4H, I) events. Therefore, these eruptions offered a unique observational window to understand silicic volcanism. The 2008 Chaitén eruption demonstrated that high-silica eruptions

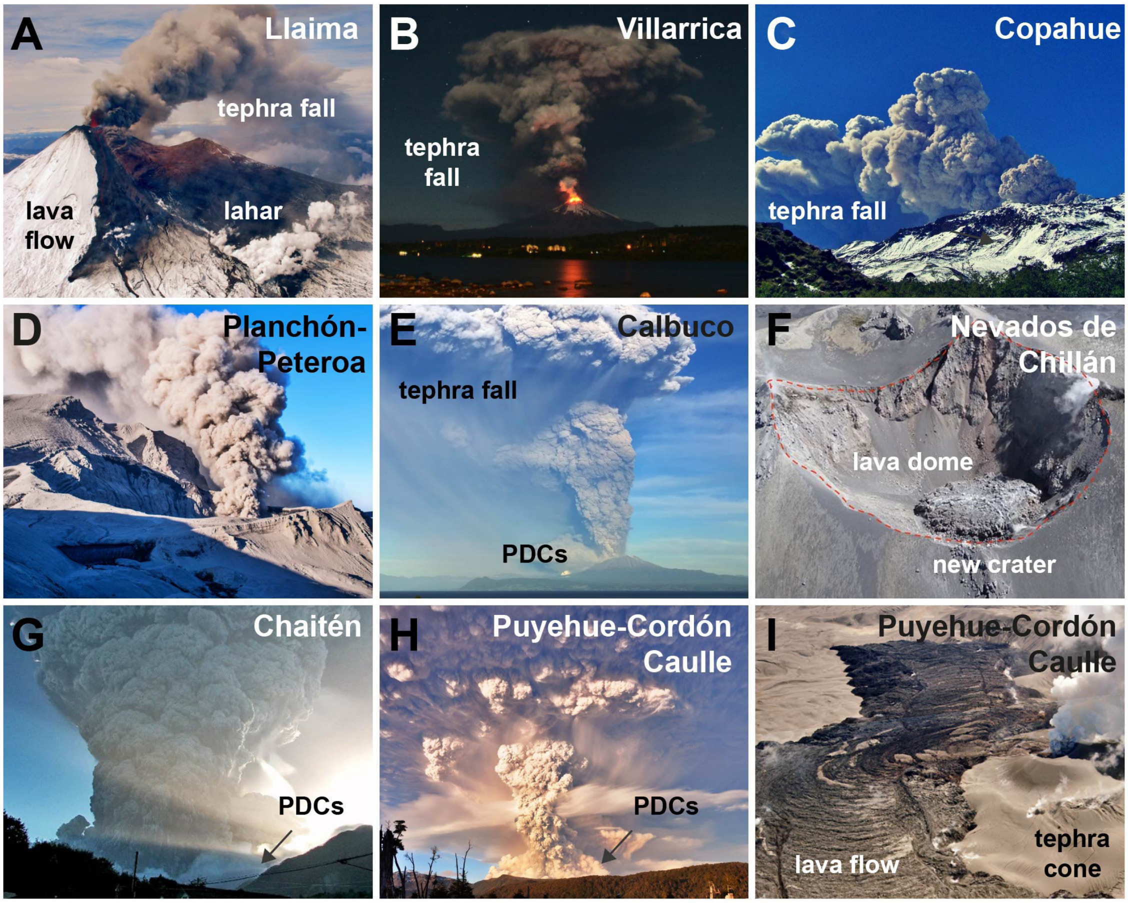

FIG. 4. Recent eruptions of SVZ volcanoes. **A.** Strombolian eruption at Llaima in 2009. **B.** Lava fountain at Villarrica in 2015 (J. Rodríguez). **C.** Phreatomagmatic eruption at Copahue in 2012 (M. Meriño). **D.** Phreatomagmatic eruption at Planchón-Peteroa in 2018-2019 (E. Berríos). **E.** Sub-Plinian Calbuco eruption in April 2015 (C. Valenzuela). **F.** Lava dome at Nevados de Chillán in 2017 (N. Luengo). **G.** Plinian eruption at Chaitén in May 2008. **H.** Sub-Plinian eruption at the PCCVC in June 2011. **I.** Hybrid silicic eruption at the PCCVC in February 2012. Photos A, G, and H by D. Basualto.

could be preceded by little warning as magma can ascend rapidly (~1 m/s), reaching the surface in a few hours (Castro and Dingwell, 2009; Wicks *et al.*, 2011) and without measurable ground deformation (Delgado *et al.*, 2022). At the PCCVC, high-silica magma erupted at relatively high temperatures through a dyke (~870-920 °C; Castro *et al.*, 2013). Petrologic experiments on Chaitén samples showed that magma H_2O content and temperature during magma-ascent driven decompression and vesiculation may dictate whether a high-silica eruption will have an effusive or explosive behaviour (Forte y Castro, 2019). Investigations at Chaitén carried out some years earlier (Alfano *et al.*, 2012) revealed that rapid decompression induced by the failure of the pre-existent dome ultimately triggered magma nucleation and explosive fragmentation. The Chaitén dome-forming stage also revealed unprecedentedly high extrusion rates (~65 m^3/s) for silicic magmas (Pallister *et al.*, 2013), an observation that was also recognized for the PCCVC rhyolitic lava flow emplaced in 2011-2012 (~70 m^3/s; Bertin *et al.*, 2015a). The simultaneous explosive-effusive activity observed in these two eruptions has challenged the classic models for silicic eruption dynamics (*e.g.*, Schipper *et al.*, 2013; Tuffen *et al.*, 2013; Wadsworth *et al.*, 2022). Mechanisms such as outgassing through magmatic fracturing and localized fragmentation and welding within the conduit may have played a role in sustaining hybrid activity and facilitating explosive-effusive transitions (Schipper *et al.*, 2021; Crozier *et al.*, 2022; Wadsworth *et al.*, 2022). Both silicic eruptions were likely sourced from multiple bodies of magma as suggested by geodetic data (Delgado *et al.*, 2022) or tephra geochemistry (Alloway *et al.*, 2015).

In terms of volcanic hazards, dilute PDCs (<200 °C) during the Chaitén eruption were both produced by eruptive column and lava dome collapse. and imprinted forest disturbance (Fig. 5A) with velocities up to 40 m/s (Major *et al.*, 2013; Swanson *et al.*, 2013). In contrast, little or no research has been carried out on the PDCs produced by the paroxysmal phase of the PCCVC eruption in 2011 (Fig. 5B). At Calbuco, PDCs occurred during the two eruptive pulses, reaching ~540-603 °C and velocities up to 36 m/s, which caused extensive damage to trees (Fig. 5C; Romero *et al.*, 2023). Mixed avalanches formed by the interaction between PDCs, spatter agglutinates and ice were observed and described in the recent Llaima and Villarrica (Bertin *et al.*, 2015b; Vera and Palma, 2017[2]; Breard *et al.*, 2020).

Tephra fall deposits are the most studied products from SVZ recent eruptions. Tephra dispersed and deposited during the Chaitén and PCCVC eruptions (Fig. 5D, E) caused extensive regional impacts and long-term episodes of ash remobilisation (Table 1; Martin *et al.*, 2009; Bonadonna *et al.*, 2015; Pistolesi *et al.*, 2015; Elissondo *et al.*, 2016; Forte *et al.*, 2018; Domínguez *et al.*, 2020). The 2015 Calbuco eruption produced heavy scoriaceous tephra (Romero *et al.*, 2016) that caused roof collapses at proximal areas (Fig. 5F; Hayes *et al.*, 2019). Although tephra deposited in Argentina during this eruption was <1 cm-thick, resuspension events exacerbated the impacts of primary fallout (Reckziegel *et al.*, 2016). The erupted volumes of these eruptions (Table 1) are modest compared to the Quizapu 1932 and Hudson 1991 eruptions, whose tephra deposits blanketed the extra-Andean region and reached the Atlantic Ocean, affecting multiple countries (Hildreth and Drake, 1992; Naranjo *et al.*, 1993; Scasso *et al.*, 1994; Wilson *et al.*, 2011). The Chaitén and Calbuco eruptions were accompanied by lahars with remarkable impacts on public and private property (Table 1; Fig. 5G, H).

3.3. Recognising past explosive eruptions

As summarized in Table 1, explosive SVZ eruptions have produced the most remarkable impacts on Andean communities. Recent eruptions have inspired detailed tephrostratigraphy and tephrochronology research in the SVZ, unravelling previously unknown eruptions and expanding the late Pleistocene-Holocene eruptive history of several volcanoes. These findings have refined our understanding of volcanic hazard and the long-term (kyr-scale) evolution of this volcanic segment. For the last ~25 kyr, at least 25 significant (≥1 km^3 non-DRE) explosive eruptions have so far been recognised from 18 individual SVZ volcanoes, with a predominant eastward dispersal of fallout deposits (Fontijn *et al.*, 2014). The records comprise four ignimbrite-forming eruptions (Licán, Curacautín, Amarillo, and Pucón; Lohmar *et al.*, 2007, 2012; Silva Parejas *et al.*, 2010; Amigo *et al.*, 2013; Marshall *et al.*, 2022; Valdivia *et al.*, 2022) and repeated, moderate-scale eruptions sourced from a few volcanoes (*e.g.*, Calbuco, Chaitén, Hudson). Records of large eruptions are more frequent between *ca.* 13.0 and 9.5 ka, and since *ca.* 4.5 ka (Fontijn *et al.*, 2016). Schindlbeck *et al.* (2014) recognised over 30 <15 ka-old eruptions at Llaima, whilst at PCCVC and Antillanca, Naranjo *et al.* (2017) identified five voluminous Holocene tephra deposits. In contrast with findings from previous studies, Chaitén repeatedly erupted in the last 10 kyr and produced at least five rhyolitic eruptions with non-DRE tephra volumes between 0.5 and 4.7 km^3 (Watt *et al.*, 2013). The total eruption record at Chaitén reaches 20 <18 ka-old eruptions, not all rhyolitic in composition (Alloway *et al.*, 2017). Another twelve, mostly historical eruptions, have been correlated and described in detail at Calbuco (Bertin *et al.,* 2021; Romero *et al.*, 2021).

During the last decade, the study of SVZ volcanoes also proved an extensive compendium of late Pleistocene-Holocene activity. At the Laguna del Maule volcanic complex, for example, at least three Plinian eruptions, three moderate explosive eruptions (*i.e.*, VEI 3-4) and one ignimbrite-forming eruption, all younger than 14 ka, were identified (Fierstein *et al.*, 2013). Further south, the tephrostratigraphic record at Antuco volcano revealed 23 mid-to-late Holocene explosive eruptions, three of them with sub-Plinian characteristics (Romero *et al.*, 2020b). Similarly, 27 <12 ka-old tephra deposits were described by Gilbert *et al.* (2014) at Lonquimay volcano. Mocho-Choshuenco revealed 34 postglacial (<18 ka) explosive eruptions, including three Plinian and another 40 cone-forming eruptions from peripheral small eruptive centres (Rawson *et al.*, 2015), revealing an unprecedented record of explosive volcanism that dramatically modifies the hazard evaluation.

2 Vera, F.; Palma, J.L. 2017. Avalanchas mixtas y depósitos proximales generados en la erupción de 2015 del Volcán Villarrica y su interacción con la cubierta glacial. VIII Encuentro Nacional de Estudiantes de Geología 28.

TABLE 1. GENERAL CHARACTERISTICS AND IMPACTS OF PLINIAN AND SUB-PLINIAN ERUPTIONS OCCURRED BETWEEN 1930 AND 2015 IN THE SVZ. EFFUSIVE PHASES ARE NOT CONSIDERED.

	Quizapu 1932	**Hudson 1991**	**Chaitén 2008-2009**	**PCCVC 2011-2012**	**Calbuco 2015**
Type of eruption	Plinian[1]	Plinian[7,8]	Plinian[14,15]	Sub-Plinian[19]	Sub-Plinian[23-25]
Triggering mechanism	Magma mixing and overpressure[2,3]	Magma mixing[9]	Overpressure and rapid ascent[16,17]	Overpressure and rapid ascent[20]	Overpressure/ reheating[26-28]
Bulk rock composition	Dacite-andesite[1-3]	Basalt, Basaltic[9] andesite	Rhyolite[18]	Rhyolite, Rhyodacite[20,21]	Basaltic andesite, andesite[26,27,28]
Magnitude	5.9-6.1[4]	5.5[10]	4.5[16]	4.6[19]	4.5[23,24]
Erupted volume (DRE tephra, km^3)	3.8-6.1[4,5]	2.7[7,8,10]	1.0-1.3[15]	0.3-0.7[19]	0.13[26,29]
Number of evacuees	Unknown	~4,000[6]	~5,000[12]	~8,000[12]	~6,000[30]
Economic costs (USD)	Unknown	Unknown	48 million[12]	700 million[12]	20 million[30]
Proximal impacts	Meter-thick tephra fall deposition, geomorphologic changes nearby the eruptive centre[6]	Burial of infrastructure by tephra fallout, roof collapse, death of livestock, lahar generation, high fluorine concentration[6,7]	Lahar generation and flooding of Chaitén town. Total to partial destruction of public infrastructure[12]	Roof collapses, death of livestock, lahar generation, damage to vegetation, and closure of the international road[12]	Roof collapses, destruction of private infrastructure, road closure, bridges damage by lahars. Forest damage, geomorphological changes by PDCs and sediment delivery[30,31]
Distal impacts	Widespread ash deposition in Central Chile and in Argentina. Death of livestock, irreversible damage to agriculture. Long-term desertification and drop in local temperature[6]	Extensive damage to livestock and crops, air traffic disruption, water contamination, power outage, and forced migration. Long-term desertification[11-13]	Air traffic disruption, water and power outage, air pollution, ground contamination, long-term ash remobilisation[12]	Disruptions to transportation, water, and electricity supply. Extensive death of livestock (>30,000 animals). Air pollution and long-term ash remobilisation[22]	Air traffic disruption, air pollution, ash remobilisation, water contamination.[30, 31]

[1]Hildreth and Drake (1992); [2]Ruprecht *et al.* (2012); [3]Higgins *et al.* (2015); [4]Rebolledo, 2022; [5]Bonadonna and Costa (2012); [6]González-Ferrán (1995); [7]Naranjo and Moreno (1991); [8]Scasso *et al.* (1994); [9]Kratzmann *et al.* (2009); [10]Crossweller *et al.* (2012); [11]Araya (2015); [12]Elissondo *et al.* (2016); [13]Wilson *et al.* (2011); [14]Watt *et al.* (2009b); [15,16]Alfano *et al.* (2011, 2012); [17]Forte *et al.* (2019); [18]Castro and Dingwell (2009); [19]Pistolesi *et al.* (2015); [20]Castro *et al.* (2013); [21]Alloway *et al.* (2015); [22]Forte *et al.* (2018). [23]Romero *et al.* (2016); [24]Castruccio *et al.* (2016); [25]Van Eaton *et al.* (2016); [26]Arzilli *et al.* (2019); [27, 28]Morgado *et al.* (2019a, b); [29]Romero *et al.* (2021); [30]Mella *et al.* (2015); and [31]Hayes *et al.* (2019).

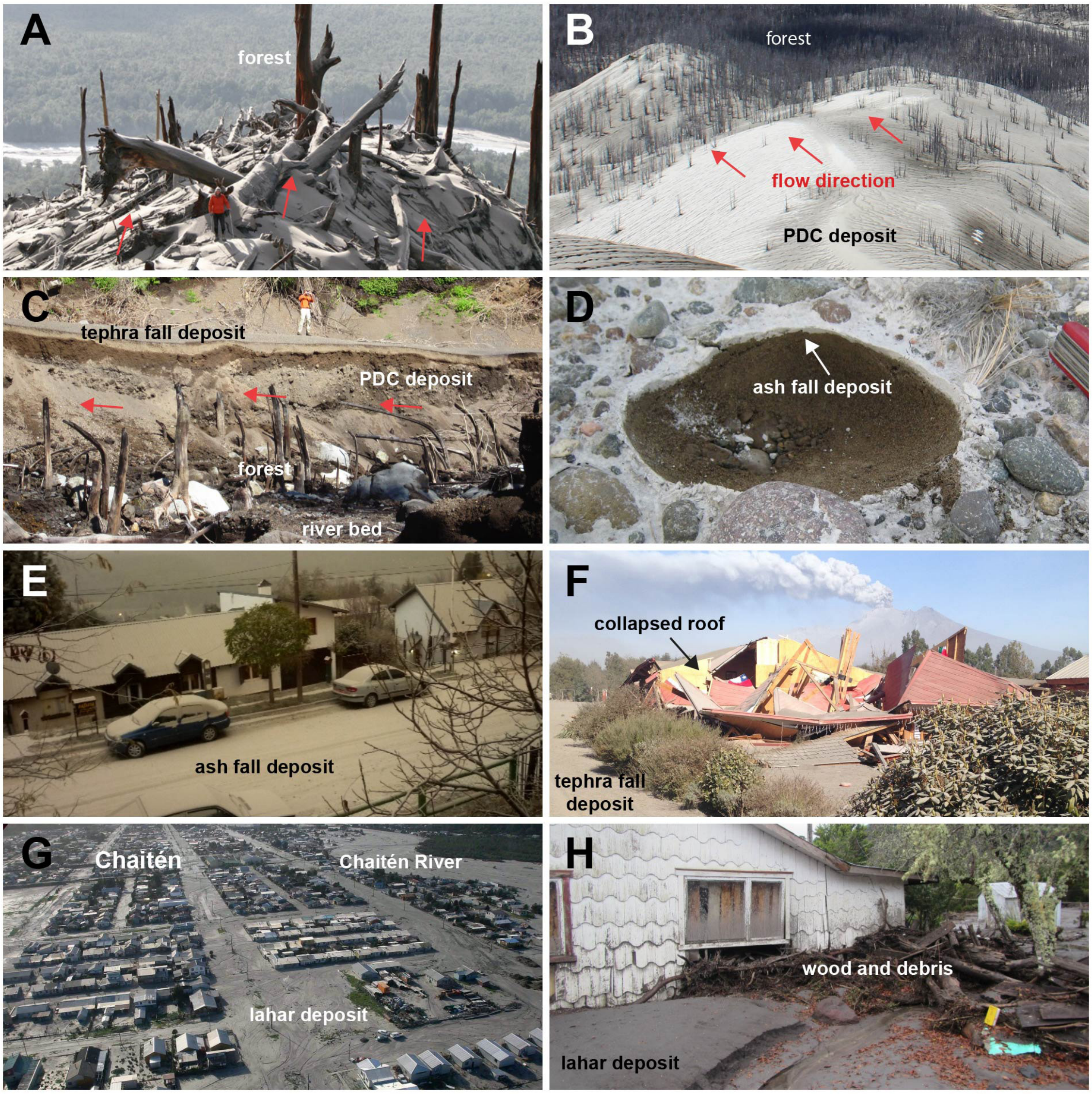

FIG. 5. Proximal and distal impacts produced by PDCs, tephra fallout, and lahars during the Chaitén, PCCVC, and Calbuco eruptions. **A**. Toppled trees in the northern flank of Chaitén, inside the blast zone (D. Basualto). **B.** Scorched zone in the northern PCCVC area (F. Swanson). **C.** Tipped trees at the Tepu River, Calbuco volcano (J.E. Romero). **D, E.** Ash fall deposits from Chaitén (S. Watt) and PCCVC eruptions (M.A. Rabhasnl). **F.** Roof collapsed by tephra overload at Ensenada, near Calbuco volcano (D. Spatafore). **G.** Flooding of Chaitén after lahars down the Chaitén river (Gobierno de Chile). **H.** Hyperconcentrated lahar floods nearby Lago Chapo, south from Calbuco volcano (M. Mella).

New Holocene eruptions sourced from Michinmahuida were recognised by Amigo *et al.* (2013), fuelled by new studies in the area as consequence of the 2008 Chaitén eruption. The Chaitén case exemplifies how catastrophic eruptions have motivated studies in other volcanoes otherwise unexplored by volcanologists.

The lacustrine tephra records have great potential to synchronise various paleoenvironmental, paleoclimatological and paleoseismological records in the region (Fontijn *et al.*, 2016). Those records, coupled with subaerial tephrostratigraphic observations, have offered clues on the composition, magnitude, and frequency of explosive eruptions in the SVZ that can be correlated to climate changes and particularly deglaciation (Rawson *et al.*, 2016b). The lacustrine records also reveal that explosive eruptions at 40-41 °S occurred in close synchrony with deglaciation during the last ~14 kyr (Alloway *et al.* 2022). At the time of writing (2024), the most updated tephrochronological dataset for the SVZ is available in Martínez *et al.* (2023).

4. Towards a holistic and interdisciplinary strategy for reducing volcanic risk in the SVZ

4.1. The local understanding of SVZ volcanoes and their hazards: an historical perspective

Historiographical studies revealed the early existence of local knowledge about volcanism (Garrido, 2017). The native communities, particularly the Mapuche people, have experienced recurrent volcanic eruptions (Atallah, 2016), understood as expressions of the *Mapu* (Mother Earth in the Mapuche language) that shape myths, beliefs, and rituals (*e.g.*, Bacigalupo, 1998; Bastías *et al.*, 2021). It is worth noting that the Spanish colonists aimed to extirpate native beliefs, such as the existence of *pillanes* (spirits) inhabiting volcanoes. Nevertheless, these beliefs have survived to the present day, partly explained by the long-lasting continuity of the Mapuche people and rural communities around several SVZ volcanoes.

The first maps, illustrations, voyage logbooks, chronicles, and descriptions of SVZ volcanoes were made centuries later by Europeans, mainly on the western (Chilean) side of the Andes (Havestadt, 1777; Poeppig, 1835; Darwin, 1840; Barros Arana, 1911; Cristi, 1953; Petit-Breuilh, 2004, 2007; Ottone, 2008; Baeza, 2009; Ramos, 2011; Lara *et al.*, 2012, 2013; Hervé and Charrier, 2016). The academic approach to understand volcanoes started in Argentina in 1865 at the University of Buenos Aires (*e.g.*, Bodenbender, 1889; Groeber and Corti, 1920 in Agusto and Vélez, 2017; Ramos, 2011; Sruoga, 2016 and references therein), and progressed to systematic investigations in the 1960s (*e.g.*, Llambías, 1964; Polanski, 1972). In Chile, the first volcanological investigations were conducted at the University of Chile (*e.g.*, Brüggen, 1950; Casertano, 1963a, b; Moreno, 1975, 1976, 2004, 2013; González-Ferrán, 1995; Charrier *et al.*, 2022) and systematic research of volcanic hazards was launched at the Chilean Geological and Mining Service (Sernageomin, by its acronym in Spanish) in 1991. All these efforts initially focused on SVZ volcanoes (Alvarado *et al.*, 1999; Amigo, 2021).

In Chile, under the current volcano monitoring and hazard assessment programme (Chilean Volcanic Surveillance Network; RNVV, by its acronym in Spanish), at least 27 hazard maps have been published for SVZ volcanoes since 1999 (Vera *et al.*, 2023), 17 of them since 2003 (Supplementary Table 2). Alongside the RNVV, several research groups, mainly from universities and research centres, work on SVZ volcanoes (Gho *et al.*, 2017[3]). Binational (Chilean-Argentinian) effort has also materialised the production of hazard maps such as at Planchón-Peteroa (Naranjo *et al.,* 1999), Laguna del Maule (Gho *et al.*, 2019), and Lanin volcano (Jara *et al.*, 2020). In Argentina, the hazard map of Copahue volcano (Kaufman *et al.,* 2023) has been recently published.

4.2. Volcano monitoring and inter-institutional collaboration

Latin American volcano monitoring institutions are comparatively younger than those in other regions of the world and, in many cases, were created after volcanic crises or disasters (Forte *et al.*, 2021). This holds true for both Argentina and Chile, where SVZ volcanic eruptions have helped in securing a regular flow of resources for volcano monitoring and hazard programs. In Chile, the Southern Andes Volcano Observatory (OVDAS, by its acronym in Spanish) was founded in 1996 to monitor the most active volcanoes of the SVZ, including Llaima and Villarrica. The creation of the RNVV in 2009, because of the 2008 Chaitén eruption, represented a turning point in volcano monitoring in Chile. Since then, surveillance of SVZ volcanoes improved significantly

3 Gho, R.; Forte, P.; Romero, J.; Perales, C.; Jácome, M.P.; González, G.; Bustos, E.; Vasconez; Lazarte, I.; Rodríguez, D. 2017. La volcanología chilena en el contexto latinoamericano: estado actual y perspectivas para las nuevas generaciones. VIII Encuentro Nacional de Estudiantes de Geología 49.

in quantity and quality, becoming a regional and world reference (Amigo, 2021; Forte *et al.*, 2021). Nowadays, the RNVV monitors 45 volcanoes, 35 of which are in the SVZ.

In Argentina, the first efforts to create a volcano observatory started after the 2011-2012 PCCVC and 2012 Copahue eruptions, being finally materialised in 2017 (García and Badi, 2021). The Argentinian Volcanic Surveillance Observatory (OAVV, by its acronym in Spanish), dependent on the Argentinian Geological and Mining Service (Segemar, by its acronym in Spanish), is the youngest volcano observatory in Latin America. Currently, OAVV monitors the activity of five SVZ volcanoes: Planchón-Peteroa, Laguna del Maule, Copahue, Domuyo, and Lanin.

The recent eruptions in the SVZ are good examples of how systematic volcano monitoring and research influence the different stages of an emergency. For example, the poorly understood eruptive history of Chaitén before 2008 and the lack of monitoring instrumentation led to an unexpected eruption onset. This eruption and its consequences dramatically modified risk perception for this volcano (Major and Lara, 2013). Contrastingly, in the PCCVC, the detailed geological mapping and the deployment of a robust monitoring network allowed successful forecast of the onset of the 2011-2012 eruption cycle and the evacuation in Chile of nearly 8,000 people (Elissondo *et al.*, 2016). In Argentina, however, the lack of an official monitoring institution coupled with an inefficient binational communication scheme took locals by surprise during the 2011-2012 PCCVC eruption (Bran *et al.*, 2023). Another example is the 2015 Villarrica eruption, whose alert level was raised from green to orange before erupting on March 3rd. The number of evacuees totalled ~2,000 (Romero *et al.*, 2018). In terms of volcano monitoring, the recent implementation of infrasound instruments around Villarrica has shown significant advances in detecting and characterising lahars and determining the height of the lava lake surface inside the volcano's crater (*e.g.*, Johnson and Palma, 2015; Johnson *et al.,* 2018), while automated discrimination of surface activity has improved with machine learning algorithms (*e.g.*, Witsil and Johnson, 2020). These techniques should allow an overall successful performance of technical alert levels at volcanoes like Villarrica. Volcano monitoring, however, assists but does not guarantee accurate eruption forecasts; as an example, Calbuco volcano recorded only limited and short-lived precursory unrest before the 22 April 2015 eruption. Unlike Chaitén, geologic and hazard maps were available for Calbuco long before 2015, favouring decision-making and the evacuation of ~6,500 people during the crisis. These examples and counterexamples highlight the importance of knowing the eruptive behaviour of volcanoes at the scale of decades to thousands of years. This is also critical for a correct understanding of their potential hazards.

4.3. Society-volcano coexistence

There is a long history of human-volcano interactions expressed in two main dimensions: 1) the ways and motivations by which society has inhabited and used volcanic spaces, and 2) the forms and strategies that society adopt for disaster risk reduction in such spaces. Regarding the first, the literature reviewed demonstrates the value of volcanic livelihoods in the SVZ (Marín *et al.*, 2020). For instance, the ice-clad volcanoes serve as important freshwater resources (*e.g.*, Rivera *et al.*, 2006, Rivera and Brown, 2013), while food availability and a benign climate have favoured human inhabitation around SVZ volcanoes since postglacial times (*e.g.*, Montané, 1968; Moreno and Varela, 1985; Dillehay and Collins, 1988; Mancini *et al.*, 2013; Pino *et al.*, 2013; Forte *et al.*, 2022). This aspect of long-standing occupation is related to the second dimension, in that post-colonial communities continued using similar locations for rural and urban development to those occupied during the pre-colonisation times (*e.g.*, Petit-Breuilh, 2004; Aguayo *et al.*, 2009; Salazar and Jalabert, 2015; Harambour, 2019; Grau and Foguet, 2021), increasing human exposure in volcanic areas.

There are social processes related to diverse understandings of inhabiting volcanic territories, such as the existing local knowledge systems about volcanic activity (Ramos and Tironi, 2022) and disaster memory on past eruptions (Petit-Breuilh, 2004, 2023; Vergara-Pinto and Marín, 2023; Walshe *et al.*, 2023), which are highly valued for people to make sense of volcanic risk. Along with this, the society-volcano coexistence includes uncertainties regarding unpredictable eruptive scenarios for populations and scientists (Vergara-Pinto and Romero, 2023). These scenarios imply reconsidering pre-existing vulnerabilities and adaptive capacity to foster the equitable resilience of populations (Matin *et al.*, 2018). From there, we recognise interdisciplinarity as an outcome of the legacy of eruptions (Fig. 6) that has opened volcanology to the social sciences

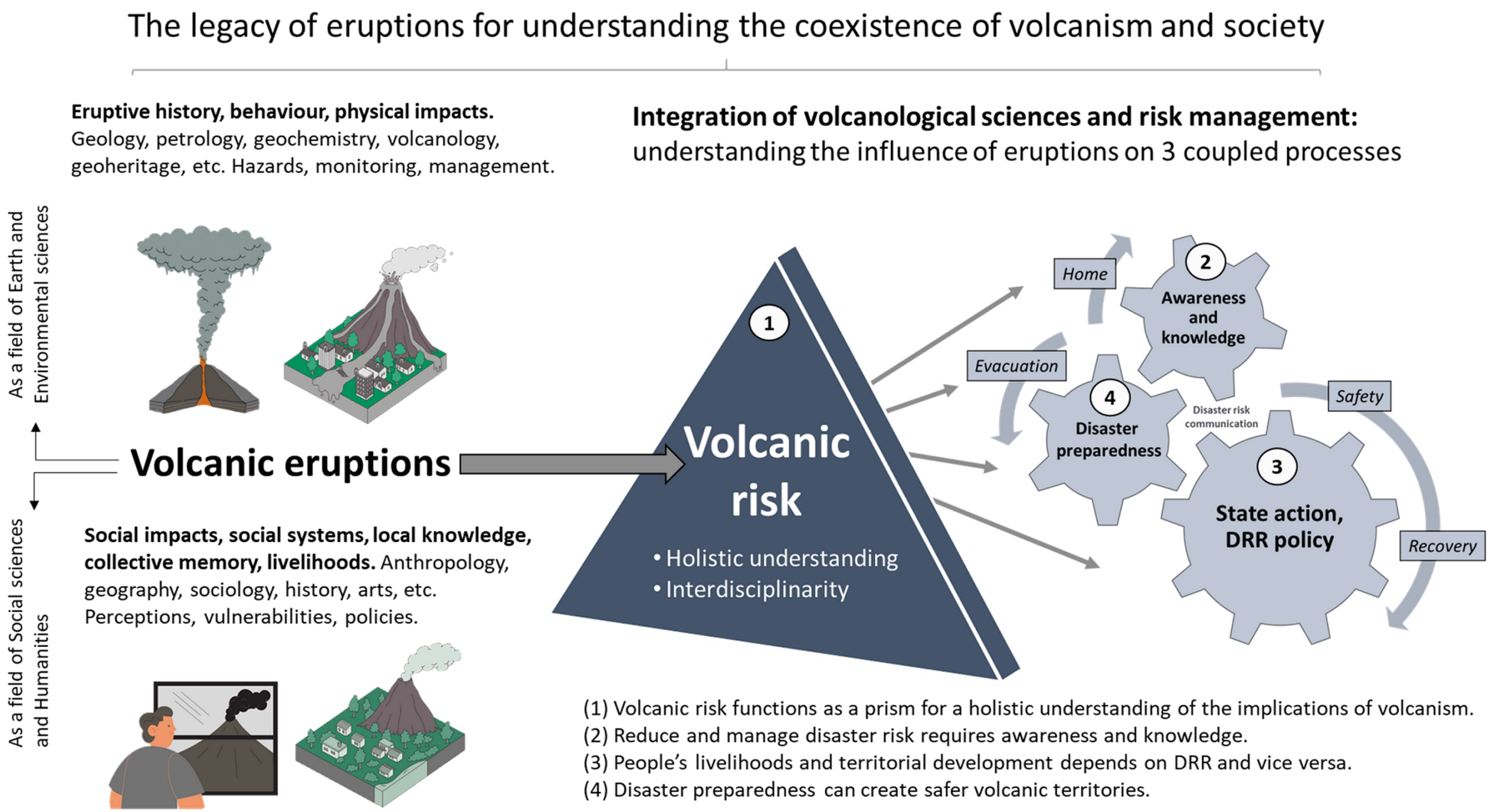

FIG. 6. Representation of the holistic understanding of volcanic risk. Illustrations from Canva.

and stakeholders in recent decades. Two aspects are therefore discussed in the next section, regarding some interdisciplinary collaborations, deemed relevant in our study, that can improve our understanding and valorisation of the SVZ volcanic systems and their impacts.

5. Opportunities for collaboration

5.1. On active magmatic-hydrothermal systems

Heat flow along the active Andean volcanic arc is responsible for the high geothermal potential in Chile, representing ~3.4% of the territory (*e.g.*, Aravena and Lahsen, 2013; Aguilera *et al.*, 2014; Daniele *et al.*, 2020; Lemus and Honores, 2021[4]), with inferred resources reaching 660 MWe (total estimated power potential equivalent to ~4.4% of the installed electric capacity; Aravena *et al.*, 2016). At least 150 geothermal zones exist in the SVZ around Holocene volcanoes. These zones, characterized by meteoric and magmatic fluid contribution, are hosted within subvolcanic volcano-sedimentary sequences and crystalline basement, and favoured by tectonic features such as the LOFS or the ATFs (Sánchez-Alfaro *et al.*, 2015; Wrage *et al.*, 2017; Daniele *et al.*, 2020; Pérez-Estay *et al.*, 2023). The most promising geothermal sites are located at Tinguiririca, Calabozos, Laguna del Maule, Nevados de Chillán, Domuyo, Copahue, Tolhuaca, Sierra Nevada, and the PCCVC (Lahsen *et al.*, 2005, 2010, 2015; Chiodini *et al.*, 2014; Barcelona *et al.*, 2021). Current research at the volcanoes related to these geothermal sites has provided new knowledge about their magmatic-hydrothermal systems, volcanic evolution, eruptive history, volcano-tectonic interplay, and potential hazards. Strong interdisciplinary collaboration is therefore expected between geothermal researchers and volcanologists to advance towards renewable energies and volcanic hazard evaluation.

Volcanoes in subduction zones typically form shallow (<4-5 km deep) ore deposits within trans-crustal magmatic systems (Hedenquist and Lowenstern, 1994), particularly porphyry-type deposits that provide 75% of the world's copper, but also gold and molybdenum (Sillitoe, 2010). In this regard, the SVZ, despite its apparent lack of ore deposits, has proven an ideal natural laboratory to explore the systematics of ore metals and volatile components in a subduction-related active volcanic arc using both melt inclusion and whole-rock geochemical approaches (*e.g.*, Zajacz and Halter, 2009; Cox *et al.*, 2019; 2020; Grondahl and Zajacz, 2022). This potential also extends to volcanoes with recent eruptions, active degassing, or active hydrothermal systems (Zajacz and Halter, 2009; Grondahl and Zajacz, 2022). Grondahl and Zajacz (2022) noticed that magmas from the thicker-crust NSVZ volcanoes have higher potential to develop ore deposits compared to magmas from the thinner-crust SSVZ due to higher volatile (S and Cl) contents needed to extract, accumulate, and precipitate metals in the upper crust. In addition, the tectono-magmatic conditions of the southern SVZ promote degassing-induced loss of crucial metal-carrying volatile elements during differentiation, precluding efficient metal extraction. However, high magma ascent rates and elevated eruptive fluxes at Villarica and Llaima volcanoes might avoid Cu-depleting fractionation processes in the lower crust and deliver high-Cu magmas to the upper crust, representing potential sites of unexposed actively forming porphyry-type deposits (Cox *et al.*, 2020). Likewise, chalcophile metals have revealed compositional trends consistent with ore metal fractionation at an early stage beneath Antuco volcano during lower crustal magmatic evolution (Cox *et al.*, 2019). Future directions could also include studies to determine the distribution and speciation of ore metals and volatiles between the different phases present in a magma (Lanzirotti *et al.,* 2019; Grondahl and Zajacz, 2022) and geophysical approaches to identify potentially metal-rich magmatic brine layers below active volcanoes (Blundy *et al.,* 2021; Hudson *et al.,* 2023). Such observations are relevant to understand active interactions between hydrothermal and magmatic activity, volcanic eruptions, and to interpret volcanic unrest processes.

5.2. Geoconservation and geoheritage

There is a variety of protected zones in Chile and Argentina that include volcanic areas (*e.g.,* Pellet *et al.*, 2005; Sruoga, 2008; Basic and Arriagada, 2012; Rivera and Vallejos-Romero, 2015; Hora, 2018; Casadevall *et al.*, 2019; Coronato and Schwarz, 2022). In Chile, volcanoes are central elements of geoheritage initiatives, represented by the Kütralkura UNESCO geopark and many projects such as Cajón del Maipo

[4] Lemus, M.; Honores, C. 2021. Sistemas geotermales de la Zona Volcánica Sur Central de los Andes de Chile (38-41° S): modelos conceptuales con base en geología y geofísica ZTEM. Servicio Nacional de Geología y Minería, Informe Registrado IR-21-92 (Inédito): 123 p.

and Pillanmapu (*e.g.,* Benado *et al.,* 2019*;* Daskam, 2022; Schilling *et al.*, 2023; Orellana *et al.*, 2023). Kütralkura contains six active volcanoes: Tolhuaca, Lonquimay, Llaima, Sollipulli, Quetrupillán, and Lanín (Schilling *et al.*, 2023), two of which have erupted in the last 35 years. The Pillanmapu project considers two main volcanic areas: Descabezados and Laguna del Maule (Orellana *et al.*, 2023). At Cajón del Maipo, three active volcanoes are considered, alongside ignimbrites, calderas, and fumarole fields (Daskam, 2022). Unprotected volcanic areas may also use their geodiversity for touristic and didactic purposes. For instance, at Nevados de Chillán, sixteen new geosites have been recognised which could provide a valuable appreciation of the landscape and its evolution for geotourism and geoeducational purposes (Vidal and Tassara, 2023). In Argentina, several volcanic landscapes within the SVZ, which include volcanoes such as Copahue, Domuyo and Lanín, as well as the Payún Matrú volcanic field, are encompassed by provincial or national protected areas.

5.3. Further considerations

To date, the local scientific efforts in the SVZ are primarily descriptive and focused on the mechanisms, dynamics, and impacts of volcanic eruptions. Considering the limited experimental laboratories and instrumental capabilities available in Chile or Argentina to obtain high-resolution analytical data, most of the research is carried out abroad (primarily in Europe and United States) and is subject primarily to funding or collaboration. These conditions prevent the rapid acquisition of data for hazard assessment or volcano monitoring during an unrest or crisis scenario. Improving the local instrumentation is central to reducing such limitations.

International collaboration has been crucial in expanding the local monitoring capacities in the region (*e.g.*, Amigo, 2021; García and Badi, 2021; Lara *et al.*, 2021). Current monitoring infrastructure requires a further step of prioritisation and instrumentation efforts, frequently focused on the most critical volcanoes (Amigo, 2021; García and Badi, 2021). In that case, dense, multiparametric monitoring networks are critical for improving knowledge about volcanic systems (*e.g.*, Hilley *et al.*, 2022). Remote sensing techniques may provide more extensive spatial coverage and quasi-instantaneous data acquisition at poorly accessible volcanoes. An obstacle for these tasks to be successfully applied is limited budgeting (or a decreasing investment in monitoring after some years of increase consequence of a catastrophic event). In those cases, institutional efforts can be focused on monitoring automation and simultaneous treatment of multiparametric data (*e.g.*, Cecioni and Pineda, 2009).

A scientifically rigorous understanding of volcanic systems needs analogous and/or numerical models to support or explain natural observations (Mader *et al.*, 2004; Fagents *et al.*, 2013). Future efforts should include expanding the use of numerical models in the SVZ (*e.g.*, Gutiérrez and Parada, 2010; Amigo, 2013; Córdoba *et al.*, 2015; Castruccio and Contreras, 2016; Reckziegel *et al.*, 2016, 2019; Castruccio *et al.*, 2017; Bertin, 2017 and Bertin *et al.*, 2019; Ruz *et al.*, 2020), machine learning (*e.g.*, Witsil and Johnson, 2020; Boschetty *et al.*, 2022; Ardid *et al.*, 2023), and other AI algorithms, using multimethod quantification of multiphase processes and upscaling experiments to near-natural scales (Poppe *et al.*, 2022). All these techniques require a fundamental field-based knowledge on the geological evolution, deposits, eruptive behaviour, and hazards of active volcanoes for accurate representations of physical phenomena.

The technical knowledge of volcanic systems should be complemented with strategies of geoconservation, geoheritage, geoeducation, and scientific divulgation (*e.g.,* Schilling *et al.,* 2023), as they enhance the sustainable development of the local economies (Sepúlveda, 2002). There is still a need for a legal framework for geoconservation and geoheritage in Chile and Argentina, but also for specialised organisations capable of evaluating, promoting, and protecting such elements. In this sense, protecting volcanic territories should result from collective efforts between volcanologists, local communities, social scientists, and cultural and educational institutions, among other relevant actors.

6. Closing remarks

During the last 35 years, volcanic eruptions in the Andean SVZ have stimulated scientific productivity, providing a natural laboratory to understand eruption mechanisms, dynamics, and impacts, particularly eruption-controlling processes, ecological and landscape response to volcanic phenomena, short- and long-term socio-economic impacts of volcanic eruptions, as well as new insights into the long-term behaviour of volcanoes. These eruptions and their impacts have triggered significant investment, technologization, and professionalisation for volcano monitoring, volcanic hazard assessment, and eruption forecast.

Despite recurrent and impactful eruptions in the SVZ, the extended presence of humans in the region implies recognising the interplay between natural and social elements in volcanic territories, as they open new avenues for a more holistic understanding of volcanic risk. We identify great opportunities with other closely related disciplines to complement the geological and hazard understanding of volcanoes and build more sustainable and safe spaces in the territory.

Acknowledgements

This contribution was visualized during an invited talk for the Commission on Explosive Volcanism of the International Association of Volcanology and Chemistry of the Earth's interior (IAVCEI). We are grateful of the reviews provided by K. Fontijn, M. Mella, and P. Sruoga, plus the editorial handling and insightful comments of D. Bertin. This contribution seeks to recognise all the brilliant volcanologists that built the existing framework on the SVZ and inspired newer generations to study these volcanoes. They are all properly cited along the text. All supplementary materials are available at: https://figshare.com/collections/_/6934411.

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Manuscript received: June 20, 2023; revised/accepted: April 2, 2024; available online: April 2, 2024.

Supplementary materials

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