Volcanic risk ranking and regional mapping of the Central Volcanic Zone of the Andes

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Abstract. The Central Volcanic Zone of the Andes (CVZA) extends from southern Peru, through the altiplano of Bolivia, to Puna ~~de Atacama ~~of northern Chile and Argentina, between latitudes 14-28°S of the Andean cordillera, with altitudes raising up to more than 4,000 m above sea level. Given the large number of active volcanoes in this area, which are often located close to both urban areas and critical infrastructure, prioritization of volcanic risk reduction strategies is crucial. ~~However, the~~The identification of hazardous active volcanoes is challenging due to the limited accessibility~~.~~, scarce historical record, and the difficulty in identifying relative or absolute ages due to the extreme arid climate. Here, we identify the ~~riskiest~~highest risk volcanoes ~~based on~~combining complementary strategies~~ including~~: i) a regional mapping based on volcanic hazard parameters and surrounding density of elements at risk ~~combined with~~and ii) the application of the recently developed Volcanic Risk Ranking (VRR) methodology that integrates hazard, exposure and vulnerability as factors that increase risk, and resilience as a factor that reduces risk. ~~The method identifies~~We identified 59 active and potentially active volcanoes that not only ~~highlights~~include the volcanic ~~centers~~centres with the most intense and frequent volcanic eruptions (e.g., El Misti and Ubinas volcanoes~~ (~~, Peru~~)) and~~) but also the highest density of exposed elements (e.g., the cities of Arequipa and Mequegua~~ (~~, Peru~~)),~~ ~~but also ~~). VRR is carried out for 19 out of 59 volcanoes, active within the last 1,000 years or with unrest signs, highlighting those with the highest potential impact ~~requiring risk mitigation actions ~~(i.e., Cerro Blanco ~~(~~in Argentina~~)~~, and Yucamane, Huaynaputina, Tutupaca, and Ticsani ~~(~~in Peru~~)).~~) and requiring risk mitigation actions to improve the capacity to face or

overcome a disaster (e.g., volcanic hazard and risk/impact assessments, monitoring systems, educational activities, and implementation of early warning systems).

1 Introduction

~~The Central Volcanic Zone of the Andes (CVZA) is one of the most active volcanic zones in South America where most volcanoes are located within 25 km of an international border, comprising Argentina, Chile, Bolivia and Peru, implying significant transboundary challenges (Donovan and Oppenheimer, 2019). Moreover, in this region, volcanoes are located on the Altiplano-Puna plateau and, therefore, several of them are higher than 6,000 m above sea level (a.s.l), including Ojos del Salado, which is the highest volcanic summit in the world (Amigo, 2021). The CVZA has been studied over the years to investigate a wide number of geological processes (e.g., geologic evolution, volcanic arc segmentation, magma genesis), but due to the difficult access, historical records of eruptions were limited until very recently (Aguilera et al., 2022). Systematic volcanological studies in the CVZA started in the 1970-80s headed by Chile (e.g., Francis et al., 1974, 1985; Gonzalez-Ferran et al., 1985; de Silva, 1989; Gardeweg and Amigo, 2015), followed by Argentina in the 1980-90s (e.g., Viramonte et al., 1984, 1994; De Silva and Francis, 1991; Coira and Kay, 1993; Martí et al., 1999; Perucca and Moreiras, 2009), Peru in the 1990s (e.g., Thouret et al., 1994, 1999; Mering et al., 1996; Fídel et al., 1997; De Silva and Zielinski, 1998; Traversa et al., 2011), and finally by Bolivia in the Western Cordillera and Altiplano at the beginning of the 21st century (e.g., Wörner et al., 2000; Sparks et al., 2008; Mamani et al., 2010; Ward et al., 2013; Michelfelder et al., 2014; Comeau et al., 2016). Given the proximity of a large number of volcanoes to urban areas and critical infrastructure, the identification of the riskiest volcanoes and, therefore, the implementation of volcanic risk reduction strategies are especially important for the CVZA. Furthermore, during the last 20 years, volcanic unrest in various areas of the CVZA has motivated the implementation of new monitoring capabilities and research investments that currently promote cross-border collaborations (Aguilera et al., 2022).~~

~~Three of the four countries of the CVZA have already produced a relative volcanic threat ranking, Peru (Macedo et al., 2016), Chile (Lara et al., 2006; Ranking de riesgo específico para volcanes activos de Chile 2019; Ranking de riesgo específico para volcanes activos de Chile 2023) and Argentina (Elissondo et al., 2016; García et al., 2018; Elissondo and Farías, 2023), based on the methodology proposed by Ewert et al. (1998; 2005). Peru ranked 16 volcanoes with four levels of risk~~The Central Volcanic Zone of the Andes (CVZA) is one of the four active volcanic zones in South America (Fig. 1). This zone within ~~the~~ latitudes 14-28°S comprises at least two volcanic segments controlled by a compressive subduction tectonics, with a diffuse boundary at 21°S between Isluga and Irruputuncu volcanoes. The northern CVZA segment, located in southern Peru, has major volcanoes aligned in a NW-SE direction and is characterized by significant historic magmatic eruptions. The southern segment within northern Chile, south-western Bolivia, and north-western Argentina on the other hand, has a more northerly trend comprising older edifices that have existed for more than a million years (e.g., Ollagüe, with a history going back as far as 800,000 years) and have longer repose periods (De Silva and Francis, 1991). The CVZA has an ongoing volcanism since the

Late Eocene-Early Oligocene, comprising a wide diversity of activity patterns, volcanic forms, products, and magma compositions (e.g., Bertin et al., 2022a; Grosse et al., 2018, 2022), including catastrophic cone collapses and a long record of voluminous silicic pyroclastic activity associated to potentially active giant ignimbrite centres and caldera systems with important implications for the safety of nearby communities (Stern, 2004).

The lack of knowledge due to scarce historical records and difficulty in identifying deposit ages together with its proximity to four geographical borders imply significant challenges for the CVZA, making it an area of interest for volcanic risk reduction. In fact, systematic studies of the CVZA only started in the 1970-80s, and increased during the last 20 years motivated by the implementation of new monitoring capabilities and research investments as a response to volcanic unrest in various areas, currently promoting cross-border collaborations (Aguilera et al., 2022; Forte et al., 2021). However, the characterization of hazardous active volcanoes is very challenging because of their limited accessibility. Several CVZA volcanoes are higher than 6,000 m above sea level (a.s.l), including Ojos del Salado, which is the highest volcanic summit of the world (Amigo, 2021). In addition, the extreme dry and arid conditions further complicate detailed studies of these volcanoes. As an example, the determination of the relative ages through morphology is difficult due to very low erosion rates making difficult the distinction between old and fresh volcanic features. Existing radiocarbon techniques are also limited because sediments contain small amounts of organic carbon (Gillespie et al., 1991; De Silva and Francis, 1991). Finally, the CVZA volcanoes are located within 25 km of ~~an~~ international border, in between Argentina, Chile, Bolivia or Peru. Andean communities have interacted with these volcanic features for more than 11,000 years, even before border delineation (Ramos Chocobar and Tironi, 2022; Loyola et al., 2022). However, the current division of borders increases the challenges of volcanic risk management since each country has multiple strategies, resources, sovereignty and intrinsic socio-economic and political conditions playing a key role when facing natural risks (e.g., Donovan and Oppenheimer, 2019; Petit-Breuilh Sepúlveda, 2016; Romero and Albornoz, 2013).

One of the major difficulties within the CVZA lies in the identification of active hazardous volcanoes. Although various nomenclatures have been proposed to describe the state of a volcano (e.g., Szakács, 1994; Auker et al., 2015), here we stick to Szakács definition, also in agreement with the Geological Services of Argentina (SEGEMAR), Chile (SERNAGEOMIN), and Peru (INGEMMET). According to Szakács (1994), "active volcano" and "extinct volcano" are mutually exclusive terms. Active volcanoes are geologically active when they had at least one eruption in the Holocene period, then, they can be subdivided into "erupting" and "dormant" types based on their current state of activity, while extinct volcanoes could be classified as "young" or "old" using criteria such as the extent of erosion or geochronological age. The term "potentially active" is reserved for those fresh-looking volcanoes lacking both documented eruptions and reliable datations. “Potentially active” volcanoes could be defined as “active-dormant” or “extinct-young” volcanoes as more information becomes available (Szakács, 1994). Alternatively, in absence of data of eruptions during the Holocene, a volcano can be considered “potentially active” when it presents visible signs of unrest activity such as degassing, seismicity or ground deformation (e.g., Simkin and Siebert, 1994; Ewert et al., 2005; Ewert, 2007; Lara et al., 2011). As a result, in this study we analyse a total of 59 volcanoes, 25 active

Holocene volcanoes and 34 potentially active volcanoes having fresh volcanic morphology or records of at least one sign of unrest (i.e., seismicity, deformation or degassing).

Volcanic rankings have been used to identify threatening volcanoes, notably based on the strategy proposed by Ewert et al. (1998; 2005; 2007), that combines hazard (the destructive natural phenomena produced by a volcano) and exposure (people and property at risk from the hazards) parameters. Based on this methodology, three of the four countries of the CVZA have already produced a relative volcanic threat ranking considering the whole country (e.g., Macedo et al., 2016; Lara et al., 2006; SERNAGEOMIN, 2020, 2023; Elissondo et al., 2016; García et al., 2018; Elissondo and Farías, 2024). Peru ranked 16 volcanoes with four levels of threat, from very low to very high (Macedo et al., 2016). Chile~~ and Argentina,~~ recently updated ~~their relative~~its volcanic ~~risk rankings ~~ranking with 87 ~~and~~active and potentially active volcanoes based on 13 hazard and 12 exposure parameters (SERNAGEOMIN, 2023). A new volcanic risk ranking for Argentina was also recently published with 38 active and potentially active volcanoes~~, respectively, (Ranking de riesgo específico para volcanes activos de Chile 2023; Elissondo and Farías, 2023). Both divided in five categories of relative risk (from low to very high), and the latter~~ based on 15 hazard ~~parameters including the type of volcano, the frequency and magnitude of eruptions, the products emitted in the Holocene, and the historical factors of unrest. Ten~~and 10 exposure parameters ~~were also considered including population, local and regional aviation, transportation and energy infrastructure.~~

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~~A new ~~(Elissondo and Farías, 2024). From these rankings~~ only~~ 26 (Chilean ranking) and 22 (Argentinian ranking) volcanic centres are part of the CVZA. However, many active and potentially active volcanoes of the CVZA and their eruptive histories remain understudied. Recently, a new Volcanic Risk Ranking (VRR) methodology was~~ recently~~ proposed, expanding the work of ~~Ewert et al. (1998; 2005) by integrating additional factors that can influence the risk level (i.e., vulnerability and resilience).~~Ewert et al. (1998; 2005), by integrating additional factors that can influence the risk level, i.e., vulnerability, as characteristics of the elements at risk that can increase the susceptibility to the impact of a natural hazard; and resilience, as the system's ability to adapt to changes, overcome disturbances and maintain functionality from the effects of a hazard (Nieto-Torres et al., 2021; Guimarães et al., 2021). This new VRR methodology was tested on Mexican volcanoes with activity recorded in the last 10,000 and 1,000 years (Nieto-Torres et al., 2021) and ~~for the~~applied to Latin American volcanoes with activity recorded in the last 1,000 years (Guimarães et al., 2021).

~~In this study, we identify the volcanoes of the CVZA with the highest potential impact based on two complementary strategies: i) the regional mapping of hazard parameters and elements at risk, and ii) the new VRR methodology (Nieto-Torres et al., 2021).~~

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In this study, we identify the volcanoes of the CVZA with the highest potential impact based on two complementary strategies: i) the regional mapping of hazard parameters and elements at risk for a total of 59 active and potentially active volcanoes, and ii) the VRR methodology proposed by Nieto-Torres et al., (2021) for 19 volcanoes considered more likely to have an eruption in the future. Our study underlines two main aspects. First, it demonstrates the challenges of regional risk assessment, especially for cross-boundary volcanoes managed by multiple institutions and associated with different geographical contexts. Second, the combination of multiple risk factors (hazard, exposure, vulnerability and resilience) provides fundamental insights for risk management. Indeed, the regional mapping and regional VRR provides the opportunity to consider transboundary volcanoes that are often neglected by local authorities, typically more focused on active volcanoes with short repose intervals, or those that lack any resilience measures.

2 Geological setting of the CVZA

The Andean Cordillera started building during the late Paleozoic, characterized by an important magmatism associated with the beginning of the subduction in the Pacific margin (Ramos and Aleman, 2000; Tilling, 2009)~~. The most significant events in the evolution of the Andes occurred after the breakup of the Farallon plate into the Cocos and Nazca plates in the Late Oligocene (~ 27±2 Ma) that caused changes in subduction geometry, and accelerated crustal shortening, thickening and uplift in the Northern and Central Andes (Jaillard et al., 2000; Ramos and Aleman, 2000; Jordan et al., 1983; Sempere et al., 1990). The resulting increase in convergence rates drove the magmatic activity along the whole Andean chain~~. The most significant events in the evolution of the Andes occurred after the breakup of the Farallon plate into the Cocos and Nazca plates in the Late Oligocene (~ 27±2 Ma) that caused changes in subduction geometry, and accelerated crustal shortening, thickening and uplift in the Northern and Central Andes (Jaillard et al., 2000; Ramos and Aleman, 2000; Jordan et al., 1983; Sempere et al., 1990; Hall et al., 2008). The resulting increase in convergence rates drove the magmatic activity nearly all along the Andean ridge (Stern, 2004)~~. Several studies discuss the Andean volcanic arc, Andean magmatism and associated volcanism (e.g., Jaillard et al., 2000; Ramos and Aleman, 2000; Stern, 2004; Hall et al., 2008). Although many of the main features of the Andes were formed during the Miocene, neotectonic deformation significantly modified the topography, controlled the location of active volcanoes and thus the distinction among small arc segments within larger volcanic zones~~. Although many of the main features of the Andes were formed during the Miocene, neotectonic deformation significantly modified the topography, controlled the location of active volcanoes and thus the distinction among small arc segments within the main volcanic zones (Stern, 2004)~~. A total of 204 out of the 1500 active volcanoes during the Holocene worldwide are part of the Andes, but their distribution is not continuous along the Andean margin (Tilling, 2009). Four segments can be identified (Fig. 1): the Northern Volcanic Zone of the Andes (NVZA) from Colombia to Ecuador; the Central Volcanic Zone of the Andes (CVZA) along southern Peru, northern Chile, southwestern Bolivia, and northwestern Argentina; the Southern Volcanic Zone of the Andes (SVZA) extending from central to southern Chile and Argentina; and finally, the Austral Volcanic Zone of the Andes (AVZA), along the southernmost region of the continent. These segments are separated from each other by volcanically inactive gaps that may also be a result of changes in the slabs dip (e.g., Barazangi and Isacks, 1976; Thorpe, 1984; Pilger, 1984; Stern, 2004; Tilling, 2009).~~

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. A total of 204 out of the 1500 active volcanoes during the Holocene worldwide are part of the Andes, but their distribution is not continuous along the Andean margin (Tilling, 2009; GVP, 2023a). Four main zones can be identified (Fig. 1): the Northern Volcanic Zone of the Andes (NVZA) from Colombia to Ecuador; the Central Volcanic Zone of the Andes (CVZA) along southern Peru, northern Chile, south-western Bolivia, and north-western Argentina; the Southern Volcanic Zone of the Andes (SVZA) extending from central to southern Chile and Argentina; and finally, the Austral Volcanic Zone of the Andes (AVZA), along the southernmost region of the continent. These segments are separated from each other by volcanically inactive gaps that may be a result of the subduction of the Nazca and Juan Fernandez ridges, which is an important factor controlling the geometry of Andean flat-slabs (e.g., Barazangi and Isacks, 1976; Thorpe et al., 1984; Pilger, 1984; Stern, 2004; Tilling, 2009; Kay and Coira, 2009).

The CVZA, the aim of this study, is located between latitudes 14° and 28°S of the Andean cordillera, between the Peruvian and Pampean flat-slab segments (Fig. 1). ~~Almost all~~All the volcanoes in this zone are above ~~4,000~~3,500 m a.s.l., constituting a high, remote, and exceptionally arid region (De Silva and Francis, 1991). It is formed by the subduction of the Nazca Plate below the South American Plate at a convergence rate of 7-9 cm~~/~~ per year and an angle of 30° to the trench (Cahill and Isacks, 1992; Hayes et al., 2018; Gianni et al., 2019). The continental crust in the CVZA reaches a thickness of up to 65-70 km, (James, 1971; Van der Meijde et al., 2013), composed of Cenozoic volcanic rocks overlying a ~~2000~~2,000 Ma basement in the northern part and Late Precambrian-to-Paleozoic substrate in the southern segment (Walker et al., 2013). Andesites, dacites and rhyolites are the dominant rock ~~types erupted~~composition in the CVZA, although basaltic andesites and occasional basalts occur. The most relevant volcanic hazards ~~in~~of the Central Andean volcanoes include tephra fallout, pyroclastic density currents, ballistics, lava flows and lava domes, debris flows, and lahars (Bertin et al., 2022a).

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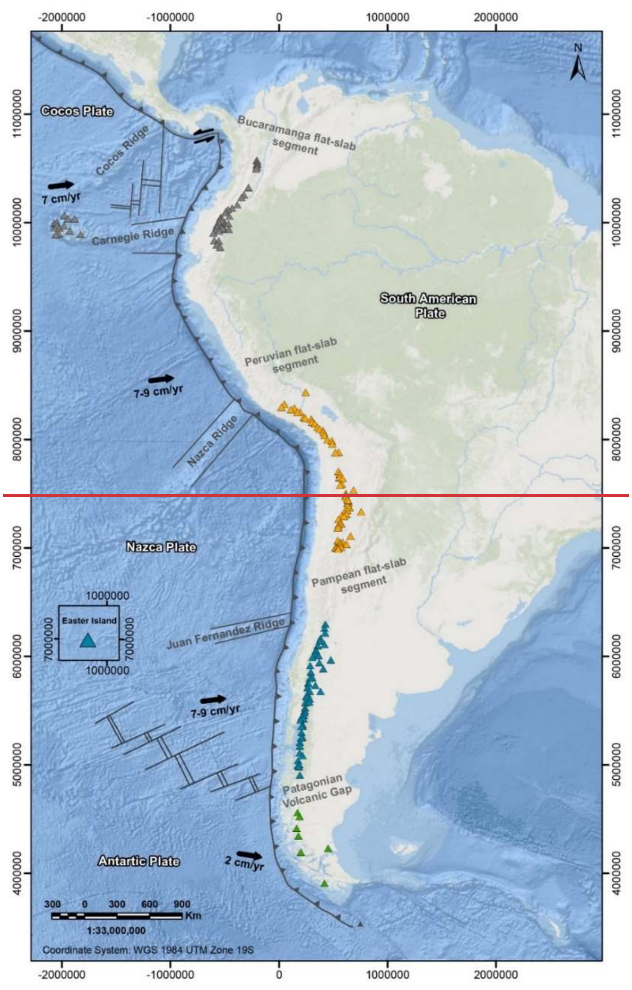
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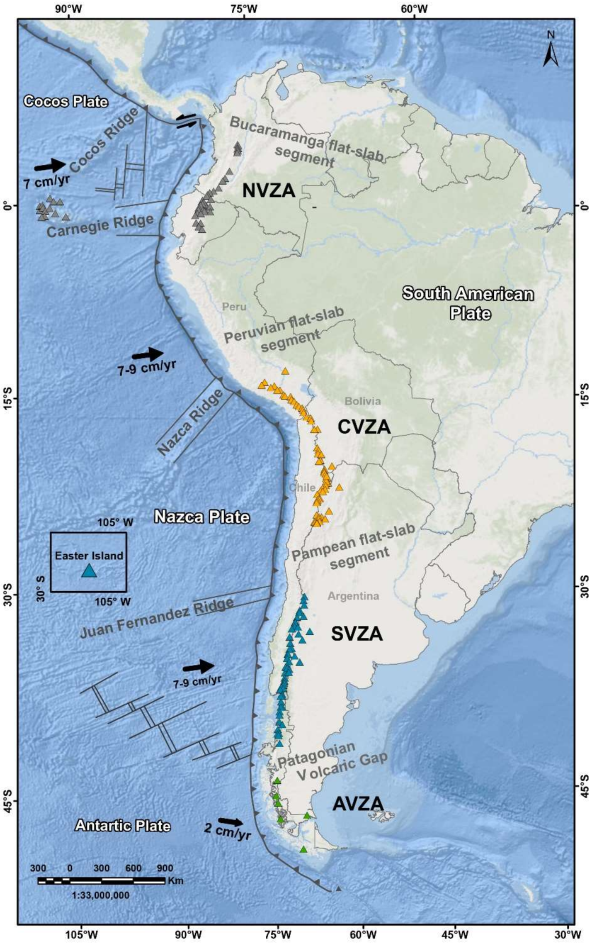

Figure 1: Location map showing the Northern Volcanic Zone of the Andes (NVZA~~) (~~; grey triangles), Central Volcanic Zone of the Andes (CVZA~~) (~~; yellow triangles), Southern Volcanic Zone of the Andes (SVZA~~) (~~; blue triangles), and Austral Volcanic Zone of the Andes (AVZA~~) (~~; green triangles). Modified from Stern (2004). ~~Service~~ Layer ~~Credits:~~ Sources: Esri, USGS, NOAA.

3 Methodology

This study includes the analysis of volcanoes in the four countries prone to be impacted by future volcanic activity ~~in~~of the CVZA (i.e., Peru, Bolivia, Argentina and Chile~~) for which four~~). Four main steps were carried out: 1) ~~update of the inventory~~compilation of active and potentially active volcanoes of the CVZA based on the existing ~~catalogs~~catalogues of De Silva and Francis (1991), GVP (2013), Macedo et al. ~~(2016), SERNAGEOMIN (2023)~~(2016), SERNAGEOMIN (2023), ~~Elissondo and Farías (2023)~~Elissondo and Farías (2023) and Aguilera et al. (2022), ~~and compilation~~including a detailed review of hazard and resilience parameters ~~(Reyes-Hardy et al., 2023); 2) compilation of elements at risk;~~, available in Reyes-Hardy et al., (2023); 2) identification of elements at risk (e.g., population, transportation and critical facilities); 3) regional mapping that includes both volcanic hazard ~~parameters~~features and surrounding elements at risk~~; 4)~~ for all the 59 active and potentially active volcanoes of the CVZA; 4) application of the VRR methodology (Nieto-Torres et al., 2021) to identify the ~~riskiest volcanoes of the CVZA.~~

~~The regional mapping was achieved using all active and potentially active volcanoes identified for the CVZA, whereas the VRR methodology was applied to the~~ highest risk volcanoes ~~that had at least one eruption in the last 1,000 years, following Guimarães et al., (2021), in addition to the volcanoes with Pleistocene or Holocene~~ of the CVZA based on the estimation and scoring of hazard, exposure, vulnerability and resilience parameters. This last step focus on volcanoes having shown ~~a~~ volcanic activity ~~but currently showing 3 types of~~ during the past 1,000 years or records of ~~the~~ three signs of unrest ~~signals~~ (i.e~~.~~., seismic ~~activity~~, ground deformation and degassing).

3.1 Identification of active and potentially active volcanoes of the CVZA

The first challenge in ranking the risk amongst volcanoes in a specific area is the selection of volcanoes to consider. Since geochronological data or preserved historical records are largely absent in the CVZA, the term "potentially active" has been widely used to account for this lack of data. ~~**3.1 Identification of active and potentially active volcanoes of the CVZA**~~

~~The first challenge in ranking the risk amongst volcanoes in a specific area is the initial selection of the active and potentially active volcanoes to consider. This is especially important for the CVZA because of the lack of geochronological evidence and/or preserved historical records for most volcanoes (Lara et al., 2021; Bertin et al., 2022a). Therefore, the first step of our study was the identification of the volcanoes of the CVZA based on a comprehensive analysis of 6 catalogs (i.e., De Silva and Francis, 1991; GVP, 2013; Macedo et al., 2016; SERNAGEOMIN, 2023; Elissondo and Farías, 2023; Aguilera et al., 2022). The identification and compilation of hazard and resilience parameters of the CVZA volcanoes included all Holocene volcanoes as well as Pleistocene volcanic centers that show unrest signs and/or fresh volcanic morphological features. Hazard and resilience parameters used for both the regional map and VRR are detailed in Supplementary material 1, based on Reyes-Hardy et al. (2023).~~

This has led to discrepancies in the CVZA volcano count evidenced in the number of potentially active eruptive centres identified by the "Volcanoes of the Central Andes" (n=73; De Silva and Francis, 1991), the Global Volcanism Program database (n=67; GVP, 2013), as well as within different catalogues accounting for CVZA volcanoes (i.e., Elissondo et al., 2016; SERNAGEOMIN, 2020; Aguilera et al., 2022; Macedo et al., 2016; SERNAGEOMIN, 2023; Elissondo and Farías, 2024). The first step of our study was the compilation of the active and potentially active volcanoes of the CVZA based on a comprehensive analysis of 6 catalogues in collaboration with SEGEMAR, SERNAGEOMIN, and INGEMMET, combined with their own updated volcanic risk rankings relative for each country (i.e., Argentina, Elissondo and Farías, 2024; Peru, Macedo et al., 2016; and Chile, SERNAGEOMIN, 2023). A total of 59 volcanic centres have been identified as active or potentially active, of which 50 have Holocene and 9 Pleistocene activity (Table 1). In terms of geographical distribution, 12 volcanoes are located in Chile, 9 in Argentina, 13 in the Chile-Argentina border, 7 in the Chile-Bolivia border, 2 in Bolivia and 16 in Peru. In terms of types of volcanoes, 34 are stratovolcanoes, 15 are volcanic complex, three are volcanic fields, one is a pyroclastic cone, four are dome complex, one is a maar and one is a caldera (Supplementary material 1). Among volcanoes with Holocene activity, 16 volcanoes had at least one eruption in the last 1,000 years. In addition, three volcanoes (one of Pleistocene and two of Holocene activity) with eruptions older than 1,000 years, showed records of ~~all~~ three signs of unrest (i.e., seismicity, ground deformation and degassing). The complexity associated with the definition of active and potentially active volcanoes of the CVZA highlights the challenging characterization of volcanoes in this area, including those with long repose interval and/or poor constrain of eruptive record. Although our volcano list is the best agreement of active and potentially active volcanoes of the CVZA, such a list can change depending on future knowledge of this zone including geochronology and monitoring studies.

Table 1. List of the active and potentially active volcanoes of the CVZA (extracted from Supplementary material 1). C.: Cerro, N.: Nevado (s), Pe: Peru, Ch: Chile, Bo: Bolivia, Ar: Argentina, H: Holocene, Pl: Pleistocene, DC: Dome complex, PC: Pyroclastic cone, ST: Stratovolcano, VF: Volcanic field, VC: Volcanic complex, S: Seismic unrest records, G: Ground deformation records, D: Fumarolic/magmatic degassing records, U: Unknown, and ND: No data. Notice that volcanoes with last eruption during the past 1,000 years and/or presenting records of all three signs of unrest are in bold.

N°	Volcano name	Latitude	Longitude	Country	Type	Age	Last eruption	Signs of unrest	Nº Holocene eruptions	Max VEI
1	Quimsachata	14.13°S	71.36°W	Pe	DC	H[*]	4450 BCE[*]	No	1	ND
2	C. Auquihuato	15.07°S	73.18°W	Pe	PC	H[*, 90]	U[*]	G[72]	ND	ND
3	Sara Sara	15.33°S	73.45°W	Pe	ST	Pl[*,1]	14000 BCE[65]	No	0[1]	ND[1]
4	**Andahua**	15.42°S	72.33°W	Pe	VF	H[*]	**1490 CE[*]**	D[90]	4 (3)	ND
5	Coropuna	15.52°S	72.65°W	Pe	ST	H[*]	~700 BP[65]	D[73]	ND	ND
6	Huambo	15.78°S	72.08°W	Pe	VF	H[*]	700 BCE[*]	No	1 (1)	ND
7	**Sabancaya**	15.78°S	71.85°W	Pe	ST	H[*]	**2016 – present[65]**	**S[76], G[74, 75], D[77]**	14 (12)	3
8	Chachani	16.19°S	71.53°W	Pe	VC	Pl[2]	56 000 ya[65]	S[78], D[79]	0	ND

9	**El Misti**	16.29°S	71.40°W	Pe	ST	H[*]	**1440 - 1470 CE[65]**	S[80], D[81]	22 (15)	5[69]
10	**Ubinas**	16.35°S	70.90°W	Pe	ST	H[*]	**2019 CE[*]**	**S[82], G[84], D[83]**	26 (23)	5
11	**Huaynaputina**	16.60°S	70.85°W	Pe	ST	H[*]	**1600 CE[*]**	D[85]	2 (2)	6
12	**Ticsani**	16.75°S	70.59°W	Pe	ST	H[*]	**1800 CE[*]**	**S[88], G[86, 87], D[89]**	1 (1)	2-3[70]
13	**Tutupaca**	17.02°S	70.37°W	Pe	ST	H[*]	**1802 CE[*]**	D[8]	5 (2)	4
14	**Yucamane**	17.18°S	70.19°W	Pe	ST	H[*]	**1787 CE[66]**	D[9, 10]	1 (1)	5
15	Purupuruni	17.32°S	69.90°W	Pe	DC	H[3]	Pl[*]	No	ND	ND
16	Casiri	17.47°S	69.81°W	Pe	ST	H[*]	2600 ± 400 BP[65]	D[11]	ND	ND
17	Tacora	17.72°S	69.77°W	Ch	ST	H[*]	U[*]	S[12, 13], D[14, 15, 16]	2 (0)	ND
18	Taapaca	18.10°S	69.50°W	Ch	VC	H[*]	320 BCE[*]	(G, D)[14]	8 (8)	ND
19	**Parinacota**	18.16°S	69.14°W	Ch-Bo	ST	H[*]	**1803 CE[67]**	S[17]	38[67] (6)	4[71]
20	**Guallatiri**	18.42°S	69.09°W	Ch	ST	H[*]	**1960 CE[*]**	S[18, 19], D[20, 21, 22]	6 (4)	2
21	Tata Sabaya	19.13°S	68.53°W	Bo	ST	H[*]	U[*]	No	ND	ND
22	**Isluga**	19.15°S	68.83°W	Ch	ST	H[*]	**1913 CE[*]**	S[23], D[5, 14, 24]	8 (7)	2
23	**Irruputuncu**	20.73°S	68.55°W	Ch-Bo	ST	H[*]	**1995 CE[*]**	(S, D)[14, 18]	2 (1)	2
24	Olca-Paruma	20.93°S	68.41°W	Ch-Bo	VC	H[*]	U[*]	D[14, 25]	1 (0)	ND
25	Aucanquilcha	21.22°S	68.47°W	Ch	ST	Pl[*]	Pl[*]	D[5]	0	ND
26	Ollagüe	21.30°S	68.18°W	Ch-Bo	ST	Pl[*]	Pl[*]	(S, D)[14, 18, 86]	0	ND
27	C. del Azufre	21.78°S	68.23°W	Ch	VC	H[*]	U[*]	G[23,45,74], D[26]	ND	ND
28	**San Pedro**	21.88°S	68.39°W	Ch	ST	H[*]	**1960 CE[*]**	D[14]	10 (6)	2
29	**Uturuncu**	22.27°S	67.18°W	Bo	ST	Pl[*]	Pl[*]	**S[30], G[74, 27, 28, 29, 32, 33, 34], D[31]**	0	ND
30	**Putana**	22.55°S	67.85°W	Ch-Bo	ST	H[*]	**1810 CE[*]**	**S[25, 28, 18], G[28], D[25, 28, 18]**	2 (1)	2
31	Escalante-Sairecabur	22.72°S	67.89°W	Ch-Bo	VC	H[*]	U[*]	No	ND	ND
32	Licancabur	22.83°S	67.88°W	Ch-Bo	ST	H[*]	U[*]	No	ND	ND
33	Acamarachi	23.29°S	67.61°W	Ch	ST	H[*]	U[*]	No	ND	ND
34	**Lascar**	23.37°S	67.73°W	Ch	ST	H[*]	**2023 CE[**]**	**S[36], G[35], D[37, 38, 39, 40]**	37 (32)[**]	4
35	Chiliques	23.58°S	67.70°W	Ch	VC	H[*]	U[*]	D[41]	ND	ND
36	Alitar	23.80°S	67.39°W	Ch	Maar	Pl[4]	Pl[4]	D[20]	0	ND
37	Puntas Negras	23.44°S	67.32°W	Ch	VC	H[5]	ND	No	ND	ND
38	Tuzgle	24.05°S	66.48°W	Ar	ST	H[*]	U[*]	No	ND	ND
39	Aracar	24.29°S	67.78°W	Ar	ST	H[*]	U[*]	No	1 (0)	2
40	Socompa	24.39°S	68.24°W	Ch-Ar	ST	H[*]	5250 BCE[*]	G[42, 43], D[5, 24, 14, 44]	1 (1)	ND
41	Arizaro	24.45°S	68.023°W	Ar	VF	H[6]	80,000 ± 60,000 BP[68]	No	ND	ND
42	**Llullaillaco**	24.72°S	68.53°W	Ch-Ar	ST	H[*]	**1877 CE[*]**	No	3 (3)	2
43	Escorial	25.08°S	68.36°W	Ch-Ar	ST	H[*]	U[*]	No	ND	ND

44	**Lastarria**	25.16°S	68.50°W	Ch-Ar	ST	H*	U*	**S[14, 18, 51], G[74, 45, 46, 47, 48, 49, 50], D[20, 22, 52, 53, 54, 55]**	ND	ND
45	Cordón del Azufre	25.33°S	68.52°W	Ch-Ar	VC	H*	U*	No	ND	ND
46	C. Bayo	25.41°S	68.58°W	Ch-Ar	VC	H*	U*	G[23,45,74]	ND	ND
47	Antofagasta	26.12°S	67.40°W	Ar	VC	H*	U*	No	ND	ND
48	Sierra Nevada	26.48°S	68.58°W	Ch-Ar	VC	H*	U*	No	ND	ND
49	Cueros de Purulla	26.55°S	67.82°W	Ar	DC	Pl[7]	ND	No	0	ND
50	Peinado	26.62°S	68.11°W	Ar	ST	H*	U*	No	ND	ND
51	C. El Cóndor	26.63°S	68.36°W	Ar	ST	H*	U*	No	ND	ND
52	**C. Blanco**	26.78°S	67.76°W	Ar	Caldera	H*	2300 BCE*	**S[60], G[74, 23, 28, 56, 57, 58, 59], D[56, 61, 62]**	1 (1)	7
53	Falso Azufre	26.80°S	68.37°W	Ch-Ar	VC	H*	U*	No	ND	ND
54	N. de Incahuasi	27.03°S	68.29°W	Ch-Ar	VC	H*	U*	No	ND	ND
55	El Fraile	27.04°S	68.37°W	Ch-Ar	DC	Pl[7]	ND	D[63]	0	ND
56	N. Tres Cruces	27.08°S	68.80°W	Ch-Ar	ST	Pl*	Pl*	No	0	ND
57	El Solo	27.10°S	68.71°W	Ch-Ar	ST	H*	U*	No	ND	ND
58	N. Ojos del Salado	27.10°S	68.54°W	Ch-Ar	VC	H*	750 CE*	D[86,64]	2 (1)	1
59	C. Tipas	27.19°S	68.56°W	Ar	VC	H*	U*	No	ND	ND

* GVP (2013), ** GVP (2023a, b), [1]Rivera et al. (2020), [2]Aguilar et al. (2022), [3]Bromley et al. (2019), [4]Amigo et al. (2012), [5]De Silva and Francis (1991), [6]Viramonte et al. (1984), [7]Bertin (2022), [8]Mariño et al. (2019), [9]Fídel and Huamaní (2001), [10]Cruz et al. (2010), [11]Cruz et al. (2020), [12]Clavero et al. (2006), [13]Pavez et al. (2019), [14]Lara et al. (2011), [15]Capaccioni et al. (2011), [16]Contreras (2013), [17]REAV Parinacota (2020), [18]Pritchard et al. (2014), [19]SERNAGEOMIN (2021), [20]Aguilera (2008), [21]Inostroza et al. (2020a), [22]Inostroza et al. (2020b), [23]Pritchard and Simons (2004), [24]González-Ferrán (1995), [25]Tassi et al. (2011), [26]Aguilera et al. (2020), [27]Fialko and Pearse (2012), [28]Henderson and Pritchard (2013), [29]Hickey et al. (2013), [30]Jay et al. (2012), [31]Sparks et al. (2008), [32]Gottsmann et al. (2017), [33]Henderson et al. (2017), [34]Pritchard et al. (2018), [35]Pavez et al. (2006), [36]Gaete et al. (2019), [37]Matthews et al. (1997), [38]Aguilera et al. (2006), [39]Tassi et al. (2009), [40]Bredemeyer et al. (2018), [41]Pieri and Abrams (2004), [42]Liu et al. (2022), [43]Liu et al. (2023), [44]Seggiaro and Apaza (2018), [45]Froger et al. (2007), [46]Ruch et al. (2008), [47]Ruch et al. (2009), [48]Anderssohn et al. (2009), [49]Ruch and Walter (2010), [50]Budach et al. (2011), [51]Spica et al. (2012), [52]Naranjo (1985), [53]Aguilera et al. (2012), [54]Aguilera et al. (2016), [55]Robidoux et al. (2020), [56]Viramonte et al. (2005), [57]Brunori et al. (2013), [58]Vélez et al. (2021), [59]Báez et al. (2015), [60]Mulcahy et al. (2010), [61]Chiodi et al. (2019), [62]Lamberti et al. (2021), [63]Salas (2022, pers. comm.), [64]Gardeweg et al. (1998), [65]IGP (2021), [66]OVI (2021), [67]Bertin et al. (2022b), [68]Schoenbohm and Carrapa (2015), [69]Harpel et al. (2011), [70]Cruz (2020), [71]Clavero et al. (2004), [72]Morales Rivera et al. (2016), [73]Ramos (2019), [74]Pritchard and Simons (2002), [75]Jay et al. (2015), [76]Samaniego et al. (2016), [77]BGVN (2021), [78]Centeno et al. (2013), [79]Gałaś et al. (2014), [80]Sandri et al. (2014), [81]Thouret et al. (2001), [82]Del Carpio and Torres (2020), [83]Rivera et al. (2010), [84]Apaza et al. (2021), [85]Antayhua et al. (2013), [86]Jay et al. (2013), [87]Gonzáles et al. (2006), [88]Holtkamp et al. (2011), [89]Byrdina et al. (2013), [90]Macedo et al. (2016). Notice that if not indicated otherwise, the “Max VEI” and "N° Holocene eruptions" values correspond to the maximum VEI, and the number of eruptions and confirmed eruptions (in parenthesis) during the Holocene according to GVP (2013, 2023a).

3.2 Elements at risk

In this study, the elements at risk include population, residential buildings, critical infrastructure (e.g., transportation, power, water and telecommunication supply networks), emergency facilities (e.g., police and fire stations), critical facilities (e.g., government offices, schools), and economic activities (e.g., parks and protected areas, mines, ~~salts~~salt pans, farmlands, industrial areas). Each dataset is country-specific, ~~favoring~~favouring official sources (e.g., ministries, national geographic institutes, national observatories, statistical institutes). Open-source datasets (e.g., HOT, 2020) were used to complete missing official information. All details and sources of elements at risk are available in Supplementary material 2.

Concerning the population, density data are provided by WorldPop - Open Spatial Demographic Data and Research (WorldPop, 2018). Worldpop data used in this study represent the spatial distribution of resident population density in 2020 per grid-cell (inhabitants per km^2), and they are provided at country level (i.e., Peru, Bolivia, Argentina, and Chile), with a resolution of ~~about 1km. They are obtained~~30 arc seconds (approximately 1 km at the equator). Obtained from the so-called top-down unconstrained modelling~~ (WorldPop, 2023). However~~, this method misplaces the population in some ~~places indicating~~locations showing the presence of people in uninhabited areas (WorldPop, 2023). ~~We corrected the error of~~A validation with satellite images was used to correct and reclassify the discrepancies with non-zero population ~~using mainly satellite images and we reclassified the pixels in~~to the range of 0-0.1 inhabitants per km^2. This data correction ~~of data~~ allowed us to obtain results of population density that were more consistent with the density and distribution of ~~population and residential buildings~~populated centres (see Supplementary material 2). National censuses were used to extract socio-economic data required to constrain the VRR exposure parameters (IGN, 2010; INDEC, 2010; INE, 2012, 2017a, 2017b; INEI, 2017; IDE, 2021; ONEMI, 2021a, 2021b).

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~~**Table 1. Transportation factor resources. ND: No Data.**~~

~~References by country~~	~~Road network~~	~~Rail network~~	~~Airports and air routes~~	~~Harbors~~	~~Ferry terminals along rivers and lakes~~	~~Border crossing check posts~~
~~Argentina~~	~~Ministerio de Transporte, 2016b, 2016a, 2018; IGN, 2021; Vialidad Nacional, 2021; HOT, 2020~~	~~APT, 2021; CNRT, 2021; Tren a las Nubes, 2021; Tren Patagónico, 2021; Trenes Argentinos, 2021; FEPSA, 2021; Ferrosur Roca, 2021; Ferrovías, 2021; La Tronchita, 2021; Metrovias, 2021; Patagonia~~	~~ICAO, 2022~~	~~Puertos Argentina, 2019; Terminales Portuarias, 2021; Worldport, 2021~~	~~ICAO, 2022~~	~~SENASA, 2018; Fronteras Argentina, 2022~~

		~~express, 2021; TACL, 2021; TAOF, 2021; HOT, 2020~~				
~~Bolivia~~	~~GeoBolivia, 2021; UDAPE, 2021; INE, 2022; HOT, 2020~~	~~OCHA, 2021; HOT, 2020~~	~~ICAO, 2022~~	~~Worldport, 2021~~	~~HOT, 2020~~	~~ND~~
~~Chile~~	~~BCN, 2019, 2021; Conaset, 2021; MOP, 2021b, 2021a, 2021c; HOT, 2020~~	~~EFE, 2021; Ferrocarril Antofagasta, 2021; Merval, 2021; Metro de Santiago, 2021; HOT, 2020~~	~~ICAO, 2022~~	~~DOP, 2021; Worldport, 2021~~	~~HOT, 2020~~	~~Fronteras Chile, 2022~~
~~Peru~~	~~MTC, 2021; HOT, 2020~~	~~Ferrocarril Trasandino, 2021; FVCA, 2021; Metro de Lima, 2021; HOT, 2020~~	~~ICAO, 2022~~	~~Worldport, 2021~~	~~HOT, 2020~~	~~ND~~

Transportation includes: i) road network, ii) rail network, iii) airports and air routes, iv) ~~harbors~~harbours, v) ferry terminals along rivers and lakes, and vi) border crossing check posts (~~Table 1). The~~ Supplementary material 2). A taxonomy homogenization of the road network ~~is classified in four~~was required to reclassify in five categories~~: primary, secondary, tertiary, urban and rural for each country~~ as described in Table 2. In the case of rural paths, only connecting routes between rural ~~centers~~centres (i.e., ~~critical~~important exposed element in the CVZA) have been considered. There are no distinctions between railways (e.g., passenger transport, freight, tourist lines) and all lines and train stations have been included. Ferry terminals along rivers and lakes are also included. Given the geographical characteristics of the countries ~~analyzed~~analysed, particularly the hydrological characteristics, these facilities are essential~~ before, after, and during any hazardous event. ~~.

Table 2. Standardization of road classification in Argentina, Bolivia, Chile and Peru.

Road type	ARGENTINA	BOLIVIA	CHILE	PERU
Primary Road ~~Network~~	Red Vial Primaria	Red Vial Fundamental (RVF)	Ruta Internacional, Ruta Nacional	Red Vial Nacional
Secondary Road ~~Network~~	Red Vial Secundaria	Redes Departamentales	Caminos Regionales Principales	Red Vial Departamental
Tertiary Road ~~Network~~	Red Vial Terciaria	Redes Municipales	Caminos Regionales Provinciales	Red Vial Vecinal
Urban Road ~~Network~~	Red Vial Urbana	Local network	Caminos Regionales Comunales y de Acceso	Local network
Rural Paths	Senda Rural	Rural Paths	Vías Rurales	Rural Paths

Facilities ~~considered ~~are «all manmade structures or other improvements that, because of their function, size, service area, or uniqueness, have the potential to cause serious bodily harm, extensive property damage, or disruption of vital socio-economic activities if they are destroyed, damaged, or if their functionality is impaired» (FEMA 2007). ~~The structures analyzed~~Facilities considered are divided into two groups: i) emergency facilities (~~i.~~e.g., civil protection ~~installations~~headquarters, police stations, fire stations~~, health sites, emergency operations centers and ranger stations, and heliports) (Table 3);~~; see Supplementary Material 2) and ii) critical facilities~~ (i.e., schools and government offices).~~. The first group consists of essential services to public safety and health; the second one includes strategic structures for social and economic sectors.

~~Table 3. Emergency facilities resources.~~

			~~Emergency facilities~~			
~~References by country~~	~~Civil protection headquarters~~	~~Police stations~~	~~Fire stations~~	~~Health centers~~	~~Emergency operations centers and ranger stations~~	~~Heliports~~
~~Argentina~~	~~SGRPC, 2021~~	~~GNA, 2021; PFA, 2021; HOT, 2020~~	~~BVRA, 2021; MINSEG, 2021; HOT, 2020~~	~~GHMP, 2021; REFES, 2021; OCHA, 2021 ; HOT, 2020~~	~~Guardaparques Nacionales, 2021; HOT, 2020~~	~~IGNSIG, 2021; HOT, 2020~~
~~Bolivia~~	~~VIDECI, 2021~~	~~HOT, 2020~~	~~HOT, 2020~~	~~GHMP, 2021; RAEP, 2021; OCHA, 2021; HOT, 2020~~	~~SERNAP, 2021; HOT, 2020~~	~~HOT, 2020~~
~~Chile~~	~~MDCC, 2021; MINEDUC, 2021~~	~~Carabineros de Chile, 2021; PDI, 2021; HOT, 2020~~	~~Bomberos de Chile, 2021; HOT, 2020~~	~~DEIS, 2021; GHMP, 2021; OCHA, 2021; HOT, 2020~~	~~CONAF, 2021; HOT, 2020~~	~~HOT, 2020~~
~~Peru~~	~~INDECI, 2021~~	~~PNP, 2021; HOT, 2020~~	~~CGBVP, 2021; HOT, 2020~~	~~EDSP, 2021; GHMP, 2021; MINSA, 2021; OCHA, 2021; HOT, 2020~~	~~SERNAP, 2021; HOT, 2020~~	~~MINTC, 2021; HOT, 2020~~

3.3 Regional mapping

The regional mapping ~~step ~~consists in combining volcanic hazard ~~parameters~~features and elements at risk, representing a first-order analysis of volcanoes that could have a potential impact in the region. In terms of hazard~~ parameters~~, the number of eruptions and the maximum VEI during the Holocene have been represented as well as the age of ~~the volcanoes~~their last eruption. In terms of elements at risk, density maps were produced for population, transportation and critical and emergency facilities at a 1 km spatial resolution. For the population density map, we classified population density in four ranges (i.e., 0-1, 1-10, 10-100, and >100 inhabitants per km^2). The transport density combines point features expressed in the number of structures per km^2 (i.e., train stations, airports, ~~harbors~~harbours, and border crossings) and linear features expressed in ~~kilometers~~kilometres of infrastructure per km^2 (i.e., road network, railways, and air routes). Critical and emergency facilities are expressed as number of facilities per km^2. Separate layers of hazard and density of elements at risk are presented in Supplementary ~~material~~Material 3.

3.4 ~~The~~ Volcanic Risk Ranking

The identification of the volcanic systems with the highest potential risk was performed using the VRR methodology introduced by Nieto-Torres et al. (2021) and applied to Latin American volcanoes by Guimarães et al. (2021). The VRR step ~~considered~~is carried out for the 19 active and potentially active volcanoes ~~having had~~identified based on their activity ~~in~~during the past 1,000 years ~~in addition to the volcanoes with Pleistocene~~ or ~~Holocene activity currently showing 3 types~~records of three signs of unrest~~,~~ (i.e.~~.~~., seismic ~~activity~~, ground deformation and degassing~~.~~). We apply the VRR ~~(~~-0~~)~~ (2 factors), VRR ~~(~~-1~~)~~ (3 factors) and VRR ~~(~~-2~~)~~ (4 factors) strategies of Nieto-Torres et al. (2021):

$$VRR\cancel{(}-0\cancel{)(}\ (threat) = Hazard \times Exposure, \qquad (1)$$

$$VRR\cancel{(}-1\cancel{)}\ \cancel{=}= Hazard \times Exposure \times Vulnerability, \qquad (2)$$

$$VRR\cancel{(}-2\cancel{)}\ \cancel{= (}= (Hazard \times Exposure \times Vulnerability)/(\cancel{Res}Resilience + 1), \qquad (3)$$

Vulnerability considers 4 dimensions (physical, systemic, social, and economic), while resilience includes 2 dimensions (mitigation measures and response) (Nieto-Torres et al., 2021). ~~The resilience factor~~As VRR – 2 is a ratio, the resilience factor is mathematically corrected ~~in order for the formula~~with the value of 1, after the aggregation of resilience parameters and before normalization, to ~~stay valid~~obtain a VRR result even ~~in those~~for cases where the resilience factor is equal to zero (Nieto-Torres et al., 2021).

There are 9 hazard parameters, 9 exposure parameters, 10 vulnerability parameters and 13 resilience parameters (details in Supplementary material 4). The scores previously assigned for each parameter by Guimarães et al. (2021) have been updated as more recent information ~~was~~became available (e.g., historical eruption of Parinacota volcano~~). The normalization is,~~

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increasing population density, telecommunication facilities; ~~and~~ updated multiple economic activities). Each risk factor (i.e., hazard, vulnerability, exposure and resilience) was normalized to the maximum possible score and multiplied by the value of 10, to guarantee the same weight. Therefore, the scores were normalized based on the maximum possible value for each of the evaluated factors (19 for hazard, 48 for exposure, 95 for vulnerability, and 18 for ~~hazard, exposure, vulnerability, and~~ resilience~~, respectively~~). The maximum hazard score represents the highest intensity of each volcanic process; the maximum exposure score is the largest quantity of ~~elements~~assets prone to be affected; and the maximum vulnerability score, represents the highest level of susceptibility to damage or loss. In contrast, the maximum resilience score represents the maximum level of capacity to face or overcome a disaster (Nieto-Torres et al., 2021). ~~Each risk factor was normalized to the maximum possible score and multiplied by the value of 10, to guarantee the same weight for each risk factor. For VRR (2), the value of 1 is added after the aggregation of resilience parameters, before normalization (Nieto-Torres et al., 2021).~~

4. Results

4.1 ~~Active and potentially active volcanoes of the CVZA~~

~~From our detailed analysis of the existing catalogs and published work, a total of 59 volcanic centers have been identified as active or potentially active, of which 50 have Holocene and 9 Pleistocene activity (Table 4). In terms of geographical distribution, 12 volcanoes are located in Chile, 9 in Argentina, 13 in the Chile-Argentina border, 7 in the Chile-Bolivia border, 2 in Bolivia and 16 in Peru. In terms of types of volcanoes, 34 are stratovolcanoes, 15 are volcanic complex, 3 are volcanic fields, 1 is a pyroclastic cone, 4 are dome complex, 1 is a maar and 1 is a caldera (Supplementary material 1). Among the Holocene volcanoes, 16 volcanoes had at least one eruption in the last 1,000 years. In addition, 36 volcanoes out of the 59 show at least one sign of unrest whereas 3 volcanoes, 1 Pleistocene and 2 Holocene with eruptions older than 1,000 years, show 3 signs of unrest (seismicity, ground deformation and degassing).~~

~~Table 4. New list of the active and potentially active volcanoes of the CVZA (extracted from Supplementary material 1). C.: Cerro, N.: Nevado(s), VF: Volcanic Field, Pe: Peru, Ch: Chile, Bo: Bolivia, Ar: Argentina, H: Holocene, and Pl: Pleistocene.~~

~~Nº~~	~~Volcano name~~	~~Country~~	~~Age~~
~~1~~	~~Quimsachata~~	~~Pe~~	~~H~~
~~2~~	~~Cerro Auquihuato~~	~~Pe~~	~~H~~
~~3~~	~~Sara Sara~~	~~Pe~~	~~P~~
~~4~~	~~Andahua VF~~	~~Pe~~	~~H~~
~~5~~	~~Coropuna~~	~~Pe~~	~~H~~
~~6~~	~~Huambo~~	~~Pe~~	~~H~~
~~7~~	~~Sabancaya~~	~~Pe~~	~~H~~
~~8~~	~~Chachani~~	~~Pe~~	~~P~~

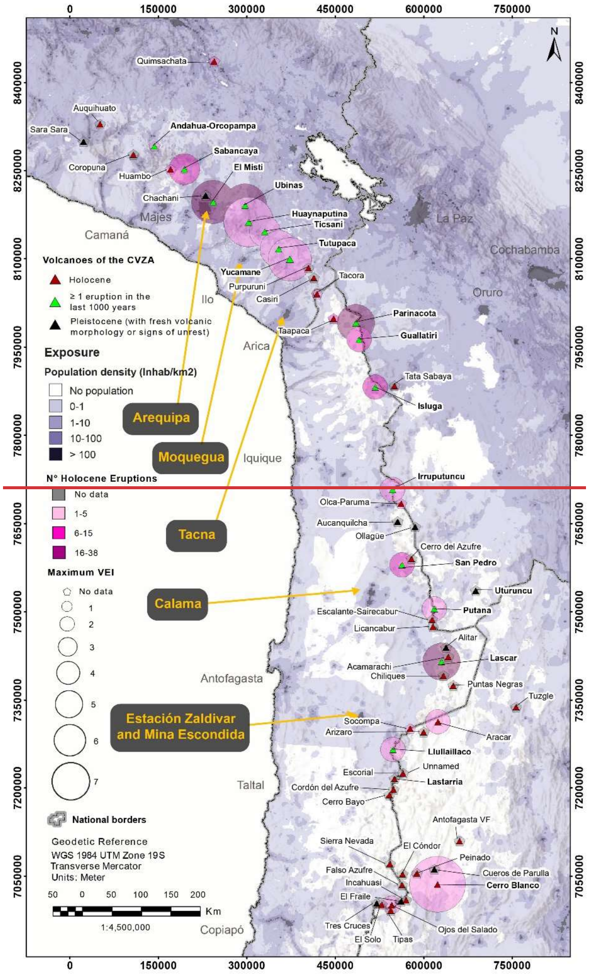
~~9~~	~~El Misti~~	~~Pe~~	~~H~~
~~10~~	~~Ubinas~~	~~Pe~~	~~H~~
~~11~~	~~Huaynaputina~~	~~Pe~~	~~H~~
~~12~~	~~Ticsani~~	~~Pe~~	~~H~~
~~13~~	~~Tutupaca~~	~~Pe~~	~~H~~
~~14~~	~~Yucamane~~	~~Pe~~	~~H~~
~~15~~	~~Purupuruni~~	~~Pe~~	~~H~~
~~16~~	~~Casiri~~	~~Pe~~	~~H~~
~~17~~	~~Tacora~~	~~Ch~~	~~H~~
~~18~~	~~Taapaca~~	~~Ch~~	~~H~~
~~19~~	~~Parinacota~~	~~Ch-Bo~~	~~H~~
~~20~~	~~Guallatiri~~	~~Ch~~	~~H~~
~~21~~	~~Tata Sabaya~~	~~Bo~~	~~H~~
~~22~~	~~Isluga~~	~~Ch~~	~~H~~
~~23~~	~~Irruputuncu~~	~~Ch-Bo~~	~~H~~
~~24~~	~~Olca-Paruma~~	~~Ch-Bo~~	~~H~~
~~25~~	~~Aucanquilcha~~	~~Ch~~	~~P~~
~~26~~	~~Ollagüe~~	~~Ch-Bo~~	~~P~~
~~27~~	~~C. del Azufre~~	~~Ch~~	~~H~~
~~28~~	~~San Pedro~~	~~Ch~~	~~H~~
~~29~~	~~Uturuncu~~	~~Bo~~	~~P~~
~~30~~	~~Putana~~	~~Ch-Bo~~	~~H~~
~~31~~	~~Escalante-Sairecabur~~	~~Ch-Bo~~	~~H~~
~~32~~	~~Licancabur~~	~~Ch-Bo~~	~~H~~
~~33~~	~~Acamarachi~~	~~Ch~~	~~H~~
~~34~~	~~Lascar~~	~~Ch~~	~~H~~
~~35~~	~~Chiliques~~	~~Ch~~	~~H~~
~~36~~	~~Alitar~~	~~Ch~~	~~P~~
~~37~~	~~Puntas Negras~~	~~Ch~~	~~H~~
~~38~~	~~Tuzgle~~	~~Ar~~	~~H~~
~~39~~	~~Aracar~~	~~Ar~~	~~H~~
~~40~~	~~Socompa~~	~~Ch-Ar~~	~~H~~
~~41~~	~~Arizaro VF~~	~~Ar~~	~~H~~
~~42~~	~~Llullaillaco~~	~~Ch-Ar~~	~~H~~
~~43~~	~~Escorial~~	~~Ch-Ar~~	~~H~~
~~44~~	~~Lastarria~~	~~Ch-Ar~~	~~H~~
~~45~~	~~Cordón del Azufre~~	~~Ch-Ar~~	~~H~~

~~46~~	~~C. Bayo~~	~~Ch-Ar~~	~~H~~
~~47~~	~~Antofagasta volcanic field~~	~~Ar~~	~~H~~
~~48~~	~~Sierra Nevada~~	~~Ch-Ar~~	~~H~~
~~49~~	~~Cueros de Purulla~~	~~Ar~~	~~P~~
~~50~~	~~Peinado~~	~~Ar~~	~~H~~
~~51~~	~~C. El Cóndor~~	~~Ar~~	~~H~~
~~52~~	~~C. Blanco~~	~~Ar~~	~~H~~
~~53~~	~~Falso Azufre~~	~~Ch-Ar~~	~~H~~
~~54~~	~~N. de Incahuasi~~	~~Ch-Ar~~	~~H~~
~~55~~	~~El Fraile~~	~~Ch-Ar~~	~~P~~
~~56~~	~~N. Tres Cruces~~	~~Ch-Ar~~	~~P~~
~~57~~	~~El Solo~~	~~Ch-Ar~~	~~H~~
~~58~~	~~N. Ojos del Salado~~	~~Ch-Ar~~	~~H~~
~~59~~	~~C. Tipas~~	~~Ar~~	~~H~~

~~4.2~~ Regional mapping of the CVZA

The regional maps resulting from the combination of the ~~total~~59 CVZA active and potentially active volcanoes with the density maps of population, transportation and facilities are shown in Fig. 2, 3 and 4, respectively. Five zones with more than 100 inhabitants per km^2 are identified close to volcanoes showing various eruptive frequencies and VEIs (Fig. 2). The first zone includes the city of Arequipa (Peru), with El Misti and Ubinas volcanoes standing out due to their high eruptive frequency (22 and 26 Holocene eruptions, respectively). The second zone comprises the city of Moquegua (Peru), close to Huaynaputina (maximum VEI of 6), and Ticsani, Tutupaca and Yucamane volcanoes (VEI 2-3, 4 and 5, respectively). The third zone includes the city of Tacna (Peru) close to Tacora, Casiri, Purupuruni and Yucamane volcanoes with the ~~latter~~last having a maximum VEI of 5. The fourth zone comprises the city of Calama (Chile) close to San Pedro volcano with a medium eruptive frequency (10 Holocene eruptions). The fifth zone corresponds to the mining stations “Estación Zaldivar” and “Mina Escondida”, close to Llullaillaco volcano with low eruptive frequency and VEI (3 Holocene eruptions and VEI 2). Additionally, in the southern zone of the CVZA there is Cerro Blanco volcano (Argentina), whose eruption is among the largest volcanic eruptions of the Holocene globally (VEI 7~~) (~~; Fernandez-Turiel et al~~.~~., 2019). Even though Cerro Blanco is not close to inhabited ~~area~~areas with more than 100 inhabitants per km^2, there are important populated localities within 100 km around the volcano: Antofagasta de la Sierra (730 inhabitants), Palo Blanco (992 inhabitants), Corral Quemado (1200 inhabitants), Punta del Agua (172 inhabitants~~),~~) and Antinaco (105 inhabitants) (see Supplementary material 2).

Six areas can be identified based on the highest density distribution of transport infrastructure (Fig. 3): ~~First,~~1) the cities of Arequipa, Moquegua, and Tacna (Peru), close to the volcanoes Sabancaya, El Misti, Ubinas, Huaynaputina, Ticsani, Tutupaca, Yucamane, Purupuruni, Casiri and Tacora~~; second,~~. 2) two border crossings, i.e., the triple point (geographical point where the borders of Peru, Bolivia and Chile meet) and Colchane customs post (one of the border ~~crossing~~crossings between Bolivia and Chile), close to the volcanoes Casiri, Tacora and Taapaca (with no confirmed VEI); and Tata Sabaya and Isluga respectively ~~(~~, with no information and a medium eruptive frequency (8 Holocene eruptions) and VEI (2), respectively~~); third,~~. 3) the Collahuasi mining district~~ (a large copper mine, which represents~~, representing one of the largest copper reserves in Chile and in the world~~),~~, close to Irruputuncu and Olca-Paruma volcanoes~~ (with~~, which have a low number of Holocene eruptions and low VEI (2) or not confirmed~~); fourth,~~. 4) Calama city and San Pedro volcano~~ (~~, with a medium eruptive frequency (10 Holocene eruptions) and low VEI (2~~)); fifth,~~). 5) San Pedro de Atacama town~~ (~~, a popular tourist destination in Antofagasta region~~, –~~ (Chile) close to Putana, Escalante-Sairecabur and Licancabur volcanoes (~~with ~~the ~~former~~first having 2 Holocene eruptions and VEI 2, and the last two with no information available); and ~~sixth, SQM~~ (6) Sociedad Química y Minera de Chile~~,~~ (SQM), the world's biggest lithium producer~~)~~ close to Lascar volcano~~ (with~~, which has a high eruptive frequency (37 Holocene eruptions) and maximum VEI (4~~)).~~). Finally, the area with the highest amount of emergency and critical facilities per km^2 is concentrated in Arequipa city (Peru) close to Sabancaya, El Misti and Ubinas volcanoes (Fig. 4).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Huaynaputina
Ticsani
Tutupaca
Yucamane
Purpuruni
Casiri
Tacora
Taapaca
Parinacota
Guallatiri
Tata Sabaya
Isluga
Irruputuncu
Olca-Paruma
Aucanquilcha
Ollagüe
Cerro del Azufre
San Pedro
Uturuncu
Escalante-Sairecabur
Putana
Licancabur
Alitar
Lascar
Acamarachi
Chiliques
Puntas Negras
Tuzgle
Socompa
Arizaro
Aracar
Llullaillaco
Unnamed
Escorial
Lastarria
Cordón del Azufre
Cerro Bayo
Antofagasta VF
Sierra Nevada
El Cóndor
Peinado
Falso Azufre
Cueros de Purulla
Cerro Blanco
Incahuasi
El Fraile
Tres Cruces
El Solo
Tipas
Ojos del Salado
Camaná
Majes
Ilo
Arica
Iquique
Antofagasta
Taltal
Copiapó
La Paz
Cochabamba
Oruro
Arequipa
Moquegua
Tacna
Calama
Estación Zaldivar and Mina Escondida
Volcanoes of the CVZA
Holocene
≥ 1 eruption in the last 1000 years
Pleistocene (with fresh volcanic morphology or signs of unrest)
Exposure
Population density (Inhab/km2)
No population
0-1
1-10
10-100
> 100
N° Holocene Eruptions
No data
1-5
6-15
16-38
Maximum VEI
No data
1
2
3
4
5
6
7
National borders
Geodetic Reference
WGS 1984 UTM Zone 19S
Transverse Mercator
Units: Meter
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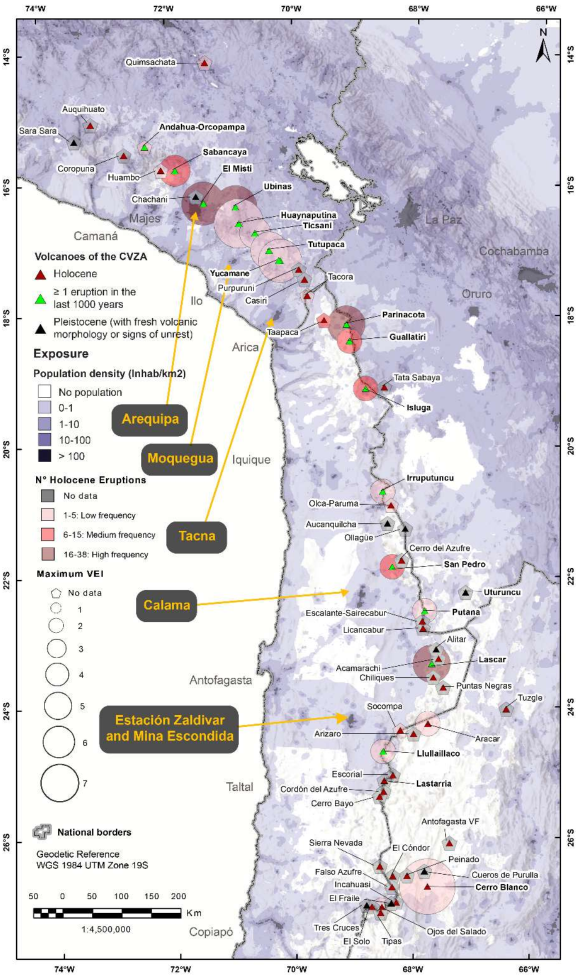
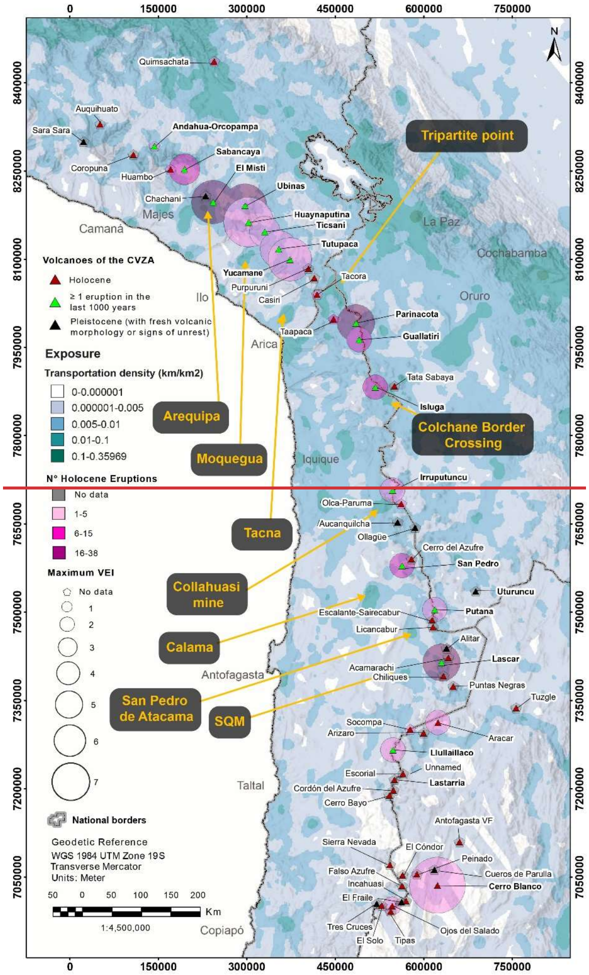


Figure 2: Regional map including the ~~total~~ CVZA active and potentially active volcanoes and population density, with the Maximum VEI during the Holocene and the number of Holocene eruptions of the CVZA volcanoes superimposed. Notice that ~~volcano names having had activity in~~ the ~~past 1,000 years in addition to the~~ 19 volcanoes ~~with Pleistocene or Holocene activity currently showing 3 types of unrest~~considered for the VRR analysis are in bold. ~~Service~~ Layer ~~Credits:~~ Sources: Esri, USGS, NOAA.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Auquihuato
Sara Sara
Andahua-Orcopampa
Sabancaya
Coropuna
Huambo
El Misti
Chachani
Ubinas
Majes
Camaná
Huaynaputina
Ticsani
Tutupaca
Yucamane
Purpuruni
Casiri
Tacora
Ilo
Tripartite point
La Paz
Cochabamba
Oruro
Parinacota
Taapaca
Guallatiri
Arica
Tata Sabaya
Isluga
Colchane Border Crossing
Arequipa
Moquegua
Iquique
Irruputuncu
Olca-Paruma
Aucanquilcha
Ollagüe
Tacna
Cerro del Azufre
San Pedro
Uturuncu
Collahuasi mine
Escalante-Sairecabur
Putana
Licancabur
Calama
Alitar
Lascar
Acamarachi
Chiliques
Antofagasta
Puntas Negras
Tuzgle
San Pedro de Atacama
SQM
Socompa
Arizaro
Aracar
Llullaillaco
Unnamed
Escorial
Lastarria
Cordón del Azufre
Cerro Bayo
Taltal
Antofagasta VF
Sierra Nevada
El Cóndor
Peinado
Falso Azufre
Cueros de Parulla
Incahuasi
Cerro Blanco
El Fraile
Tres Cruces
El Solo
Tipas
Ojos del Salado
Copiapó
Volcanoes of the CVZA
Holocene
≥ 1 eruption in the last 1000 years
Pleistocene (with fresh volcanic morphology or signs of unrest)
Exposure
Transportation density (km/km2)
0-0.000001
0.000001-0.005
0.005-0.01
0.01-0.1
0.1-0.35969
N° Holocene Eruptions
No data
1-5
6-15
16-38
Maximum VEI
No data
1
2
3
4
5
6
7
National borders
Geodetic Reference
WGS 1984 UTM Zone 19S
Transverse Mercator
Units: Meter
50 0 50 100 150 200
Km
1:4,500,000

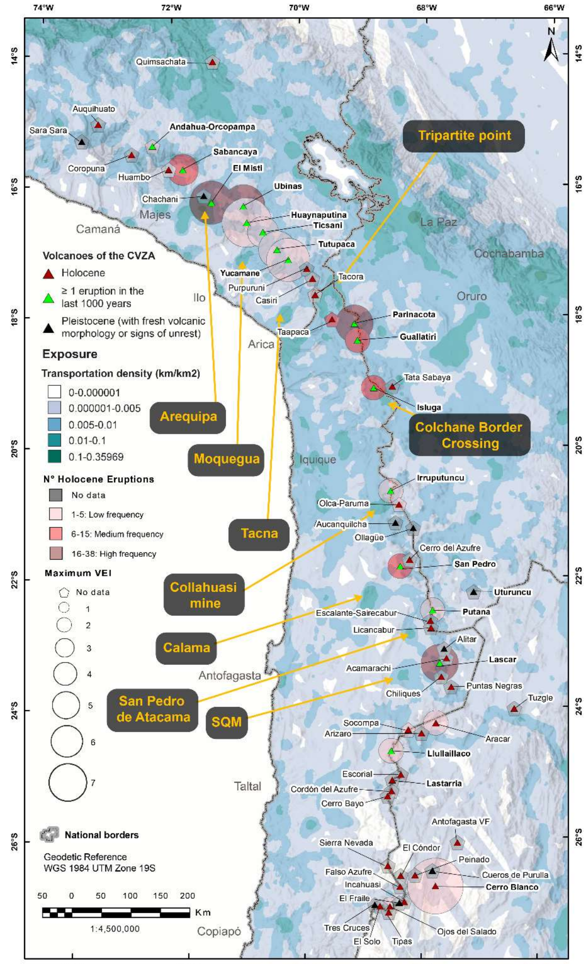
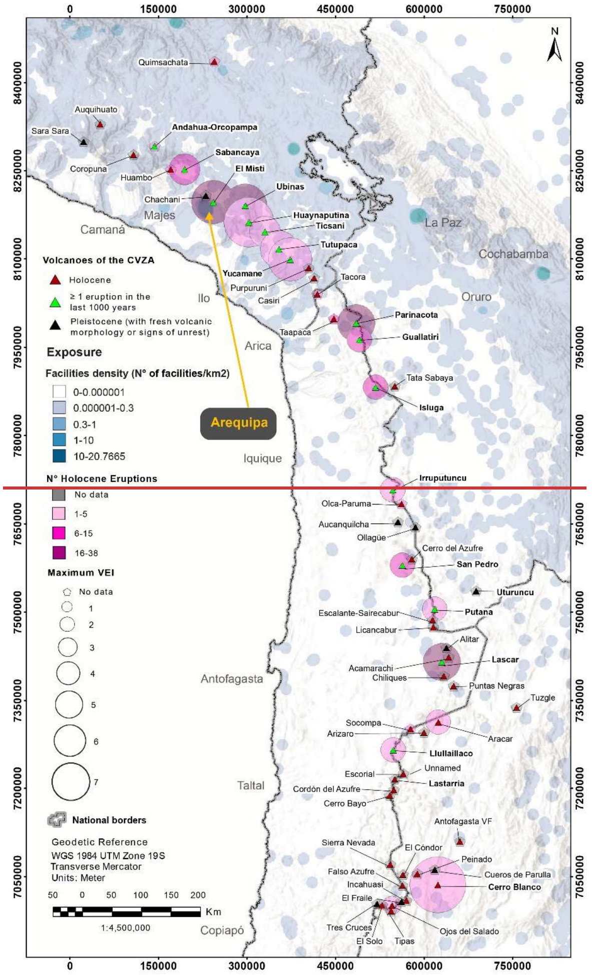


Figure 3: Regional map including the ~~total~~ CVZA active and potentially active volcanoes ~~with~~and transportation density, with the Maximum VEI during the Holocene and the number of Holocene eruptions of the CVZA volcanoes superimposed. Notice that ~~volcano names having had activity in~~ the ~~past 1,000 years in addition to the~~ 19 volcanoes ~~with Pleistocene or Holocene activity currently showing 3 types of unrest~~considered for the VRR analysis are in bold. ~~Service~~ Layer ~~Credits:~~ Sources: Esri, USGS, NOAA.



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Sara Sara
Andahua-Orcopampa
Sabancaya
Coropuna
Huambo
El Misti
Chachani
Ubinas
Huaynaputina
Ticsani
Tutupaca
Yucamane
Purpuruni
Casiri
Tacora
Taapaca
Parinacota
Guallatiri
Tata Sabaya
Isluga
Irruputuncu
Olca-Paruma
Aucanquilcha
Ollagüe
Cerro del Azufre
San Pedro
Uturuncu
Escalante-Sairecabur
Putana
Licancabur
Alitar
Lascar
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Chiliques
Puntas Negras
Tuzgle
Socompa
Arizaro
Aracar
Llullaillaco
Unnamed
Escorial
Lastarria
Cordón del Azufre
Cerro Bayo
Antofagasta VF
Sierra Nevada
El Cóndor
Peinado
Falso Azufre
Incahuasi
Cueros de Purulla
Cerro Blanco
El Fraile
Tres Cruces
El Solo
Tipas
Ojos del Salado
Camaná
Majes
Ilo
Arica
Iquique
Antofagasta
Taltal
Copiapó
La Paz
Cochabamba
Oruro
Arequipa
Volcanoes of the CVZA
Holocene
≥ 1 eruption in the last 1000 years
Pleistocene (with fresh volcanic morphology or signs of unrest)
Exposure
Facilities density (N° of facilities/km2)
0-0.000001
0.000001-0.3
0.3-1
1-10
10-20.7665
N° Holocene Eruptions
No data
1-5
6-15
16-38
Maximum VEI
No data
1
2
3
4
5
6
7
National borders
Geodetic Reference
WGS 1984 UTM Zone 19S
Transverse Mercator
Units: Meter
50 0 50 100 150 200
Km
1:4,500,000

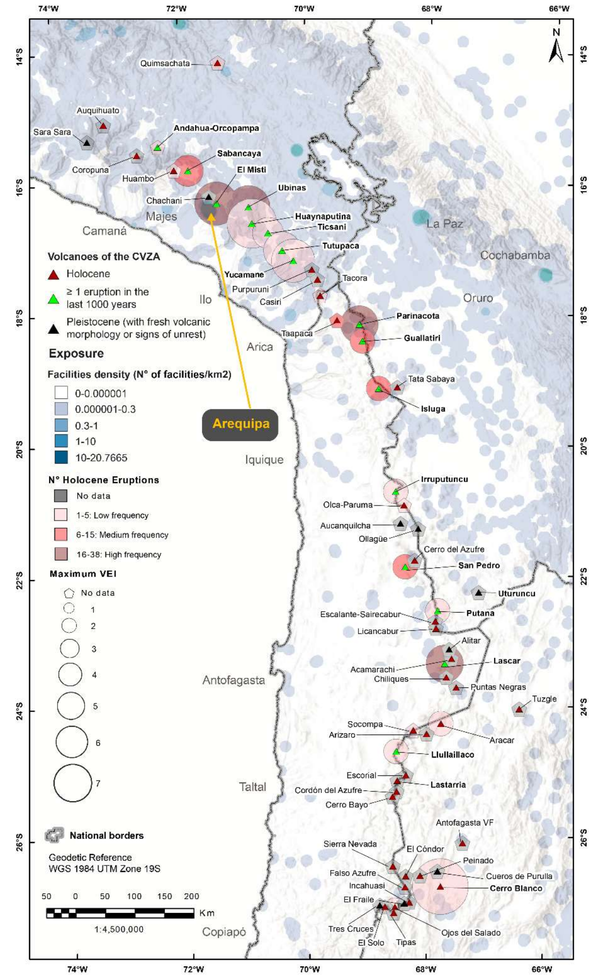
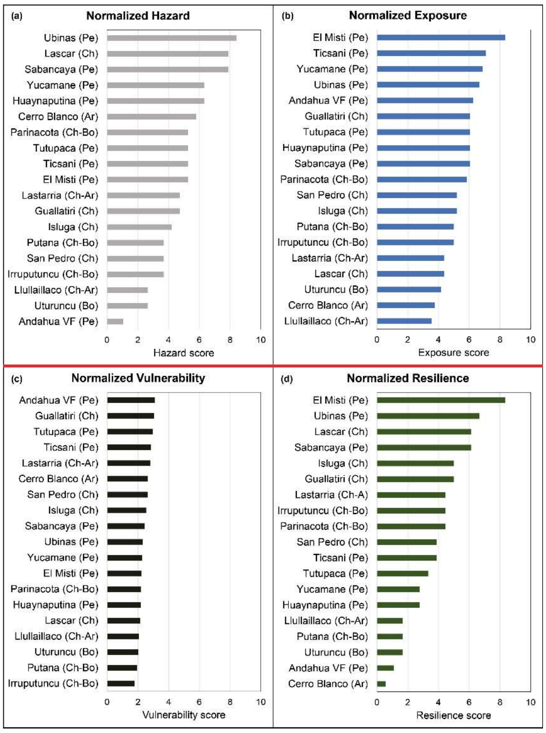


Figure 4: Regional map including the ~~total~~ CVZA active and potentially active volcanoes ~~with~~and facilities density, with the Maximum VEI during the Holocene and the number of Holocene eruptions of the CVZA volcanoes superimposed. Notice that ~~volcano names having had activity in~~ the ~~past 1,000 years in addition to the~~ 19 volcanoes ~~with Pleistocene or Holocene activity currently showing 3 types of unrest~~considered for the VRR analysis are in bold. ~~Service~~ Layer ~~Credits:~~ Sources: Esri, USGS, NOAA.

4.~~3~~2 The ~~2-factor, 3-factor and 4-factor~~ Volcanic Risk Ranking

The ~~16~~19 ~~out of the 59~~ CVZA active and potentially active volcanoes that had an eruption ~~in~~during the last 1,000 years ~~and the 3 volcanoes showing 3 signs~~or have significant records of unrest signals were ranked based on the 4 normalized factors of the VRR, i.e., hazard, exposure, vulnerability and resilience (Fig. ~~5~~5). It is important to first analyse the risk factors separately to better understand what they represent and how they contribute to the overall VRR (Fig. 6). The top five volcanoes showing the highest hazard score are Ubinas (Peru), Lascar (Chile), Sabancaya (Peru), Yucamane (Peru), and Huaynaputina (Peru) (Fig. 5a). The top five volcanoes with the highest exposure score are El Misti (Peru), Ticsani (Peru), Yucamane (Peru), Ubinas (Peru), and Andahua-Orcopampa (Peru) (Fig. 5b). The volcanoes associated with the highest vulnerability scores are Andahua-Orcopampa (Peru), Guallatiri (Chile), Tutupaca (Peru), Ticsani (Peru) and Lastarria (Chile-Argentina) (Fig. 5c). Finally, the top five volcanoes with the highest resilience scores are El Misti (Peru), Ubinas (Peru), Lascar (Chile), Sabancaya (Peru) and Isluga (Chile) (Fig. 5d).


(a)
Normalized Hazard
Ubinas (Pe)
Lascar (Ch)
Sabancaya (Pe)
Yucamane (Pe)
Huaynaputina (Pe)
Cerro Blanco (Ar)
Parinacota (Ch-Bo)
Tutupaca (Pe)
Ticsani (Pe)
El Misti (Pe)
Lastarria (Ch-Ar)
Guallatiri (Ch)
Isluga (Ch)
Putana (Ch-Bo)
San Pedro (Ch)
Irruputuncu (Ch-Bo)
Llullaillaco (Ch-Ar)
Uturuncu (Bo)
Andahua VF (Pe)
0
2
4
6
8
10
Hazard score
(b)
Normalized Exposure
El Misti (Pe)
Ticsani (Pe)
Yucamane (Pe)
Ubinas (Pe)
Andahua VF (Pe)
Guallatiri (Ch)
Tutupaca (Pe)
Huaynaputina (Pe)
Sabancaya (Pe)
Parinacota (Ch-Bo)
San Pedro (Ch)
Isluga (Ch)
Putana (Ch-Bo)
Irruputuncu (Ch-Bo)
Lastarria (Ch-Ar)
Lascar (Ch)
Uturuncu (Bo)
Cerro Blanco (Ar)
Llullaillaco (Ch-Ar)
0
2
4
6
8
10
Exposure score
(c)
Normalized Vulnerability
Andahua VF (Pe)
Guallatiri (Ch)
Tutupaca (Pe)
Ticsani (Pe)
Lastarria (Ch-Ar)
Cerro Blanco (Ar)
San Pedro (Ch)
Isluga (Ch)
Sabancaya (Pe)
Ubinas (Pe)
Yucamane (Pe)
El Misti (Pe)
Parinacota (Ch-Bo)
Huaynaputina (Pe)
Lascar (Ch)
Llullaillaco (Ch-Ar)
Uturuncu (Bo)
Putana (Ch-Bo)
Irruputuncu (Ch-Bo)
0
2
4
6
8
10
Vulnerability score
(d)
Normalized Resilience
El Misti (Pe)
Ubinas (Pe)
Lascar (Ch)
Sabancaya (Pe)
Isluga (Ch)
Guallatiri (Ch)
Lastarria (Ch-A)
Irruputuncu (Ch-Bo)
Parinacota (Ch-Bo)
San Pedro (Ch)
Ticsani (Pe)
Tutupaca (Pe)
Yucamane (Pe)
Huaynaputina (Pe)
Llullaillaco (Ch-Ar)
Putana (Ch-Bo)
Uturuncu (Bo)
Andahua VF (Pe)
Cerro Blanco (Ar)
0
2
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6
8
10
Resilience score

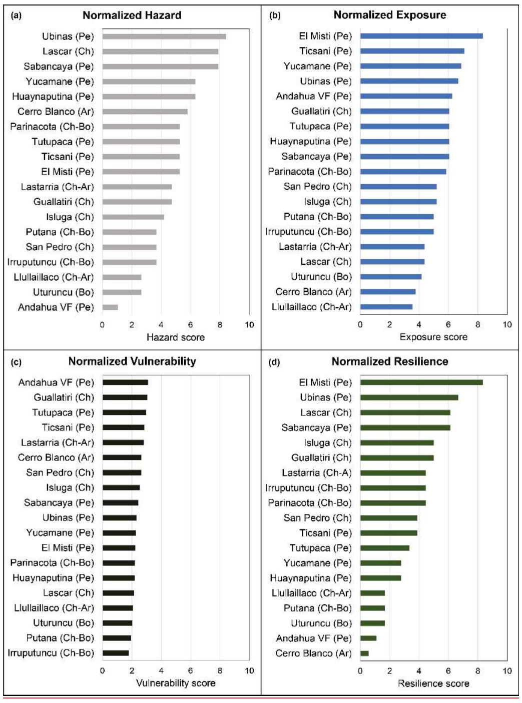
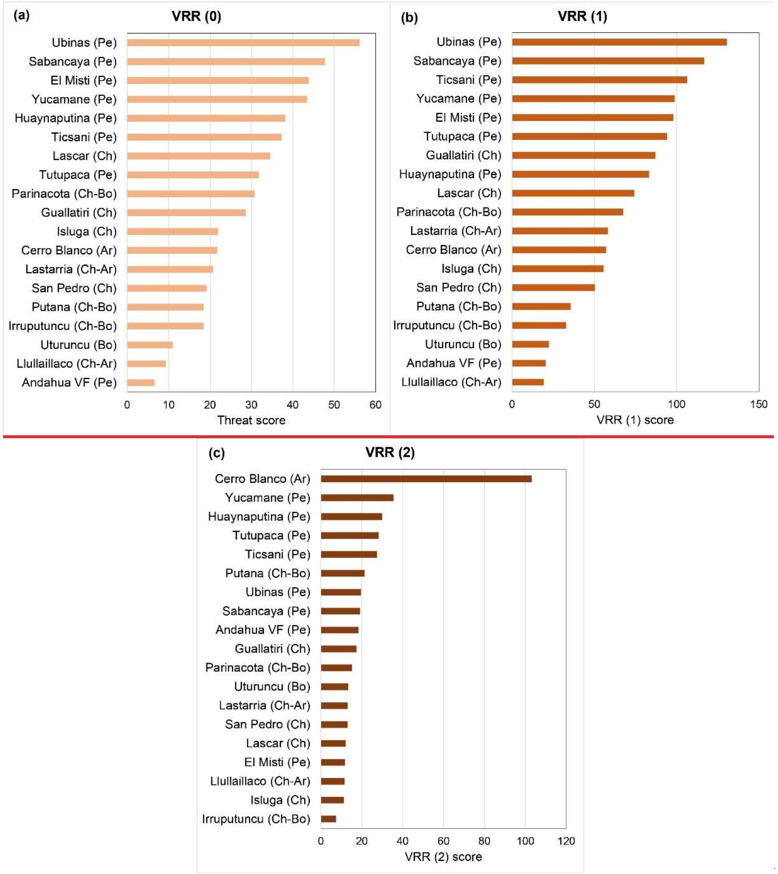


Figure 5: Factors of the volcanic risk ranking ~~analyzed~~analysed separately. (a) hazard scoring; (b) exposure scoring; (c) vulnerability scoring; and (d) resilience scoring.

When VRR factors are combined, the top five volcanoes with the highest VRR~~(~~_0~~)~~ scores (i.e., hazard and exposure) are Ubinas, Sabancaya, El Misti, Yucamane, and Huaynaputina (Peru) (Fig. 6a); the volcanoes with the 5 highest VRR~~(~~_1~~)~~ scores (i.e., hazard, exposure, vulnerability) are~~ shown by~~ Ubinas, Sabancaya, Ticsani, Yucamane, and El Misti (Peru) (Fig. 6b); while the top five volcanoes with the highest VRR~~(~~_2~~)~~ scores (i.e., hazard, exposure, vulnerability and resilience) are Cerro Blanco (Argentina), Yucamane, Huaynaputina, Tutupaca, and Ticsani (Peru) (Fig. 6c).


(a)
VRR (0)
Ubinas (Pe)
Sabancaya (Pe)
El Misti (Pe)
Yucamane (Pe)
Huaynaputina (Pe)
Ticsani (Pe)
Lascar (Ch)
Tutupaca (Pe)
Parinacota (Ch-Bo)
Guallatiri (Ch)
Isluga (Ch)
Cerro Blanco (Ar)
Lastarria (Ch-Ar)
San Pedro (Ch)
Putana (Ch-Bo)
Irruputuncu (Ch-Bo)
Uturuncu (Bo)
Llullaillaco (Ch-Ar)
Andahua VF (Pe)
0
10
20
30
40
50
60
Threat score
(b)
VRR (1)
Ubinas (Pe)
Sabancaya (Pe)
Ticsani (Pe)
Yucamane (Pe)
El Misti (Pe)
Tutupaca (Pe)
Guallatiri (Ch)
Huaynaputina (Pe)
Lascar (Ch)
Parinacota (Ch-Bo)
Lastarria (Ch-Ar)
Cerro Blanco (Ar)
Isluga (Ch)
San Pedro (Ch)
Putana (Ch-Bo)
Irruputuncu (Ch-Bo)
Uturuncu (Bo)
Andahua VF (Pe)
Llullaillaco (Ch-Ar)
0
50
100
150
VRR (1) score
(c)
VRR (2)
Cerro Blanco (Ar)
Yucamane (Pe)
Huaynaputina (Pe)
Tutupaca (Pe)
Ticsani (Pe)
Putana (Ch-Bo)
Ubinas (Pe)
Sabancaya (Pe)
Andahua VF (Pe)
Guallatiri (Ch)
Parinacota (Ch-Bo)
Uturuncu (Bo)
Lastarria (Ch-Ar)
San Pedro (Ch)
Lascar (Ch)
El Misti (Pe)
Llullaillaco (Ch-Ar)
Isluga (Ch)
Irruputuncu (Ch-Bo)
0
20
40
60
80
100
120
VRR (2) score

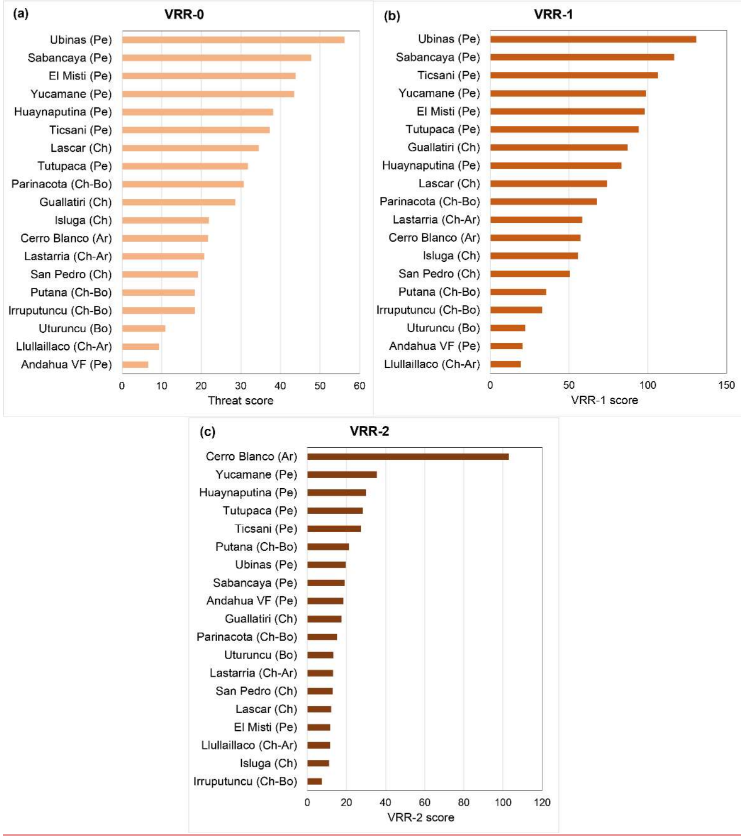


Figure 6: (a) The 2-factor~~,~~ (VRR-0), (b) 3-factor~~,~~ (VRR-1), and (c) 4-factor volcanic risk ranking (VRR-2) applied to the 19 CVZA selected volcanoes.

5 Discussion

~~5.1 Identification of active and potentially active volcanoes~~

~~Various nomenclatures have been proposed to describe the state of a volcano (e.g., Szakács, 1994; Auker et al., 2015) and, consequently, when ranking volcanoes of a specific area, the total number of active volcanoes and resulting top-ranked can vary depending on the criterion used (e.g., historical records, geochronological data, recognition of fresh deposits, signals of~~

~~unrest). According to Szakács (1994) "active volcano" and "extinct volcano" are mutually exclusive terms. Active volcanoes could be subdivided into "erupting" and "dormant" types based on their current state of activity, while extinct volcanoes could be classified as "young" or "old" using convenient criteria such as the extent of erosion or geochronological age. The term "potentially active" is reserved for those fresh-looking volcanoes lacking both documented eruptions and reliable dating; therefore "potentially active" volcanoes could be "active-dormant" or "extinct-young" volcanoes as more information becomes available (Szakács, 1994). A more recent and restrictive criterion for classification was proposed by Auker et al. (2015). Taking AD 1900 as base year, Auker et al. (2015) defined four frequency classes: active, semi-active, semi-dormant, and fully dormant taking into consideration the period of the last eruption(s) and the unrest. As an example, applying this framework to Chile results in 23 active volcanoes. In contrast, the most recent version of the official Chilean catalog considers 87 volcanoes (Ranking de riesgo específico para volcanes activos de Chile 2023) following the assumption that a volcano is considered geologically active when it has had at least one eruption in the last 11,700 years, i.e., the Holocene period according to Walker et al. (2018), or when, in absence of data of past eruptions in that period, it presents visible signs of current activity such as degassing, seismicity or ground deformation (modified from Simkin and Siebert, 1994; Ewert et al., 2005; Ewert, 2007; Lara et al., 2011). Lara et al. (2021) noticed that the uncertainty on the number of CVZA active volcanoes relies mostly on the lack of geochronological data and/or preserved historical records, in part due to arid erosive conditions, which preclude the morphological distinction between Pleistocene and Holocene units.~~

5.1~~Since geochronological data or preserved historical records are largely absent in the CVZA, the term "potentially active" has been widely used to account for this lack of data. The first comprehensive studies to count active CVZA volcanoes was Casertano (1963) in Chile and Hantke and Parodi (1966) in Peru. Later, the IAVCEI (1973) and Siebert et al. (2011), compiled a list of all the active volcanoes at a global scale also including the CVZA. However, because of the limited knowledge on CVZA volcanoes, most of recent volcanism signs in the Altiplano-Puna catalogs were detected through the analysis of Landsat Thematic Mapper (TM) and experimental Modular Optoelectronic Multispectral Scanner (MOMS) satellite images to identify moraines and valley glaciers left by the last major ice regression in the Central Andes (i.e., 11,000 yr BP). It helped to recognize: i) heavily glaciated volcanoes with no signs of activity since the last deglaciation. ii) Volcanoes with well-preserved surfaces and wholly formed in postglacial times. iii) Volcanoes with no clear relationships between volcanic and glacial features, which were considered to be potentially active if they had fresh volcanic morphological features (i.e., no signs of glaciation, summit craters and flank lava flows with pristine morphology, and flank lava flows with low albedos since lava flows are brighten with age). Besides field observations supported by conventional air photography to provide ground truth for the TM data (De Silva and Francis, 1991). After an extensive data compilation in collaboration with the Geological Services of Argentina (SEGEMAR), Chile (SERNAGEOMIN), and Peru (INGEMMET), combined with a review of the updated volcanic risk rankings of Argentina, Peru and Chile (i.e., Elissondo and Farías, 2023; Macedo et al., 2016; SERNAGEOMIN, 2023; respectively) , we observed a discrepancy between the number of potentially active eruptive centers identified by the "Volcanoes of the Central Andes" (n=73; De Silva and Francis, 1991) and the Global Volcanism Program database (n=67;~~

~~GVP, 2013). As a consequence, the first step of this study was the identification and compilation of all Holocene volcanoes as well as Pleistocene volcanic centers that show unrest signs and/or fresh volcanic morphological features.~~

~~Since we considered the geological surveys' criteria, our volcano list does not match neither the list of the "Volcanoes of the Central Andes" nor the Global Volcanism Program (De Silva and Francis, 1991; GVP, 2013; respectively). On the other hand, considering previous versions of the relative volcanic risk rankings of Chile and Argentina (i.e., Elissondo et al., 2016; SERNAGEOMIN, 2020) the number of volcanoes considered in Aguilera et al. (2022), were the same (n= 62), even though with some differences. First, Aguilera et al. (2022) did not consider Quimsachata volcano amongst the Peruvian volcanoes, but it is considered by INGEMMET; secondly, they included Ampato volcano as separate from Sabancaya. In our inventory (Table 4), we consider that Sabancaya is the youngest and most recently active system of the Ampato-Sabancaya Volcanic Complex (Rivera et al., 2016; Macedo et al., 2016), also in agreement with INGEMMET and IGP. We removed Caichinque, Pular-Pajonales, Chascon-Purico complex, and Colachi volcanoes as they are no longer considered by SERNAGEOMIN (Ranking de riesgo específico para volcanes activos de Chile 2023), as well as the Unnamed volcano (or volcan Sin Nombre) now considered within the Arizaro volcanic field (Elissondo and Farías, 2023). We included Cueros de Parulla and El Fraile volcanoes as they are now in the relative risk ranking of Argentine and neighboring volcanoes (Elissondo and Farías, 2023), and even if Sierra Nevada and Nevado de Incahuasi volcanoes have been removed from the Chilean ranking, we maintain them in our list as they are still considered in the Argentinean ranking.~~

~~5.2~~ Significance of regional mapping and VRR for the CVZA

Regional maps allow for a spatial representation of the areas with a high potential for volcanic impact based on the identification of volcanoes with the largest eruptions and the highest eruptive frequency, as well as the highest density of elements at risk (e.g., population, transport infrastructure, emergency and critical facilities) (~~Fig~~Figs. 2-4). ~~In the case of~~ As an example, the transport-density map~~, for example, it is possible to visualize~~ highlights the areas having a high concentration of rural and urban infrastructure, which could ~~also~~ be potentially impacted with ~~some~~ economic consequences on the country. ~~Such~~This is the case of the Collahuasi mining district in Chile~~, that has been developed since 1880 when its systems of high-grade copper and silver veins began to be exploited~~ (https://www.collahuasi.cl/en/quienes-somos/nuestra-historia/). Nonetheless, these regional maps do not provide the details at local scale (e.g., the type or quality of transport infrastructure and facilities). ~~The~~Our regional map of the CVZA ~~could be helpful for stakeholders as~~provides a first preliminary step to quickly identify target areas that require a more detailed risk analysis~~.~~, representing a helpful approach for stakeholders. The VRR methodology, on the other hand, provides a more spatially discretized and in-depth relative risk analysis that considers 9 hazard, 9 exposure, 10 vulnerability and 13 resilience parameters (Nieto-Torres et al., 2021 and Guimarães et al., 2021). The analysed elements at risk include population, residential buildings and critical infrastructures exposed within four distance radii ~~(i.e.,~~ 5, 10, 30 and 100 km), these surfaces cover the area most susceptible to the impact of the different types of hazards, such as tephra fallout, pyroclastic density currents and lahars. In case of volcanic fields and calderas, the exposure is analysed

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for elements inside the volcanic field and for the same radius but from the field's boundary, which is defined by the connection of the outermost volcanic edifices that compose it. Differences in the hierarchy of the volcanoes evaluated are mostly due to population density and the diversity of critical infrastructures considered that ensure more densely populated areas to have higher scores in the threat ranking. The vulnerability factor in VRR-1 differentiates volcanic systems with equal or similar threat, while the resilience factor in VRR-2 help to identify volcanoes with no or few mitigation and response measures. The variability between the various VRR approaches (e.g., equations 1–3) confirm the importance of including hazard, exposure, vulnerability and resilience in an integrative ranking analysis ~~in order~~ to capture the risk complexity and best prioritize risk reduction strategies (Fig. 5, 6). Broad common patterns between the regional maps and the VRR are discussed below.

From a hazard perspective, both the regional maps (Fig. 2-4) and the VRR (Fig. 5a) allow to identify Ubinas (Peru), Lascar (Chile), Huaynaputina (Peru) and Cerro Blanco (Chile) as the most hazardous volcanoes. However, El Misti (Peru) and Parinacota (Chile) occupy only the ~~10th~~10th and 7th position on the hazard factor of the VRR, respectively, even though they have a high eruptive frequency (22 and 38 events during the Holocene). The reason is that overall, the maximum hazard score on the VRR represents the highest intensity of each volcanic process, not only eruptive frequency and maximum VEI as in the regional mapping. On the contrary, Sabancaya and Yucamane (Peru) appear at the 3rd and 4th position on the normalized hazard factor of the VRR but are not highlighted in the regional map since they have a medium to low eruptive frequency (14 and 1 event, respectively)~~;~~ and maximum VEIs (3 and 5, respectively).

~~It is worth noticing that focusing on the VRR analysis of the last 1,000 years of volcanic activity might exclude potentially impactful volcanoes. We constrained this aspect by integrating into the VRR analysis all the volcanoes presenting 3 signs of unrest (i.e., Uturuncu, Lastarria, and Cerro Blanco).~~

It is worth noticing that the basis of focusing in the last 1,000 years of volcanic activity for the VRR analysis is in line with the methodology proposed by Nieto-Torres et al. (2021) and applied by Guimaraes et al. (2021). Nieto-Torres et al. (2021) found that the volcanoes associated with the highest risk score for Mexican volcanoes were the same, regardless of the analysed time window of eruption occurrence (i.e., <1 and <10 ka). Additionally, Guimaraes et al. (2021), who first applied this methodology on Latin American volcanoes, found that this criterion considers eruptions that are the best constrained in the eruptive records. The grouping of volcanoes based on the age, most recent eruptions and eruption periodicities has also been previously used to rank volcanoes in a general order of "decreasing concern" (e.g., Bailey et al., 1983) and currently the occurrence of eruptions within the last 1,000 years represents one of the controlling factors in developing strategies to increase resilience (Nieto-Torres et al., 2021). However, focusing on the VRR analysis of the last 1,000 years of volcanic activity might exclude potentially impactful volcanoes. For this reason, we constrained this aspect by also integrating into the VRR analysis ~~all~~ the volcanoes presenting records of three signs of unrest (i.e., Uturuncu, Lastarria, and Cerro Blanco). For a more comprehensive analysis and to confirm our preliminary results, future works could apply the VRR to all 59 active and potentially active volcanoes.

When hazard and exposure are ~~combined~~considered, both ~~approaches~~regional mapping and VRR highlight Ubinas, El Misti, and Huaynaputina as the volcanoes with the highest potential risk (~~Fig~~Figs. 2-4 and 6a). ~~However,~~ Sabancaya and Yucamane appear on the ~~2th~~2nd and 4th positions of the threat score (VRR~~(~~-0~~)~~)) and are not highlighted on the regional mapping. The reason is that the regional map only considers the number of Holocene eruptions and maximum VEI as hazard parameters ~~which~~, with an overlap on the different layers of elements at risk, whilst the VRR evaluates the interaction of 9 hazard and 9 exposure parameters at different radius from the volcanic vent, which turns into a more exhaustive analysis.

The vulnerability factor, which is not considered for the regional mapping, ~~help~~helps to best distinguish volcanic systems with similar threat (i.e., H×E) but different vulnerabilities (e.g., Irruputuncu and Putana volcanoes ~~(~~, Chile~~)).~~). In particular, the variety of parameters related to the systemic vulnerability helps to highlight the volcanoes with high exposure and low redundancy and accessibility to infrastructures ~~(e.g., Ticsani volcano (Peru)). Finally, the inclusion of resilience in VRR(2) contributes to highlight those systems with moderate (e.g., Tutupaca, Huaynaputina (Peru), and Cerro Blanco (Argentina)) to high score (e.g., Ticsani and Yucamane (Peru)) in the VRR(1) (Fig. 6),~~(e.g., Ticsani ~~volcano~~, Peru). Finally, the inclusion of resilience in VRR-2 contributes to highlight those systems with moderate (e.g., Tutupaca, Huaynaputina, Peru; ~~and~~ Cerro Blanco, Argentina) to high score (e.g., Ticsani and Yucamane, Peru) in the VRR-1 (Fig. 6) but having none or few resilience measures implemented (Fig. 5d) (Guimarães et al., 2021). In fact, ~~while~~whilst the inclusion of vulnerability only affects a few volcanoes (VRR~~(~~-0~~)~~ versus VRR~~(~~-1~~),~~, Fig. 6a-b~~,~~), the influence of resilience is quite remarkable for all volcanoes, highlighting those systems with none or few mitigation and response (resilience) measures implemented (i.e., Cerro Blanco ~~(~~, Argentina~~),~~; Yucamane, Huaynaputina, Tutupaca, and Ticsani ~~(~~, Peru~~))~~) (Fig. 6c). As an example, Ubinas (Peru) has the highest normalized score in terms of hazard and medium normalized score in terms of vulnerability, but the second highest normalized score in terms of resilience (see Fig. 5), which explains the 1st position in the VRR~~(~~-1~~)~~ and the 7th position in the VRR~~(~~-2~~)~~ (Fig. 6b-c). The systems taking the top positions of the VRR~~(~~-2~~)~~ are those either with high hazard, medium-high exposure~~,~~ and vulnerability ~~values~~scores, or few to no mitigation and response measures implemented (e.g~~.~~., Cerro Blanco ~~(~~, Argentina~~),~~; Yucamane, Huaynaputina, Tutupaca, and Ticsani ~~(~~, Peru~~)). Considering the low resilience,~~). Cerro Blanco (Argentina) scores as the ~~riskiest~~highest risk volcano of the CVZA due to its low resilience (Fig. 6c).

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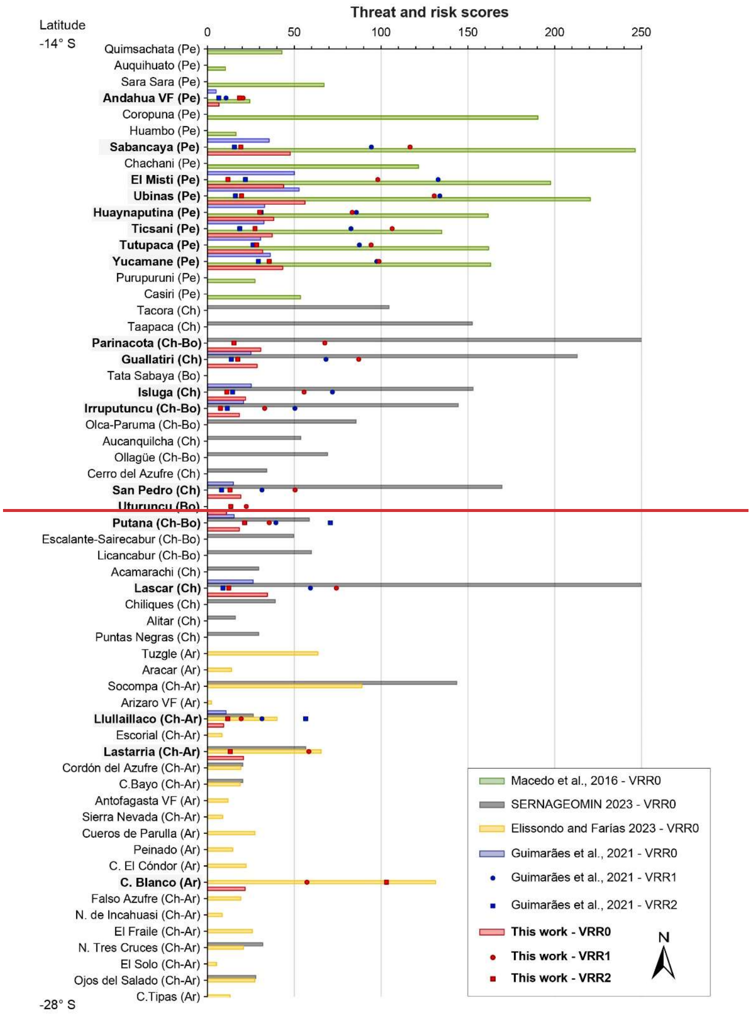
~~5.3 Comparison with existing volcanic rankings~~

Overall, as different dimensions of vulnerability are closely related to the elements at risk, it is important to rethink land-use planning to not increase or create new risk. To reduce vulnerability, it is advisable to create redundancy (e.g., alternative power infrastructure within 100 km of Cerro Blanco) and accessibility to critical infrastructure (e.g., connections to power, water, telecommunication and emergency facilities within 100 km of Cerro Blanco, Ticsani and Tutupaca volcanoes). In addition, diversification of economic activities should be promoted, especially within 5-30 km around Cerro Blanco, Tutupaca, Ticsani, Ubinas and Sabancaya volcanoes. However, priority risk reduction strategies should be put in place or improved in order to increase resilience. First, volcanic records should be better constrained at target volcanoes in order to compile up-to-date hazard assessments. Within the top five VRR-1 and VRR-2 high risk volcanoes, only Cerro Blanco has no hazard maps, but it is important to make sure that the existent ones are up-to-date and available for the entire community. Second, monitoring system should be improved for Tutupaca (basic real time), Huaynaputina and Yucamane (limited) and implemented at Cerro Blanco (non-existent). Third, efforts should be made to compile risk assessments, that is missing at all ~~these~~ 5 high-risk volcanoes (Cerro Blanco, Yucamane, Huaynaputina, Tutupaca, and Ticsani). Fourth, educational activities should be promoted to raise awareness in population living around Ticsani, Yucamane, Huaynaputina, Tutupaca, and Cerro Blanco; and existing ones should be supported and strengthened around Ubinas, Sabancaya and El Misti. Finally, local authorities might invest in preparedness (e.g., evacuation plans and exercises or simulations for institutions and population), insurance coverage, engineering mitigation measures and implementation of early warning systems.

5.2 Comparison with existing volcanic rankings

To visualize the different existing volcanic rankings~~ easier~~, we have collected ~~their~~the threat and risk scores in a comparative diagram shown in Fig. 7. At the time of our investigation, three of the four ~~bordering~~CVZA countries~~ of the CVZA~~ have already developed a relative volcanic threat ranking (~~i.e., ~~Peru, Chile and Argentina) based on the methodology proposed by Ewert et al. (1998; 2005), in addition ~~with~~to the study of Guimarães et al. (2021) applying the VRR strategy to Latin American volcanoes with activity recorded in the last 1,000 years. The comparison between these rankings is not straightforward because they are all based on diverse ways of considering the risk factors. Consequently, we can find relative threat and risk scores ranging from 0 to 250 (Fig. 7). In addition, each country evaluates only the volcanoes that concern ~~its~~their own territory whilst ~~the~~our VRR strategy~~, comprising a regional scale,~~ considers volcanoes from the four ~~bordering~~CVZA countries~~ of the CVZA~~. Regardless of the relative scoring, ~~there~~this difference of approaches is ~~a general trend ~~evidenced in Fig. 7~~, when~~ by the clustering of volcanoes per country. Colours represent each catalogue, comparing the Peruvian volcanoes in green (Macedo et al., 2016), Chilean and bordering volcanoes in grey ~~(Ranking de riesgo específico para volcanes activos de Chile 2023)~~(SERNAGEOMIN, 2023) and Argentinian and bordering volcanoes in yellow ~~(Elissondo and Farías, 2023) against the VRR results in blue (Guimarães et al., 2021) and red (this study) bars~~(Elissondo and Farías, 2024) against the VRR results in blue (Guimarães et al., 2021) and red (this study) bars, that are spread along the latitudes 14-28°S.


Threat and risk scores
Latitude
-14° S
-28° S
0
50
100
150
200
250
Quimsachata (Pe)
Auquihuato (Pe)
Sara Sara (Pe)
Andahua VF (Pe)
Coropuna (Pe)
Huambo (Pe)
Sabancaya (Pe)
Chachani (Pe)
El Misti (Pe)
Ubinas (Pe)
Huaynaputina (Pe)
Ticsani (Pe)
Tutupaca (Pe)
Yucamane (Pe)
Purupuruni (Pe)
Casiri (Pe)
Tacora (Ch)
Taapaca (Ch)
Parinacota (Ch-Bo)
Guallatiri (Ch)
Tata Sabaya (Bo)
Isluga (Ch)
Irruputuncu (Ch-Bo)
Olca-Paruma (Ch-Bo)
Aucanquilcha (Ch)
Ollagüe (Ch-Bo)
Cerro del Azufre (Ch)
San Pedro (Ch)
Uturuncu (Bo)
Putana (Ch-Bo)
Escalante-Sairecabur (Ch-Bo)
Licancabur (Ch-Bo)
Acamarachi (Ch)
Lascar (Ch)
Chiliques (Ch)
Alitar (Ch)
Puntas Negras (Ch)
Tuzgle (Ar)
Aracar (Ar)
Socompa (Ch-Ar)
Arizaro VF (Ar)
Llullaillaco (Ch-Ar)
Escorial (Ch-Ar)
Lastarria (Ch-Ar)
Cordón del Azufre (Ch-Ar)
C.Bayo (Ch-Ar)
Antofagasta VF (Ar)
Sierra Nevada (Ch-Ar)
Cueros de Parulla (Ar)
Peinado (Ar)
C. El Cóndor (Ar)
C. Blanco (Ar)
Falso Azufre (Ch-Ar)
N. de Incahuasi (Ch-Ar)
El Fraile (Ch-Ar)
N. Tres Cruces (Ch-Ar)
El Solo (Ch-Ar)
Ojos del Salado (Ch-Ar)
C.Tipas (Ar)
Macedo et al., 2016 - VRR0
SERNAGEOMIN 2023 - VRR0
Elissondo and Farías 2023 - VRR0
Guimarães et al., 2021 - VRR0
Guimarães et al., 2021 - VRR1
Guimarães et al., 2021 - VRR2
This work - VRR0
This work - VRR1
This work - VRR2
N

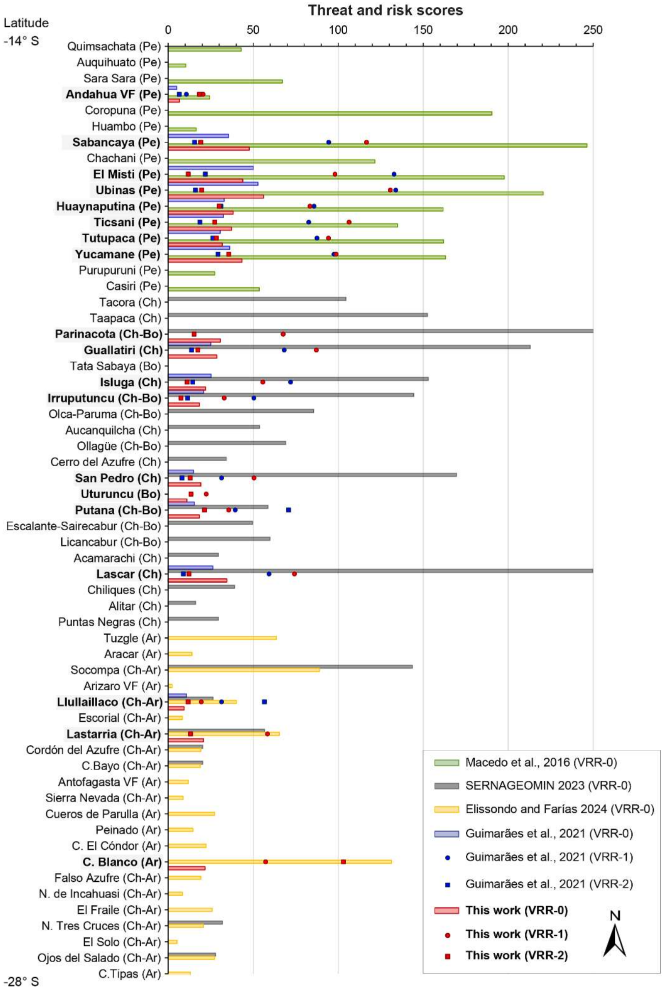


Figure 7: Comparison of existing volcanic threat and risk rankings. The CVZA volcanoes are organized by latitude, the volcanic systems in bold highlight the ~~ones analyzed~~19 analysed for the VRR in this work. Notice that bars represent threat rankings (i.e., ~~VRR0~~VRR-0 (HxE~~))~~)), circles represent the 3-factor ~~VRR1~~VRR-1, and squares the 4-factor ~~VRR2~~VRR-2. The threat ranking of INGEMMET (Macedo et al., 2016) in green, SERNAGEOMIN (SERNAGEOMIN, 2023) in grey, SEGEMAR (Elissondo and Farías,

~~2023~~2024) in yellow, the threat and risk rankings of Guimarães et al. (2021) in ~~a scale of blues~~blue, and the ones of this work in ~~a scale of reds~~red.

Comparing threat rankings in particular, we can point out that three of the five rankings share the same volcanoes in the top 5, with slight differences in the order (Table ~~5~~3, Fig. 7). The difference ~~in order~~ for the VRR~~(~~-0~~) of~~ between this study and Guimarães et al. (2021) is related to the ~~current~~ update of ~~available~~ data~~, or~~ used, and ~~subsequently~~ the ~~eruptive period considered.~~scoring of some indicators such as the recurrence rate. The difference with Macedo et al. (2016) is the absence of Coropuna volcano (Peru) in the list. Interestingly, Coropuna has a higher exposure than Huaynaputina, but was not considered in the work of Guimarães et al. (2021) nor in this study because it ~~didn't have~~ does not account for eruptions during the last 1,000 years ~~or no current~~, nor records of all three signs of unrest ~~are monitored.~~. The Chilean and Argentinian threat rankings are not directly comparable since ~~none of these Peruvian~~their ranking doesn't consider volcanoes ~~are considered for being~~ outside ~~of~~ their territory, and ~~regarding~~there is no existing ranking for Bolivian volcanoes~~, they have not yet its own ranking.~~.

Table ~~5~~3. Comparison of the top 5 CVZA volcanoes of existing threat rankings~~,~~ considering hazard and exposure (VRR~~(~~-0~~)).~~). Pe: Peru, Ch: Chile, Bo: Bolivia, Ar: Argentina. Underlined volcanoes highlight the ones ~~repeated~~appearing in different threat rankings.

	This work VRR~~(~~-0~~)~~	Guimarães et al. (2021) VRR~~(~~-0~~)~~	SERNAGEOMIN (2023)	Elissondo and Farias (~~2023~~2024)	Macedo et al. (2016)
1	Ubinas (Pe)	Ubinas (Pe)	Lascar (Ch)	Cerro Blanco (Ar)	Sabancaya (Pe)
2	Sabancaya (Pe)	El Misti (Pe)	Parinacota (Ch-Bo)	Socompa (Ch-Ar)	Ubinas (Pe)
3	El Misti (Pe)	Yucamane (Pe)	Guallatiri (Ch)	Lastarria (Ch-Ar)	El Misti (Pe)
4	Yucamane (Pe)	Sabancaya (Pe)	San Pedro (Ch)	Tuzgle (Ar)	Coropuna (Pe)
5	Huaynaputina (Pe)	Huaynaputina (Pe)	Isluga (Ch)	Llullaillaco (Ch-Ar)	Yucamane (Pe)

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When comparing the existing threat rankings without the Peruvian (Table 4), it is interesting ~~to notice~~ that the top first volcano is the same for Guimarães et al. (2021), SENARGEOMIN, (2023) and this work, i.e. Lascar volcano located in Chile. With respect to the Chilian or transboundary volcanoes, the top 3 volcanoes are the same between our ranking and the one of SERNAGEOMIN. ~~Then, the~~ Cerro Blanco volcano, which is the top one Argentinian CVZA volcano, appears at the 5th position in our threat ranking. ~~It was considered in our work due to the fact that it has shown the three signs of unrest.~~ Except from this volcano, none of the volcanoes listed by Elissondo and Farias (2014) appears in the top five in the other rankings. This demonstrated the influence of the scale of analysis, country versus region.

Table 4. Comparison of the top 5 CVZA volcanoes of existing threat rankings, considering hazard and exposure (VRR-0) only for Chilean and Argentinian volcanoes. Ch: Chile, Bo: Bolivia, Ar: Argentina. Underlined volcanoes highlight the ones appearing in different threat rankings.

	This work VRR-0	Guimarães et al. (2021) VRR-0	SERNAGEOMIN (2023)	Elissondo and Farias (2024)
1	Lascar (Ch)	Lascar (Ch)	Lascar (Ch)	Cerro Blanco (Ar)
2	Parinacota (Ch-Bo)	Isluga (Ch)	Parinacota (Ch-Bo)	Socompa (Ch-Ar)
3	Guallatiri (Ch)	Guallatiri (Ch)	Guallatiri (Ch)	Lastarria (Ch-Ar)
4	Isluga (Ch)	Irruputuncu (Ch-Bo)	San Pedro (Ch)	Tuzgle (Ar)
5	Cerro Blanco (Ar)	Putana (Ch-Bo)	Isluga (Ch)	Llullaillaco (Ch-Ar)

When accounting for the vulnerability and resilience factors (VRR~~(~~-1~~)~~ and VRR~~(~~-2~~)),~~), only this work and that of Guimarães et al. (2021) can be compared (Table ~~6~~5, Fig. 7). When hazard, exposure and vulnerability are combined, both approaches highlight Ubinas, Sabancaya, El Misti and Yucamane within the top five VRR~~(~~-1~~)~~ volcanoes. However, Ticsani appears in the 3rd position of this work and the 7th position of Guimarães et al. (2021), whilst Tutupaca is ~~in the~~ 5th position of Guimarães et al. (2021) and ~~the~~ 6th position of this work. Both volcanoes have the same hazard scores in both studies, however, Ticsani has a higher exposure score, even if the vulnerability is lower than Tutupaca, leading to a higher overall rank in the VRR~~(~~-1~~)~~ ~~produced in this work~~. The reasons for this are i) a higher population density within the 10, 30 and 100 km; ii) telecommunications score, not considered in Guimarães et al. (2021); and iii) the multiple economic activity source within 100 km for both volcanoes that have been updated with respect to Guimarães et al. (2021).

Table ~~6~~5. Comparison of the top 5 CVZA volcanoes of existing risk rankings, considering hazard, exposure, vulnerability ~~(~~VRR~~(~~-1~~))~~ and resilience ~~(~~VRR~~(~~-2~~)).~~. Pe: Peru, Ch: Chile, Bo: Bolivia, Ar: Argentina. Underlined volcanoes highlight the ones repeated in both ranking strategies.

	This work VRR~~(~~-1~~)~~	Guimarães et al. (2021) VRR~~(~~-1~~)~~	This work VRR~~(~~-2~~)~~	Guimarães et al. (2021) VRR~~(~~-2~~)~~
1	Ubinas (Pe)	Ubinas (Pe)	Cerro Blanco (Ar)	Putana (Ch-Bo)
2	Sabancaya (Pe)	El Misti (Pe)	Yucamane (Pe)	Llullaillaco (Ch-Ar)
3	Ticsani (Pe)	Yucamane (Pe)	Huaynaputina (Pe)	Huaynaputina (Pe)
4	Yucamane (Pe)	Sabancaya (Pe)	Tutupaca (Pe)	Yucamane (Pe)
5	El Misti (Pe)	Tutupaca (Pe)	Ticsani (Pe)	Tutupaca (Pe)

The major differences occur when considering resilience (VRR~~(~~-2~~)~~ in ~~Table 6~~Tables 4, 5 and Fig. 7). Both studies share 3 volcanoes, Yucamane, Huaynaputina and Tutupaca, although in different order. However, Cerro Blanco and Ticsani appear in the 1st and 5th position of our VRR~~(~~-2~~),~~, respectively, whilst Putana and Llullaillaco are in the 1st and 2nd position of Guimarães et al., (2021) but only in the 6th and 17th positions of our VRR~~(~~-2~~).~~. There are significant differences in all parameters when scoring these volcanoes in both studies due to a better knowledge of the CVZA volcanoes as well as the available vulnerability and resilience data. Few examples are discussed below.

~~With a VEI of 7, Cerro Blanco represents an important case for the CVZA since its last eruption is one of the largest eruptions worldwide (Fernandez-Turiel et al. 2019). However, it was not considered by Guimarães et al. (2021) because it didn't have an eruption in the past 1,000 years. It is included in our study because we considered volcanoes showing also 3 signs of unrest. From the regional map analysis, we also found that there are important localities within 100 km radius, such as Antofagasta de la Sierra or Corral Quemado (with 730 and 1200 inhabitants per locality, respectively).~~

With a VEI of 7, Cerro Blanco represents an important case for the CVZA since its last caldera eruption is one of the largest eruptions worldwide (Fernandez-Turiel et al., 2019). Whilst it was not considered by Guimarães et al. (2021), not having an eruption in the past 1,000 years, we account for the presence of unrest signs, in agreement with SERNAGEOMIN criteria.

From the regional map analysis, we also found that there are important localities within 100 km radius around Cerro Blanco, such as Antofagasta de la Sierra or Corral Quemado (with 730 and 1200 inhabitants, respectively).

On the other hand, Putana has the same hazard score, but higher exposure, lower vulnerability and higher resilience scores, leading to a lower overall VRR~~(~~-2~~)~~ in this work with respect to Guimarães et al. (2021). Regarding Lullaillaco volcano, it has ~~a~~ lower hazard and vulnerability scores and higher exposure and resilience scores, leading to a lower overall VRR~~(~~-2~~)~~ in our work ~~with respectin contrast to Guimarães et al. (2021)~~. The biggest differences for these ~~2~~two volcanoes are found in the vulnerability ~~factor, mainly due to~~scoring given by the typology of buildings, its proximity to the Argentina-Chile border, the lack of redundancy of power and telecommunication infrastructures and the multiple economic activities within 30 km radius. In addition,~~-~~ according to our updated information, there are existing hazard maps for Putana volcano (Amigo et al., 2012) increasing its resilience score with respect to Guimarães et al. (2021).

5.~~4~~3 Data limitations

It is important to notice the dynamic dimension of all risk factors and emphasize that the parameters of the rankings can be easily updated when new information becomes available, consequently modifying the final score (e.g., Guimarães et al~~. (~~., 2021~~)~~ versus this work). This is particularly true for the CVZA given the large uncertainties associated with this volcanic zone. Factor scoring highly depends on the availability, quality and accuracy of data, for either regional mapping or VRR analysis. The complexity and diversity of volcanic hazards and their impacts can exacerbate existing cross-border differences with respect to hazard information, elements at risk, vulnerability, scientific resources, disaster management, mitigation capacity, and public awareness. These differences affect the development of research, sharing of data, accessibility to the information, expertise and resources, and, consequently, the availability and analysis of data (Donovan and Oppenheimer, 2019). ~~Therefore, one of the main challenges for this study was the accessibility to the same level of data and heterogeneity of available datasets across countries, in terms of format, typology (e.g., different names for building types), spatial and temporal scales. As previous works,~~Therefore, one of the main challenges for this study was the accessibility to the same level of precision and heterogeneity of available datasets across countries, in terms of format, taxonomy (e.g., different names for building types or roads), spatial and temporal resolutions. As previous works (e.g., Guimarães et al., 2021), we also recognize the limitations of the GVP database especially in relation to the eruptive history. For example, after ~~their~~the last update, San Pedro volcano is now listed as Pleistocene ~~(GVP, 2023) San Pedro volcano now is listed as Pleistocene, whilst according with previous information it was~~(GVP, 2023b), being catalogued previously as Holocene (GVP, 2013), with 10 eruptive events and maximum VEI 2, ~~also~~ in agreement with SERNAGEOMIN. In the case of Parinacota volcano, the number of eruptions is also ~~disagree~~not consistent, i.e., 6 according to the GVP~~,~~ (2023), and at least 38 after the updated hazard map~~ of Parinacota~~ recently published by SERNAGEOMIN (Bertin et al., 2022b). Another case is Yucamane volcano, for which the GVP ~~list~~(2023) lists its last eruption as 1320 BCE, which would leave this volcano out of our VRR but according to INGEMMET its last eruption was 1787 CE

(Macedo et al., 2016). Additionally, the ~~time of remote acquisition~~ ~~of~~up-to-dateness data, in particular for the elements at risk and their vulnerability, is ~~quite~~highly variable~~ and that affects~~, influencing the accuracy of the analysis.

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6 Conclusions

Regional mapping and volcanic risk rankings represent an important tool to identify volcanoes requiring a prioritization of strategies and efforts in volcanic risk reduction. However, the final results strongly depend on the assumptions of the selected VRR methodology and on the availability of data. The selection of volcanoes to evaluate can also vary depending on the objective of the study. Our analysis shows that the most comprehensive list of volcanoes of the CVZA currently comprises a total of 59 active and potentially active volcanic ~~centers.~~ centres. However, this number could change in the future if additional information on the various volcanoes become available.

The regional maps compiled for a general visualization of hazard and ~~exposure~~ elements at risk for the 59 volcanoes show that:

- ~~El Misti, Ubinas,~~ Huaynaputina~~, Parinacota, Lascar~~ and Cerro Blanco are the volcanoes with the highest eruption magnitude (VEI 6~~, Huaynaputina;~~ and VEI 7, ~~Cerro Blanco) or~~respectively) and the volcanoes with the highest eruption frequency are El Misti (22~~, El Misti;~~), Ubinas (26~~, Ubinas;~~), Parinacota (38~~, Parinacota;~~) and Lascar (37~~, Lascar~~).
- Arequipa, Moquegua, and Tacna (Peru), Calama and the mining stations “Estación Zaldivar” and “Mina Escondida” (Chile) are associated with the highest population density~~ of people~~ per km^2.
- Arequipa, Moquegua, and Tacna cities (Peru), the tripartite point and Colchane customs post (between Peru-Bolivia-Chile and Bolivia-Chile, respectively), and the Collahuasi mining district, Calama city, San Pedro de Atacama town, and SQM (Chile) are associated with the highest density of transport infrastructure per km^2.
- Arequipa (Peru) is associated with the highest density of facilities per km^2.

The most threatening volcanoes according to our regional mapping are El Misti and Ubinas, as they are the closest to Arequipa city (Peru), which represents the highest densely populated area, also associated with the highest density of transport infrastructure and facilities per km^2.

While the regional map provides a~~ fast~~ visual assessment of potential volcanic impact at regional scale, the VRR provides a more comprehensive regional analysis by integrating ~~various~~4 different risk factors. ~~Moreover, integrating all~~In this study, the VRR was focused on the 19 active or potentially active volcanoes ~~presenting 3 signs of unrest allowed the identification of Cerro Blanco, which otherwise would have gone unnoticed in our VRR analysis-based volcanoes having a volcanic activity~~that had eruption in the last 1,000 years~~.~~ or show significant signs of unrest. Results help identifying the ~~riskiest~~highest risk volcanoes and those that need to be prioritized in terms of implementing risk reduction strategies. In particular:

- The ~~3-factor~~ VRR~~ (~~-0, which considers hazard and exposure, highlights Ubinas, Sabancaya, El Misti, Yucamane and Huaynaputina as the most threatening volcanoes.
- The VRR~~ (~~-1~~), Eq.2)~~, which considers hazard, exposure, and vulnerability, highlights Ubinas, Sabancaya, Ticsani, Yucamane, and El Misti as the ~~riskiest volcanoes, while Cerro Blanco, Yucamane, Huaynaputina, Tutupaca, and Ticsani represent the riskiest~~ highest-risk volcanoes~~ when,~~
- The VRR-2, which also includes resilience parameters, identifies Cerro Blanco, Yucamane, Huaynaputina, Tutupaca, and Ticsani as the ~~4-factor VRR (VRR (2), Eq.3) is applied~~highest-risk volcanoes.
- ~~As~~Given that volcanic hazard and exposure are difficult to modify and reduce, the implementation of risk ~~mitigation measures should~~reduction strategies might focus on reducing vulnerability and increasing resilience, which are highlighted by results of VRR-1 and VRR-2.

We encourage the use of volcanic risk rankings to characterize volcanic systems and support risk reduction strategies at regional scale, which is especially ~~for Cerro Blanco, Yucamane, Huaynaputina, Tutupaca, and Ticsani volcanoes.~~valuable in case of cross-border volcanoes. In fact, risk rankings are often carried out at national level, neglecting the complexity of crisis management in case of cross-border eruptions. In the case of the CVZA, most volcanoes are located within less than 25 km from an international border and ~~at least~~ 20 of them share borders, which could result in challenging crisis managements and complex impact patterns. With the hope that our work promotes cooperation between CVZA countries to increase resilience through the co-production of hazard and risk maps, the development of coordinated emergency plans and co-creation of protocols to manage potential impacts, we recommend that further studies are carried out at different scales and this regional VRR could be continuously updated as new information becomes available.

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7 Competing interests

The authors declare that they have no conflict of interest.

8 Author Contributions

MPRH carried out the compilation of hazard and resilience parameters with the contribution of ME, SG, RA, and GP. LSDM carried out the compilation of exposure and vulnerability parameters with the contribution of LD and CF. MPRH, LSDM and LF carried out the Volcanic Risk Ranking. MPRH and LSDM carried out the regional mapping and drafted the first draft of the manuscript with the contribution of LD, CF, SB, and CB. All authors contributed to the finalization of the manuscript.

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References

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~~Acosta, H., Alván, A., Mamani, M., Oviedo, M., and Rodriguez, J.: Geología de los cuadrángulos de Pachía (36-v) y Palca (36-x), escala 1:50 000, INGEMMET, Boletín, Ser. A Cart. Geológica Nac., 100, 7 mapas, 2010.~~

Aguilar, R., Thouret, J.-C., Samaniego, P., Wörner, G., Jicha, B., Paquette, J.-L., Suaña, E., and Finizola, A.: Growth and evolution of long-lived, large volcanic clusters in the Central Andes: The Chachani Volcano Cluster, southern Peru, J. Volcanol. Geotherm. Res., 426, 107539, https://doi.org/10.1016/j.jvolgeores.2022.107539, 2022.

Aguilera, F.: Origen y naturaleza de los fluidos en los sistemas volcánicos, geotermales y termales de baja entalpía de la Zona Volcánica Central entre los 17°43´S y 25°10´S, Chile, Ph.D. Thesis. Univ. Católica del Norte. (In Spanish), 393, 2008.

Aguilera, F., Viramonte, J., Medina, E., Guzmán, K., Becchio, R., Delgado, H., and Arnosio, M.: Eruptive Activity From Lascar Volcano (2003 – 2005), XI Congr. Geológico Chil. Antofagasta, II Región, Chile, 2, 397–400, 2006.

Aguilera, F., Tassi, F., Darrah, T., Moune, S., and Vaselli, O.: Geochemical model of a magmatic–hydrothermal system at the Lastarria volcano, northern Chile, Bull. Volcanol., 74, 119–134, https://doi.org/10.1007/s00445-011-0489-5, 2012.

Aguilera, F., Layana, S., Rodríguez-Díaz, A., González, C., Cortés, J., and Inostroza, M.: Hydrothermal alteration, fumarolic deposits and fluids from Lastarria Volcanic Complex: A multidisciplinary study, Andean Geol., 43, 166, https://doi.org/10.5027/andgeoV43n2-a02, 2016.

Aguilera, F., Layana, S., Rojas, F., Arratia, P., Wilkes, T. C., González, C., Inostroza, M., McGonigle, A. J. S., Pering, T. D., and Ureta, G.: First measurements of gas flux with a low-cost smartphone sensor-based uv camera on the volcanoes of Northern Chile, Remote Sens., 12, https://doi.org/10.3390/rs12132122, 2020.

Aguilera, F., Apaza, F., Del Carpio, J., Grosse, P., Jiménez, N., Ureta, G., Inostroza, M., Báez, W., Layana, S., Gonzalez, C., Rivera, M., Ortega, M., Gonzalez, R., and Iriarte, R.: Advances in scientific understanding of the Central Volcanic Zone of

Formatted: English (United Kingdom)

the Andes: a review of contributing factors, Bull. Volcanol., 84, 1–8, https://doi.org/10.1007/s00445-022-01526-y, 2022.

Amigo, A., Bertin, D., and Orozco, G.: Peligros volcanicos de la zona norte de Chile, Regiones de Arica y Parinacota, Tarapacá, Antofagasta y Atacama. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Ambiental, 2012.

~~Argentina Passenger transport Líneas de trenes pasajeros. Website: Argentina.gob.ar.: https://www.argentina.gob.ar/transporte/cnrt/lineas-de-trenes-pasajeros, last access: 18 September 2021.~~

Anderssohn, J., Motagh, M., Walter, T. R., Rosenau, M., Kaufmann, H., and Oncken, O.: Surface deformation time series and source modeling for a volcanic complex system based on satellite wide swath and image mode interferometry: The Lazufre system, central Andes, Remote Sens. Environ., 113, 2062–2075, https://doi.org/10.1016/j.rse.2009.05.004, 2009.

Antayhua, Y., Ramos, D., and Masías, P.: Monitoreo de los volcanes Ticsani, Sabancaya y Huaynaputina: Periodo 2006-2012, INGEMMET, Boletín No 53 Ser. C Geodinámica e Ing. Geológica, 124, 2013.

Apaza, F., Kern, C., Ortega, M., and Miranda, R.: The July 2019 explosive activity of Ubinas Volcano , Peru, EGU21-3529, 1, https://doi.org/https://doi.org/10.5194/egusphere-egu21-3529, 2021.

Auker, M. R., Sparks, R. S. J., Jenkins, S. F., Aspinall, W., Brown, S. K., Deligne, N. I., Jolly, G., Loughlin, S. C., Marzocchi, W., Newhall, C. G., and Palma, J. L.: Development of a new global Volcanic Hazard Index (VHI), in: Global Volcanic Hazards and Risk, ~~edited by: Loughlin, S. C., Sparks, S., Brown, S. K., Jenkins, S. F., and Vye-Brown, C.,~~ Cambridge University Press~~, Cambridge~~, 349–358, https://doi.org/10.1017/CBO9781316276273.024, 2015.

~~Baker, P. E., González-Ferrán, O., and Rex, D. C.: Geology and geochemistry of the Ojos del Salado volcanic region, Chile., J. Geol. Soc. London, 144, 85–96, 1987.~~

Báez, W., Arnosio, M., Chiodi, A., Ortiz-Yañes, A., Viramonte, J. G., Bustos, E., Giordano, G., and López, J. F.: Stratigraphy and evolution of the Cerro Blanco Volcanic Complex, Puna Austral, Argentina, Rev. Mex. Ciencias Geológicas, 32, 29–49, 2015.

Bailey, R. A., Beauchemin, P. R., Kapinos, F. P., and Klick, D. W.: The Volcano Hazards Program: objectives and long-range plans, Open-File Rep. 83-400. Reston, VA U.S. Geol. Surv., 33 p, https://doi.org/10.3133/ofr83400, 1983.

Barazangi, M. and Isacks, B. L.: Spatial distribution of earthquakes and subduction of the Nazca plate beneath South America, Geology, 4, 686, https://doi.org/10.1130/0091-7613(1976)4<686:SDOEAS>2.0.CO;2, 1976.

Barberi, F., Coltelli, M., Ferrara, G., Innocenti, F., Navarro, J. M., and Santacroce, R.: Plio-Quaternary volcanism in Ecuador, Geol. Mag., 125, 1–14, https://doi.org/10.1017/S0016756800009328, 1988.

~~Baumont, D., Paul, A., Zandt, G., Beck, S. L., and Pedersen, H.: Lithospheric structure of the central Andes based on surface wave dispersion, J. Geophys. Res. Solid Earth, 107, ESE 18-1-ESE 18-13, https://doi.org/10.1029/2001JB000345, 2002.~~

~~Biblioteca del Congreso Nacional: SIIT: Mapas vectoriales.: https://www.bcn.cl/siit/mapas_vectoriales/index_html/., last access: 22 July 2021.~~

~~Biblioteca del Congreso Nacional: Ley Chile. Website: bcn.cl/leychile.: https://www.bcn.cl/leychile/navegar?idNorma=1041213., last access: 22 July 2021.~~

Bertin, D.: Volcano-tectonic history and volcanic hazard assessment of the 22.5-29 °S segment of the Central Volcanic Zone

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of the Andes, Dr. Diss. Res. Space@ Auckland. Univ. Auckl., 248, 2022.

Bertin, D., Lindsay, J. M., Cronin, S. J., de Silva, S. L., Connor, C. B., Caffe, P. J., Grosse, P., Báez, W., Bustos, E., and Constantinescu, R.: Probabilistic Volcanic Hazard Assessment of the 22.5–28°S Segment of the Central Volcanic Zone of the Andes, Front. Earth Sci., 10, https://doi.org/10.3389/feart.2022.875439, 2022a.

Formatted: Spanish (Spain)

Bertin, L. ., Jara, G. ., and Toloza, V.: Peligros del volcán Parinacota, región de Arica y Parinacota. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie de Geología Ambiental: X p., 1 mapa escala 1:50.000, Santiago., 2022b.

~~Bomberos de Chile. Website: Bomberos de Chile.: https://www.bomberos.cl/., last access: 12 August 2021.~~

~~Bonatti,~~ BGVN: Report on Sabancaya (Peru) (Crafford, A.E., ~~Harrison, C. G. A., Fisher, D.~~and Venzke, E., ~~Honnorez, J., Schilling, J.-G., Stipp, J. J., and Zentilli, M.: Easter~~eds.), Glob. Volcanism Program, 2021. Bull. Glob. Volcanism Network. Smithson. Institution., 46, 2021.

Bredemeyer, S., Ulmer, F.-G., Hansteen, T., and Walter, T.: Radar Path Delay Effects in Volcanic ~~Chain (southeast Pacific): A mantle hot line, J. Geophys. Res., 82, 2457–2478~~Gas Plumes: The Case of Láscar Volcano, Northern Chile, Remote Sens., 10, 1514, https://doi.org/10.~~1029/JB082i017p02457, 1977~~3390/rs10101514, 2018.

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

~~Bomberos Voluntarios De La República Argentina. Website: Argentina.gob.ar.: https://www.bomberosra.org.ar/., last access: 12 August 2021.~~

Bromley, G. R. M., Thouret, J.-C., Schimmelpfennig, I., Mariño, J., Valdivia, D., Rademaker, K., del Pilar Vivanco Lopez, S., Team, A., Aumaître, G., Bourlès, D., and Keddadouche, K.: In situ cosmogenic 3He and 36Cl and radiocarbon dating of volcanic deposits refine the Pleistocene and Holocene eruption chronology of SW Peru, Bull. Volcanol., 81, 64, https://doi.org/10.1007/s00445-019-1325-6, 2019.

Brunori, C. A., Bignami, C., Stramondo, S., and Bustos, E.: 20 years of active deformation on volcano caldera: Joint analysis of InSAR and AInSAR techniques, Int. J. Appl. Earth Obs. Geoinf., 23, 279–287, https://doi.org/10.1016/j.jag.2012.10.003, 2013.

Budach, I., Brasse, H., and Díaz, D.: Imaging of conductivity anomalies at Lazufre volcanic complex , Northern Chile , through 3-D inversion of magnetotelluric data, Schmucker-Weidelt-Kolloquium Neustadt an der Weinstraße, 27–34, 2011.

Byrdina, S., Ramos, D., Vandemeulebrouck, J., Masias, P., Revil, A., Finizola, A., Gonzales Zuñiga, K., Cruz, V., Antayhua, Y., and Macedo, O.: Influence of the regional topography on the remote emplacement of hydrothermal systems with examples of Ticsani and Ubinas volcanoes, Southern Peru, Earth Planet. Sci. Lett., 365, 152–164, https://doi.org/10.1016/j.epsl.2013.01.018, 2013.

Cahill, T. and Isacks, B. L.: Seismicity and shape of the subducted Nazca Plate, J. Geophys. Res., 97, 17503, https://doi.org/10.1029/92JB00493, 1992.

Formatted: English (United Kingdom)

~~Carabineros de Chile. Website: Carabineros de Chile - Organizaciones - Portal de Datos Abiertos.: https://datos.gob.cl/organization/carabineros_de_chile., last access: 11 August 2021.~~

~~Casertano, L.: General and a characteristics of active andean volcanoes summary of their activities during recent centuries, Bull. Seismol. Soc. Am., 53, 1415–1433, 1963.~~

~~Cuerpo General de Bomberos Voluntarios del Peru. Website: Bomberos del Peru.: http://www.bomberosperu.gob.pe/portal/net_principal.aspx., last access: 12 August 2021.~~

~~Clavero, J., Polanco, E., Godoy, E., Aguilar, G., Sparks, R. S. J., van Wyk de Vries, B., Perez de Arce, C., and Matthews, S.: Substrata infuence in the transport and emplacement mechanism of the Ollague debris avalanche (Northern Chile), Acta Vulcanol., 16, 59–76, 2004.~~

~~Estadísticas del transporte ferroviario – CNRT Comisión Nacional de Regulación del Transporte – Ministerio de Transporte. Website: Argentina.gob.ar.: www.argentina.gob.ar/cnrt/estadisticas-ferroviarias., last access: 18 September 2021.~~

~~Coira, B. and Kay, S. M.: Implications of Quaternary volcanism at Cerro Tuzgle for crustal and mantle evolution of the Puna Plateau, Central Andes, Argentina, Contrib. to Mineral. Petrol., 113, 40–58, https://doi.org/10.1007/BF00320830, 1993.~~

~~Coira, B., Davidson, J., Mpodozis, C., and Ramos, V.: Tectonic and magmatic evolution of the Andes of northern Argentina and Chile, Earth-Science Rev., 18, 303–332, https://doi.org/10.1016/0012-8252(82)90042-3, 1982.~~

~~Comeau, M. J., Unsworth, M. J., and Cordell, D.: New constraints on the magma distribution and composition beneath Volcán Uturuncu and the southern Bolivian Altiplano from magnetotelluric data, Geosphere, 12, 1391–1421, https://doi.org/10.1130/GES01277.1, 2016.~~

~~Cuerpo de Guardaparques – Ministerio de Agricultura – Gobierno de Chile. Website: CONAF.: https://www.conaf.cl/parques-nacionales/cuerpo-de-guardaparques/., last access: 12 August 2021.~~

~~Manual de Señalización de Tránsito (Chile).: https://www.conaset.cl/manualsenalizacion/default.html., last access: 22 July 2021.~~

~~Listado De Establecimientos De Salud. Website: Ministerio de Salut (DEIS) - Gobierno de Chile.: https://reportesdeis.minsal.cl/ListaEstablecimientoWebSite/., last access: 29 July 2021.~~

~~Déruelle, B., Harmon, R. S., and Moorbath, S.: Combined Sr–O isotope relationships and petrogenesis of Andean volcanics of South America, Nature, 302, 814–816, https://doi.org/10.1038/302814a0, 1983.~~

Capaccioni, B., Aguilera, F., Tassi, F., Darrah, T., Poreda, R. J., and Vaselli, O.: Geochemical and isotopic evidences of magmatic inputs in the hydrothermal reservoir feeding the fumarolic discharges of Tacora volcano (northern Chile), J. Volcanol. Geotherm. Res., 208, 77–85, https://doi.org/10.1016/j.jvolgeores.2011.09.015, 2011.

Del Carpio, J. A. and Torres, J. L.: La actividad sísmica en el volcán Ubinas y su variación temporal (1998-2019) para la identificación de patrones de sismicidad a ser considerados en la gestión del riesgo de desastres, 71, 2020.

Centeno, R., Anccasi, R., and Macedo, O.: Sismos distales de fractura observados en la zona de los Volcanes Misti y Chachani, 4, 2013.

Chiodi, A., Tassi, F., Báez, W., Filipovich, R., Bustos, E., Glok Galli, M., Suzaño, N., Ahumada, M. F., Viramonte, J. G., Giordano, G., Pecoraino, G., and Vaselli, O.: Preliminary conceptual model of the Cerro Blanco caldera-hosted geothermal system (Southern Puna, Argentina): Inferences from geochemical investigations, J. South Am. Earth Sci., 94, 102213, https://doi.org/10.1016/j.jsames.2019.102213, 2019.

Clavero, J., Sparks, S., Polanco, E., and Pringle, M.: Evolution of Parinacota volcano, Central Andes, Northern Chile, Rev.

geológica Chile, 31, 317–347, https://doi.org/10.4067/S0716-02082004000200009, 2004.

Clavero, J., Soler, V., and Amigo, A.: Caracterización preliminar de la actividad sísmica y de desgasificación pasiva de volcanes activos de los Andes Centrales del Norte de Chile, XI Congr. Geológico Chil. Antofagasta, II Reg. Chile, 2, 443–446, 2006.

Contreras, Á.: Caracterización de la mineralogía de alteración hidrotermal en superficie del Volcán Tacora y sus alrededores, Región de Arica y Parinacota., Mem. para optar al título geólogo, 98, 2013.

Cruz, J.: Análisis de la actividad sísmica en el volcán Ticsani y su variación temporal, periodo 1999-2019, Inf. vulcanológico IGP/CENVUL-TIC/IV 2020-0001, 72, 2020.

Cruz, V., Vargas, V., and Matsuda, K.: Geochemical Characterization of Thermal Waters in the Calientes Geothermal Field, Tacna, South of Peru, Proc. World Geotherm. Congr. 2010, 7, 2010.

Cruz, V., Flores, R., and Velarde, Y.: Caracterización y evaluación del potencial geotérmico de la zona geotermal Casiri-Kallapuma, Región Tacna, NGEMMET, Boletín Ser. B Geol. Económica N° 69, 250, 2020.

Donovan, A. and Oppenheimer, C.: Volcanoes on borders: a scientific and (geo)political challenge, Bull. Volcanol., 81, 31, https://doi.org/10.1007/s00445-019-1291-z, 2019.

~~Dirección de Obras Portuarias. Website: Ministerio de Obras Públicas.: https://www.mop.cl/Direccionesyareas/DirecciondeObrasPortuarias., last access: 19 September 2021.~~

~~E-Asfalto. Red Vial Argentina, 2010.: http://www.e-asfalto.com/redvialarg/redvial.htm., last access: 13 September 2021.~~

~~E-Asfalto. Red Vial de Bolivia (commissioned by Corporacion Andina De Fomento).: http://www.e-asfalto.com/redvialbolivia/red_vial_de_bolivia.htm., last access: 17 September 2021.~~

~~Establecimientos Del Sector Salud. Website: PERU Instituto Nacional de Estadística e Informática INEI.: https://www.inei.gob.pe/estadisticas/indice-tematico/health-sector-establishments/., last access: 29 July 2021.~~

~~EFE – Empresa de los Ferrocarriles del Estado. Website: EFE Trenes de Chile.: https://www.efe.cl/., last access: 20 September 2021.~~

Elissondo and Farías: Riesgo volcánico relativo en territorio ~~argentino. Actualización y evaluación de peligrosidad de los volcanes del territorio de Antártida e islas del Atlántico Sur.,~~ Argentino., Inst. Geol. y Recur. Miner. Serv. Geológico Min. Argentino. ~~Inst. Geol. y Recur. Miner.~~ Ser. Contrib. Técnicas Peligrosidad Geológica ~~N° XX., 2023.~~

~~Elissondo, M., Farías, C., and Collini, E.: Evaluacion del riesgo volcanico relativo en argentina, Cities Volcanoes 9, Puerto Varas, Chile., Poster, 2016.~~

~~Ewert, J. W.: System for Ranking Relative Threats of U.S. Volcanoes, Nat. Hazards Rev., 8, 112–124, https://doi.org/10.1061/(ASCE)1527-6988(2007)8:4(112), 2007~~Nº 28., 99, 2024.

Ewert, J. W., Miller, C. D., Tilling, R. I., and Neal, C. A.: Revised Criteria for Identifying High-Risk Volcanoes Around theWorld., EOS Trans. Am. Geophys. Union., 79, 993, 1998.

~~Ewert, J. W., Guffanti, M., and Murray, T. L.: An assessment of volcanic threat and monitoring capabilities in the United States: Framework for a National Volcano Early Warning System (NVEWS), USGS Open-File Rep. 2005-1164, 62, 2005.~~

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Formatted: Spanish (Spain)

Formatted: English (United Kingdom)

~~FEPSA – Ferro Expreso Pompeano. Website: SCP.: https://scp.com.ar/ferroexpreso-pampeano.php., last access: 20 September 2021.~~

~~Ferrocarril Antofagasta-Salta – Huaytiquina.: https://www.argentina.gob.ar/noticias/ramal-c14-huaytiquina-ferrocarril-trasandino-de-salta, last access: 18 September 2021.~~

~~Ferrocarril del Sur y Sur Oriente – Ferrocarril Trasandino S.A. Website: Ferrocarril Trasandino.: www.ferrocarriltransandino.com., last access: 23 September 2021.~~

~~Ferrosur Roca S.A. Website: Ferrosur Roca.: www.ferrosur.com.ar., last access: 20 September 2021.~~

~~Ferrovías S.A.C – pasajeros metropolitanos.: www.ferrovias.com.ar., last access: 19 September 2021.~~

~~Fídel, L., Morche, W., and Núñez, S.: Inventario de volcanes del Peru, 80 pp., 1997.~~

~~Francis, P. and Wells, G.: Landsat Thematic Mapper observations of debris avalanche deposits in the Central Andes, Bull. Volcanol., 50, 258–278, 1988.~~

~~Francis, P. W. and Rundle, C. C.: Rates of production of the main magma types in the central Andes, Geol. Soc. Am. Bull., 87, 474, https://doi.org/10.1130/0016-7606(1976)87<474:ROPOTM>2.0.CO;2, 1976.~~

~~Francis, P. W., Roobol, M. J., Walker, G. P. L., Cobbold, P. R., and Coward, M.: The San Pedro and San Pablo volcanoes of northern Chile and their hot avalanche deposits, Geol. Rundschau, 63, 357–388, https://doi.org/10.1007/BF01820994, 1974.~~

~~Francis, P. W.,~~ Fernandez-Turiel, J. L., Perez–Torrado, F. J., Rodriguez-Gonzalez, A., Saavedra, J., Carracedo, J. C., Rejas, M., Lobo, A., Osterrieth, M., Carrizo, J. I., Esteban, G., Gallardo, J., and Ratto, N.: La gran erupción de hace 4.2 ka cal en Cerro Blanco, Zona Volcánica Central, Andes: nuevos datos sobre los depósitos eruptivos holocenos en la Puna sur y regiones adyacentes, Estud. Geológicos, 75, 088, https://doi.org/10.3989/egeol.43438.515, 2019.

Fialko, Y. and Pearse, J.: Sombrero Uplift Above the Altiplano-Puna Magma Body: Evidence of a Ballooning Mid-Crustal Diapir, Science (80-.)., 338, 250–252, https://doi.org/10.1126/science.1226358, 2012.

Fídel, L. and Huamaní, A.: Mapa preliminar de amenaza volcánica potencial del Volcán Yucamane, INGEMMET, Boletín N° 26 Ser. C Geodinámica e Ing. Geológica, 165, 2001.

Forte, P., Rodríguez, L., Jácome Paz, M. P., Caballero García, L., Alpízar Segura, Y., Bustos, E., Perales Moya, C., Espinoza, E., Vallejo, S., and Agusto, M.: Volcano monitoring in Latin America: taking a step forward, Volcanica, 4, vii–xxxiii~~Gardeweg, M., Ramirez, C. F., and Rothery, D. A.: Catastrophic debris avalanche deposit of Socompa volcano, northern Chile, Geology, 13, 5, https://doi.org/10.1130/0091-7613(1985)13<600:CDADOS>2.0.CO;2, 1985.~~

~~Pasos de Fronteras internacionales – Estado de los pasos fronterizos entre la República Argentina y los países limítrofes. Website: Argentina.gob.ar.: https://www.argentina.gob.ar/seguridad/pasosinternacionales., last access: 6 July 2022.~~

~~Complejos Fronterizos Chile. Website: Pasos Fronterizos.: http://www.pasosfronterizos.gov.cl/complejos-fronterizos/., last access: 6 July 2022.~~

~~Ferrocarril del Centro – Ferrovías Central Andina S.A. Website: FVCA.: www.ferroviasperu.com.pe., last access: 23 September 2021.~~

~~García, S., Sruoga, P., and Elissondo, M.: Programa de Evaluación de Amenazas Volcánicas del SEGEMAR, Argentina, in:~~

~~Foro Internacional: Los volcanes y su impacto, 174–178, 2018.~~

~~Gardeweg, M. and Amigo, Á.: Peligros del volcán Láscar, Región de Antofagasta, escala 1:50.000, Serv. Nac. Geol. y Minería, Cart. Geológica Chile, Ser. Geol. Ambient., 2015.~~

~~Gardeweg, M. and Ramírez, C. F.: La Pacana caldera and the Atana Ignimbrite – a major ash-flow and resurgent caldera~~, https://doi.org/10.30909/vol.04.S1.viixxxiii, 2021.

Froger, J.-L., Remy, D., Bonvalot, S., and Legrand, D.: Two scales of inflation at Lastarria-Cordon del Azufre volcanic complex ~~in the Andes of northern Chile, Bull. Volcanol., 49, 547–566, https://doi.org/10.1007/BF01080449, 1987.~~

~~Garzione, C. N., Molnar, P., Libarkin, J. C., and MacFadden, B. J.: Rapid late Miocene rise of the Bolivian Altiplano: Evidence for removal of mantle lithosphere~~, central Andes, revealed from ASAR-ENVISAT interferometric data, Earth Planet. Sci. Lett., ~~241, 543–556~~255, 148–163, https://doi.org/10.1016/j.epsl.~~2005.11.026,~~ 2006.12.012, 2007.

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

~~GeoBolivia – Infraestructura de Datos Espaciales del Estado Plurinacional de Bolivia. Portal GeoBolivia.: http://geo.gob.bo/portal/., last access: 17 September 2021.~~

~~Global Healthsites Mapping Project. Website: Healthsites.: https://healthsites.io/., last access: 14 May 2021~~Gaete, A., Cesca, S., Franco, L., San Martin, J., Cartes, C., and Walter, T. R.: Seismic activity during the 2013–2015 intereruptive phase at Lascar volcano, Chile, Geophys. J. Int., 219, 449–463, https://doi.org/10.1093/gji/ggz297, 2019.

Gałaś, A., Panajew, P., and Cuber, P.: Stratovolcanoes in the Western Cordillera – Polish Scientific Expedition to Peru 2003–2012 reconnaissance research, Geotourism/Geoturystyka, 37, 61, https://doi.org/10.7494/geotour.2014.37.61, 2014.

Gardeweg, M., ~~.~~

Mpodozis, C., and Clavero, J.: The Ojos del Salado complex: the highest active volcano of the world, Central Andes, Proc. IAVCE, Abstr. Magmat. Divers. Volcanoes their roots, 21, 1998.

Gianni, G. M., Navarrete, C., and Spagnotto, S.: Surface and mantle records reveal an ancient slab tear beneath Gondwana, Sci. Rep., 9, 19774, https://doi.org/10.1038/s41598-019-56335-9, 2019.

~~Gendarmería Nacional Argentina. Website: Argentina.gob.ar.: https://www.argentina.gob.ar/gendarmeria, last access: 11 August 2021.~~

~~Gonzalez-Ferran, O., Baker, P. E., and Rex, D. C.: Tectonic-volcanic discontinuity at latitude 27° south Andean Range, associated with Nazca Plate Subduction, Tectonophysics, 112, 423–441, https://doi.org/10.1016/0040-1951(85)90189-1, 1985.~~

Gillespie, R., Magee, J. W., Luly, J. G., Dlugokencky, E., Sparks, R. J., and Wallace, G.: AMS radiocarbon dating in the study of arid environments: Examples from Lake Eyre, South Australia, Palaeogeogr. Palaeoclimatol. Palaeoecol., 84, 333–338, https://doi.org/10.1016/0031-0182(91)90052-S, 1991.

Gonzáles, K., Froger, J., Rivera, M., and Audin, L.: Deformación co-sísmica producida por el sismo Mb=5.4 del 01 de Octubre de 2005 (Carumas-Moquegua), detectada por interferometría radar - InSAR, XIII Congr. Peru. Geolgía. Resúmenes Extendidos Soc. Geológica del Perú, 488–489, 2006.

González-Ferrán, O.: Volcanes de Chile, Instituto Geográfico Militar, 640 pp., 1995.

Formatted: Spanish (Spain)

~~Guardaparques Nacionales. Website: Argentina.gob.ar.: https://www.argentina.gob.ar/parquesnacionales/guardaparquesnacionales., last access: 12 August 2021.~~

~~Guillande, R. and Throuret, J. C.: L'activite eruptive actuelle du Volcan Nevado Sabancaya (sud du pérou) et lévaluation des menages et des risques: Geologie, cartographie et imagerie satellitaire, Ministére l'Environnement el du Cent. Natl. d'Etudes Spat. Paris, Fr., 132, 1992.~~

Gottsmann, J., Blundy, J., Henderson, S., Pritchard, M. E., and Sparks, R. S. J.: Thermomechanical modeling of the Altiplano-Puna deformation anomaly: Multiparameter insights into magma mush reorganization, Geosphere, 13, GES01420.1, https://doi.org/10.1130/GES01420.1, 2017.

Grosse, P., Orihashi, Y., Guzmán, S. R., Sumino, H., and Nagao, K.: Eruptive history of Incahuasi, Falso Azufre and El Cóndor Quaternary composite volcanoes, southern Central Andes, Bull. Volcanol., 80, 44, https://doi.org/10.1007/s00445-018-1221-5, 2018.

Grosse, P., Guzmán, S. R., Nauret, F., Orihashi, Y., and Sumino, H.: Central vs. lateral growth and evolution of the < 100 ka Peinado composite volcano, southern Central Volcanic Zone of the Andes, J. Volcanol. Geotherm. Res., 425, https://doi.org/10.1016/j.jvolgeores.2022.107532, 2022.

Guimarães, L., Nieto-Torres, A., Bonadonna, C., and Frischknecht, C.: A New Inclusive Volcanic Risk Ranking, Part 2: Application to Latin America, Front. Earth Sci., 9, 1–24, https://doi.org/10.3389/feart.2021.757742, 2021.

GVP: Global Volcanism Program, Volcanoes World, v. 4.9.2. Venzke, E (ed.). Smithson. Institution., 2013.

GVP: Global Volcanism Program, 2023. Holocene Volcanoes of the World (v. 5.1.1; 17 Aug 2023). Distributed by Smithsonian Institution, compiled by Venzke, E., https://doi.org/10.5479/si.GVP.VOTW5-2023.5.1, 2023a.

GVP: Global Volcanism Program, 2023. Pleistocene Volcanoes of the World (v. 5.1.1; 17 Aug 2023). Distributed by Smithsonian Institution, compiled by Venzke, E., https://doi.org/https://doi.org/10.5479/si.GVP.VOTW5-2023.5.1, ~~2023~~2023b.

Hall, M. L., Samaniego, P., Le Pennec, J. L., and Johnson, J. B.: Ecuadorian Andes volcanism: A review of Late Pliocene to present activity, J. Volcanol. Geotherm. Res., 176, 1–6, https://doi.org/10.1016/j.jvolgeores.2008.06.012, 2008.

~~Hantke, G. and Parodi, A.: Catalogue of the active volcanoes of the world including solfatara fields. Part XIX: Colombia, Ecuador and Peru., Int. Assoc. Volcanol. Rome, XII, 73, 1966.~~

~~Harmon, R. S., Barreiro, B. A., Moorbath, S., Huefs, J., Francis, P. W., Thorpe, R. S., Deruelle, B., McHugh, J., and Viglino, J. A.: Regional O-, Sr-, and Pb-isotope relationships in late Cenozoic calc-alkaline lavas of the Andean Cordillera, J. Geol. Soc. London., 141, 803–822, 1984.~~

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

Hayes, G. P., Moore, G. L., Portner, D. E., Hearne, M., Flamme, H., Furtney, M., and Smoczyk, G. M.: Slab2, a comprehensive subduction zone geometry model, Science (80-.)., 362, 58–61, https://doi.org/10.1126/science.aat4723, 2018.

Formatted: English (United Kingdom)

~~Hoke, L. and Lamb, S.: Cenozoic behind-arc volcanism in the Bolivian Andes, South America: implications for mantle melt generation and lithospheric structure, J. Geol. Soc. London., 164, 795–814, https://doi.org/10.1144/0016-76492006-092, 2007.~~

~~Hora, J. M., Singer, B. S., and Worner, G.: Volcano evolution and eruptive flux on the thick crust of the Andean Central Volcanic Zone: 40Ar/39Ar constraints from Volcan Parinacota, Chile, Geol. Soc. Am. Bull., 119, 343–362, https://doi.org/10.1130/B25954.1, 2007.~~

~~OpenStreetMap exports for use in GIS applications on The Humanitarian Data Exchange (HDX). Humanitarian OpenStreetMap Team (HOT).:~~

~~IAVCEI: Post-Miocene volcanoes of the world., IAVCEI Data Sheets, Rome. Int. Assoc. Volcanol. Chem. Earth's Inter., 1973.~~

~~International Civil Aviation Organization. Website: icao.maps.arcgis.com.: https://icao.maps.arcgis.com/home/index.html., last access: 14 March 2022.~~

~~Instituto Geográfico Nacional de la República Argentina.: https://www.ign.gob.ar/NuestrasActividades/Geografia/DatosArgentina/Poblacion2, last access: 13 September 2021.~~

~~Instituto Geográfico Nacional. Website: Capas SIG | Instituto Geográfico Nacional.: https://www.ign.gob.ar/NuestrasActividades/InformacionGeoespacial/CapasSIG., last access: 12 August 2021.~~

~~Instituto Nacional de Defensa Civil (INDECI). Website: INDECI – Gobierno del Perú.: https://www.gob.pe/indeci/., last access: 12 August 2021.~~

~~Instituto Nacional de Estadística. Servicios Departamentales De Caminos - Gobiernos Autónomos Municipales: Longitud de Caminos.: https://www.ine.gob.bo/index.php/estadisticas-economicas/transportes/longitud-de-caminos-cuadros-estadisticos/., last access: 21 July 2022.~~

Henderson, S. T. and Pritchard, M. E.: Decadal volcanic deformation in the Central Andes Volcanic Zone revealed by InSAR time series, Geochemistry, Geophys. Geosystems, 14, 1358–1374, https://doi.org/10.1002/ggge.20074, 2013.

Henderson, S. T., Delgado, F., Elliott, J., Pritchard, M. E., and Lundgren, P. R.: Decelerating uplift at Lazufre volcanic center, Central Andes, from A.D. 2010 to 2016, and implications for geodetic models, Geosphere, 13, 1489–1505, https://doi.org/10.1130/GES01441.1, 2017.

Hickey, J., Gottsmann, J., and del Potro, R.: The large-scale surface uplift in the Altiplano-Puna region of Bolivia: A parametric study of source characteristics and crustal rheology using finite element analysis, Geochemistry, Geophys. Geosystems, 14, 540–555, https://doi.org/10.1002/ggge.20057, 2013.

Holtkamp, S. G., Pritchard, M. E., and Lohman, R. B.: Earthquake swarms in South America, Geophys. J. Int., 187, 128–146, https://doi.org/10.1111/j.1365-246X.2011.05137.x, 2011.

IGP: Instituto Geofísico del Perú., Cent. vulcanológico Nac. Volcanes Monit. Perú, 2021.

Inostroza, M., Aguilera, F., Menzies, A., Layana, S., González, C., Ureta, G., Sepúlveda, J., Scheller, S., Böehm, S., Barraza, M., Tagle, R., and Patzschke, M.: Deposition of metals and metalloids in the fumarolic fields of Guallatiri and Lastarria volcanoes, northern Chile, J. Volcanol. Geotherm. Res., 393, 106803, https://doi.org/10.1016/j.jvolgeores.2020.106803, 2020a.

Inostroza, M., Tassi, F., Aguilera, F., Sepúlveda, J. P., Capecchiacci, F., Venturi, S., and Capasso, G.: Geochemistry of gas and water discharge from the magmatic-hydrothermal system of Guallatiri volcano, northern Chile, Bull. Volcanol., 82, 57, https://doi.org/10.1007/s00445-020-01396-2, 2020b.

Jaillard, E., Hérail, G., Monfret, T., Diaz-Martinez, E., Baby, P., Lavenu, A., and Dumont, J. F.: Tectonic evolution of the Andes of Ecuador, Peru, Bolivia and Northernmost Chile. In Tectonic evolution of South America (Cordani, U.; Milani, E.; Thomaz Filho, A.; Campos; D.; editors), Tecton. Evol. South Am., 31, 481–559, 2000.

James, D. E.: Andean crustal and upper mantle structure, J. Geophys. Res., 76, 3246–3271, https://doi.org/10.1029/JB076i014p03246, 1971.

Jay, J. A., Pritchard, M. E., West, M. E., Christensen, D., Haney, M., Minaya, E., Sunagua, M., McNutt, S. R., and Zabala, M.: Shallow seismicity, triggered seismicity, and ambient noise tomography at the long-dormant Uturuncu Volcano, Bolivia, Bull. Volcanol., 74, 817–837, https://doi.org/10.1007/s00445-011-0568-7, 2012.

Jay, J. A., Welch, M., Pritchard, M. E., Mares, P. J., Mnich, M. E., Melkonian, A. K., Aguilera, F., Naranjo, J. A., Sunagua, M., and Clavero, J.: Volcanic hotspots of the central and southern Andes as seen from space by ASTER and MODVOLC between the years 2000 and 2010, Geol. Soc. London, Spec. Publ., 380, 161–185, https://doi.org/10.1144/SP380.1, 2013.

Jay, J. A., Delgado, F. J., Torres, J. L., Pritchard, M. E., Macedo, O., and Aguilar, V.: Deformation and seismicity near Sabancaya volcano, southern Peru, from 2002 to 2015, Geophys. Res. Lett., 42, 2780–2788, https://doi.org/10.1002/2015GL063589, 2015.

Jordan, T., Isacks, B., Allmendinger, R., Brewer, J., Ramos, V., and Ando, C.: Andean tectonics related to geometry of subducted Nazca plate, Geol. Soc. Am. Bull., 94, 341, https://doi.org/10.1130/0016-7606(1983)94<341:ATRTGO>2.0.CO;2, 1983.

Kay, ~~R. W~~S. M. and ~~Mahlburg Kay, S.: Delamination~~Coira, B. L.: Shallowing and ~~delamination~~steepening subduction zones, continental lithospheric loss, magmatism, ~~Tectonophysics, 219, 177–189~~and crustal flow under the Central Andean Altiplano-Puna Plateau, Mem. Geol. Soc. Am., 204, 229–259, https://doi.org/10.~~1016/0040-1951(93)90295-U, 1993~~1130/2009.1204(11), 2009.

~~Kay, S.~~Lamberti, M~~., Coira, B~~. C., Chiodi, A., Agusto, M., Filipovich, R., Massenzio, A., Báez, W., Tassi, F., and ~~Viramonte, J.: Young mafic back arc volcanic rocks~~Vaselli, O.: Carbon dioxide diffuse degassing as ~~indicators of continental lithospheric delamination beneath~~a tool for computing the ~~Argentine~~thermal energy release at Cerro Blanco Geothermal System, Southern Puna ~~Plateau, central Andes, J. Geophys. Res. Solid~~(NW Argentina), J. South Am. Earth~~, 99, 24323–24339~~ Sci., 105, 102833, https://doi.org/10.~~1029/94JB00896, 1994~~1016/j.jsames.2020.102833, 2021.

Lara, L. ., Orozco, G., Amigo, A., and Silva, C.: Peligros Volcánicos de Chile. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Ambiental, 0–24, 1 mapa escala 1:2.000.000, 2011.

~~Lara, L. E., Clavero~~Liu, F., Elliott, J., ~~Hinojosa, M., Huerta~~Ebmeier, S., ~~Wall, R., ~~Craig, T., Hooper, A., Novoa, C., and ~~Moreno, H.: NVEWS-CHILE: Sistema de Clasificación semicuantitativa de la vulnerabilidad volcánica., Congr. Geológico Chil., 11, 487–490, 2006.~~

Formatted: English (United Kingdom)

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Formatted: Spanish (Spain)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

~~Lara, L. E., Flores, F., Calderón, R., and Cardona, C.:~~Delgado, F.: Unrest Detected at Socompa Volcano~~ hazards and risks in~~, Northern Chile, ~~in: Forecasting and Planning for Volcanic Hazards, Risks, and Disasters, Elsevier, 617–633, https://doi.org/10.1016/B978-0-12-818082-2.00017-2, 2021.~~

from Geodetic Observations, AGU Fall Meet. Abstr., G46A-02, 2022.

Liu, F., Elliott, J. R., Ebmeier, S. K., Craig, T. J., Hooper, A., Novoa Lizama, C., and Delgado, F.: First Onset of Unrest Captured at Socompa: A Recent Geodetic Survey at Central Andean Volcanoes in Northern Chile, Geophys. Res. Lett., 50, https://doi.org/10.1029/2022GL102480, 2023.

Loyola, R., Figueroa, V., Núñez, L., Vasquez, M., Espíndola, C., Valenzuela, M., and Prieto, M.: The Volcanic Landscapes of the Ancient Hunter-Gatherers of the Atacama Desert Through Their Lithic Remains, Front. Earth Sci., 10, 1–22, https://doi.org/10.3389/feart.2022.897307, 2022.

Macedo, O., Taipe, E., Del Carpio, J., Ticona, J., Ramos, D., Puma, N., Aguilar, V., Machacca, R., Torres, J., Cueva, K., Cruz, J., Lazarte, I., Centeno, R., Miranda, R., Álvarez, Y., Masias, P., Vilca, J., Apaza, F., Chijcheapaza, R., Calderón, J., Cáceres, J., and Vela, J.: Evaluación del Riesgo Volcánico en el Sur del Perú, situación actual de la vigilancia actual y requerimientos de monitoreo en el futuro, Arequipa, 2016.

~~Mamani, M., Worner, G~~Mariño, J., Samaniego, P., Manrique, N., Valderrama, P., and ~~Sempere, T.: Geochemical variations in igneous rocks of the Central Andean orocline (13 S to 18 S): Tracing crustal thickening~~Macedo, L.: Geología y Mapa de Peligros del Complejo Volcánico Tutupaca, INGEMMET, Boletín Ser. C Geodinámica e Ing. Geológica N° 66, 168, 2019.

Matthews, S. J., Gardeweg, M. C., and ~~magma generation through time~~Sparks, R. S. J.: The 1984 to 1996 cyclic activity of Lascar Volcano, northern Chile: cycles of dome growth, dome subsidence, degassing and ~~space, Geol. Soc. Am.~~explosive eruptions, Bull~~., 122, 162–182~~. Volcanol., 59, 72–82, https://doi.org/10.~~1130/B26538.1, 2010~~1007/s004450050176, 1997.

~~Martí, J., Soriano, C., and Dingwell, D. B.: Tube pumices as strain markers of the ductile–brittle transition during magma fragmentation, Nature, 402, 650–653, https://doi.org/10.1038/45219, 1999.~~

~~Defensa Civil de Chile – Ministerio de Defensa Nacional. Website: Defensa Civil de Chile.: https://www.defensacivil.cl/., last access: 12 August 2021.~~

Van der Meijde, M., Julià, J., and Assumpção, M.: Gravity derived Moho for South America, Tectonophysics, 609, 456–467, https://doi.org/10.1016/j.tecto.2013.03.023, 2013.

Méndez-Fajury, R. A.: Catálogo de Volcanes Activos en Colombia, Boletín Geológico INGEOMINAS, 30, 1–75, 1989.

~~Mering, C., Huaman-Rodrigo, D., Chorowicz, J., Deffontaines, B., and Guillande, R.: New data on the geodynamics of southern Peru from computerized analysis of SPOT and SAR ERS-1 images, Tectonophysics, 259, 153–169, https://doi.org/10.1016/0040-1951(96)00034-0, 1996.~~

~~Metro Regional de Valparaíso S.A. Website: Merval.: http://www.merval.cl/, last access: 20 September 2021.~~

~~Metro de Lima – GyM Ferrovías S.A. Website: Línea 1 del Metro de Lima. .: www.lineauno.pe., last access: 23 September 2021.~~

~~Metro de Santiago.: https://www.metro.cl/., last access: 20 September 2021.~~

Formatted: Spanish (Spain)

Formatted: Spanish (Spain)

Formatted: Spanish (Spain)

~~Metrovias S.~~Morales Rivera, A. M., Amelung, F., and Mothes, P.: Volcano deformation survey over the Northern and Central Andes with ALOS InSAR time series, Geochemistry, Geophys. Geosystems, 17, 2869–2883, https://doi.org/10.1002/2016GC006393, 2016.

Mulcahy, P., Chen, C., Kay, S. M., Brown, L. D., Alvarado, P. M., Sandvol, E. A., Heit, B., and Yuan, X.: The Southern Puna seismic experiment: shape of the subducting Nazca Plate, areas of concentrated mantle and crustal earthquakes, and crustal focal mechanisms, Am. Geophys. Union, Fall Meet. 2010, Abstr. id. T11A-2050, 1, 2010.

Naranjo, J. A~~. – pasajeros metropolitanos.: www.metrovias.com.ar., last access: 19 September 2021.~~

~~Michelfelder, G. S., Feeley, T. C., and Wilder, A. D.: The Volcanic Evolution of Cerro Uturuncu: A High-K, Composite Volcano~~ .: Sulphur flows at Lastarria volcano in the ~~Back-Arc of the Central Andes of SW Bolivia, Int. J. Geosci., 05, 1263–1281~~North Chilean Andes, Nature, 313, 778–780, https://doi.org/10.~~4236/ijg.2014.511105, 2014.~~

~~Mapa de Riesgo - Unidad de Reducción de Riesgo de Desastres – MINEDUC. Website: Ministerio de ministerio de Educación – Gobierno de Chile.: https://emergenciaydesastres.mineduc.cl/mapa-de-resgo/#., last access: 12 August 2021.~~

~~Ministerio de Transporte Argentina datasets. Caminos terciarios de la República Argentina. Relevados por el Instituto Geográfico Nacional, 2016.: https://datos.transporte.gob.ar/dataset/caminos-terciarios., last access: 16 September 2021.~~

~~Ministerio de Transporte Argentina datasets. Rutas Provinciales de la República Argentina. Relevadas por el Instituto Geográfico Nacional, 2016.: https://datos.transporte.gob.ar/dataset/rutas-provinciales., last access: 16 September 2021.~~

~~Ministerio de Transporte Argentina datasets. Rutas nacionales de la República Argentina. Relevadas por la Dirección Nacional de Vialidad, 2018.: https://datos.transporte.gob.ar/dataset/rutas-nacionales., last access: 16 September 2021.~~

~~Establecimientos de salud de primer nivel de atención en el Perú. Website: Ministerio de Salud – Gobierno del Perú.: https://www.gob.pe/institucion/minsa/informes-publicaciones/391864-establecimientos-de-salud-del-ministerio-de-salud., last access: 29 July 2021.~~

~~Ministerio de Seguridad. Website: Argentina.gob.ar.: https://www.argentina.gob.ar/seguridad/bomberosvoluntarios., last access: 12 August 2021.~~

~~Informes y publicaciones - Descarga de datos – Ministerio de Transportes y Comunicaciones. Website: Ministerio de Transportes y Comunicaciones.: https://portal.mtc.gob.pe/estadisticas/descarga.html., last access: 12 August 2021.~~

~~Carta Caminera. MOP - Dirección de Vialidad.: http://www.mapas.mop.cl/., last access: 22 July 2021.~~

~~Ministerio de Obras Públicas- Dirección de Vialidad. Website: Arcgis Map Viewer.: https://www.arcgis.com/apps/mapviewer/index.html?layers=1033053d2fec412bb22e11f320312f9a&layerId=0., last access: 22 July 2021.~~

~~Ministerio de Obras Públicas - Dirección de Vialidad.: https://vialidad.mop.gob.cl/., last access: 22 July 2021.~~

~~Ministerio de Transportes y Comunicaciones Perù - Informes y publicaciones / Descarga de datos: https://portal.mtc.gob.pe/estadisticas/descarga.html., last access: 23 July 2021~~1038/313778a0, 1985.

Nieto-Torres, A., Guimarães, L. F., Bonadonna, C., and Frischknecht, C.: A New Inclusive Volcanic Risk Ranking, Part 1: Methodology, Front. Earth Sci., 9, 1–22, https://doi.org/10.3389/feart.2021.697451, 2021.

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

~~O'Callaghan, L. J. and Francis, P. W.: Volcanological and petrological evolution of San Pedro volcano, Provincia El Loa, North Chile, J. Geol. Soc. London., 143, 275–286, https://doi.org/10.1144/gsjgs.143.2.0275, 1986.~~

~~Ort, M. H., De Silva, S. L., Jiménez C., N., Jicha, B. R., and Singer, B. S.: Correlation of ignimbrites using characteristic remanent magnetization and anisotropy of magnetic susceptibility, Central Andes, Bolivia, Geochemistry, Geophys. Geosystems, 14, 141–157, https://doi.org/10.1029/2012GC004276, 2013.~~

~~La excursión de la Trochita en Esquel. Website: Patagonia Express.: https://www.patagoniaexpress.com/index.php/excursiones/la-trochita., last access: 19 September 2021.~~

~~Policía de Investigaciones de Chile. Website: PDI - Policía De Investigaciones De Chile.: https://pdichile.cl/., last access: 11 August 2021.~~

~~Perucca, L. P. and Moreiras, S. M.: Seismic and Volcanic Hazards in Argentina., Dev. Earth Surf. Process., 13, 267–300, https://doi.org/10.1016/S0928-2025(08) 10014-1, 2009.~~

~~Policía Federal Argentina. . Website: Argentina.gob.ar.: https://www.argentina.gob.ar/policia-federal-argentina, last access: 11 August 2021.~~

Nieto, A.: Volcanic Risk Ranking for México and Central América, Spec. Certif. Assess. Manag. Geol. Clim. Relat. risk, CERG-C 2019, 42, 2020.

OVI: Observatorio Vulcanológico del INGEMMET, Inst. Geol. Min. y Metal., 2021.

Pavez, A., Remy, D., Bonvalot, S., Diament, M., Gabalda, G., Froger, J.-L., Julien, P., Legrand, D., and Moisset, D.: Insight into ground deformations at Lascar volcano (Chile) from SAR interferometry, photogrammetry and GPS data: Implications on volcano dynamics and future space monitoring, Remote Sens. Environ., 100, 307–320, https://doi.org/10.1016/j.rse.2005.10.013, 2006.

Pavez, C., Comte, D., Gutiérrez, F., and Gaytán, D.: Analysis of the magmatic – Hydrothermal volcanic field of Tacora Volcano, northern Chile using travel time tomography, J. South Am. Earth Sci., 94, 102247, https://doi.org/10.1016/j.jsames.2019.102247, 2019.

Petit-Breuilh Sepúlveda, M.: Volcanes fronterizos en América Latina y la importancia de los comités de frontera en casos de desastre: Chile y Argentina en el siglo XX., in: Clima, desastres y convulsiones sociales en España e Hispanoamérica, siglos XVII-XX., 2016.

Pieri, D. and Abrams, M.: ASTER watches the world's volcanoes: a new paradigm for volcanological observations from orbit, J. Volcanol. Geotherm. Res., 135, 13–28, https://doi.org/10.1016/j.jvolgeores.2003.12.018, 2004.

Pilger, R. H.: Cenozoic plate kinematics, subduction and magmatism: South American Andes, J. Geol. Soc. London., 141, 793–802, https://doi.org/10.1144/gsjgs.141.5.0793, 1984.

~~Policía Nacional del Perú (PNP). Website: PNP - Gobierno del Perú.: https://www.gob.pe/pnp., last access: 11 August 2021.~~

~~del Potro, R., Díez~~Pritchard, M~~., Blundy, J., Camacho, A. G., ~~. and ~~Gottsmann, J.: Diapiric ascent~~Simons, M.: An InSAR-based survey of ~~silicic magma beneath~~volcanic deformation in the ~~Bolivian Altiplano~~central Andes, Geochemistry, Geophys. ~~Res. Lett., 40, 2044–2048~~Geosystems, 5, 1–42, https://doi.org/10.~~1002/grl.50493, 2013~~1029/2003GC000610, 2004.

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

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Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

~~Puertos – Dirección de Observatorio Nacional de Transport – Puertos públicos y privados de la República Argentina, relevados por la Direccional Nacional de Puertos y el Observatorio Nacional de Transporte – 2019. Website: Argentina.gob.ar.: https://datos.transporte.gob.ar/dataset/puertos., last access: 19 September 2021.~~

~~Registros Administrativos Estado Prurinacional de Bolivia. Website: INE – 63. Instituto Nacional de Estadisticas.: https://www.ine.gob.bo/index.php/registros-administrativos-salud/., last access: 29 July 2021.~~

Pritchard, M. E. and Simons, M.: A satellite geodetic survey of large-scale deformation of volcanic centres in the central Andes, Nature, 418, 167–171, https://doi.org/10.1038/nature00872, 2002.

Pritchard, M. E., Henderson, S. T., Jay, J. A., Soler, V., Krzesni, D. A., Button, N. E., Welch, M. D., Semple, A. G., Glass, B., Sunagua, M., Minaya, E., Amigo, A., and Clavero, J.: Reconnaissance earthquake studies at nine volcanic areas of the central Andes with coincident satellite thermal and InSAR observations, J. Volcanol. Geotherm. Res., 280, 90–103, https://doi.org/10.1016/j.jvolgeores.2014.05.004, 2014.

Pritchard, M. E., de Silva, S. L., Michelfelder, G., Zandt, G., McNutt, S. R., Gottsmann, J., West, M. E., Blundy, J., Christensen, D. H., Finnegan, N. J., Minaya, E., Sparks, R. S. J., Sunagua, M., Unsworth, M. J., Alvizuri, C., Comeau, M. J., del Potro, R., Díaz, D., Diez, M., Farrell, A., Henderson, S. T., Jay, J. A., Lopez, T., Legrand, D., Naranjo, J. A., McFarlin, H., Muir, D., Perkins, J. P., Spica, Z., Wilder, A., and Ward, K. M.: Synthesis: PLUTONS: Investigating the relationship between pluton growth and volcanism in the Central Andes, Geosphere, 14, 954–982, https://doi.org/10.1130/GES01578.1, 2018.

Ramos Chocobar, S. and Tironi, M.: An Inside Sun: Lickanantay Volcanology in the Salar de Atacama, Front. Earth Sci., 10, 1–11, https://doi.org/10.3389/feart.2022.909967, 2022.

Ramos, D.: Evaluación de la Actividad de los Volcanes Misti y Coropuna, INGEMMET, Inf. Técnico N°A69, 27, 2019.

Ramos, V. A. and Aleman, A.: Tectonic evolution of the Andes, 31st Int. Geol. Congr., 635–685, 2000.

~~Listado Establecimientos de Salud Asentados en el Registro Federal (REFES). Website: Datos Abiertos del Ministerio de Salud Argentina.: http://datos.salud.gob.ar/dataset/listado-establecimientos-de-salud-asentados-en-el-registro-federal-refes/., last access: 29 July 2021.~~

REAV Parinacota: Reporte Especial de Actividad Volcánica, Región de Arica y Parinacota, Volcán Parinacota, Serv. Nac. Geol. y Minería, 2, 2020.

Reyes-Hardy, M.-P., Di Maio, L. S., Dominguez, L., Frischknecht, C., Biasse, S., Guimarães, L., Nieto-Torres, A., Elissondo, M., Pedreros, G., Aguilar, R., Amigo, Á., Garcia, S., Forte, P., and Bonadonna, C.: Active and potentially active volcanoes of the Central Volcanic Zone of the Andes (CVZA), Arch. Ouvert. UNIGE, 123, https://doi.org/10.13097/archive-ouverte/unige, 2023.

Rivera, M., ~~Mariño, J., Samaniego, P., Delgado, R., and Manrique, N.: Geología y Evaluación de Peligros del Complejo Volcánico Ampato – Sabancaya (Arequipa), INGEMMET, Boletín Ser. C Geodinámica e Ing. Geológica N° 61, 133, 2016~~Thouret, J.-C., Mariño, J., Berolatti, R., and Fuentes, J.: Characteristics and management of the 2006–2008 volcanic crisis at the Ubinas volcano (Peru), J. Volcanol. Geotherm. Res., 198, 19–34, https://doi.org/10.1016/j.jvolgeores.2010.07.020, 2010.

Formatted: English (United Kingdom)

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Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

~~Salisbury, M. J., Jicha, B. R., de Silva, S. L., Singer, B. S., Jiménez, N. C., and Ort, M. H.: 40Ar/39Ar chronostratigraphy of Altiplano-Puna volcanic complex ignimbrites reveals the development of a major magmatic province, Bull. Geol. Soc. Am., 123, 821–840, https://doi.org/10.1130/B30280.1, 2011.~~

~~Salisbury, M. J., Kent~~Rivera, M., Cueva, K., Vela, J., Soncco, Y., Manrique, N., Le Pennec, J.-L., and Samaniego, P.: Mapa Geológico del Volcán Sara Sara (Ayacucho) Escala 1:25,000, 1, 1 mapa, 2020.

Robidoux, P., Rizzo, A. ~~J. R., Jiménez, N~~L., Aguilera, F., Aiuppa, A., Artale, M., Liuzzo, M., Nazzari, M., and ~~Jicha, B. R.: Geochemistry~~Zummo, F.: Petrological and ~~40 Ar/ 39 Ar geochronology of lavas from Tunupa volcano, Bolivia: Implications for plateau volcanism in the~~ noble gas features of Lascar and Lastarria volcanoes (Chile): Inferences on plumbing systems and mantle characteristics, Lithos, 370–371, 105615, https://doi.org/10.1016/j.lithos.2020.105615, 2020.

Romero, H. and Albornoz, C.: Erupciones volcánicas, en Chile, Rev. Retratos la Esc. Brasília, 7, 513–527, 2013.

Ruch, J. and Walter, T. R.: Relationship between the InSAR-measured uplift, the structural framework, and the present-day stress field at Lazufre volcanic area, central ~~Andean Plateau, Lithosphere, 7, 95–107~~Andes, Tectonophysics, 492, 133–140, https://doi.org/10.~~1130/L399.1,~~ 1016/j.tecto.2010.06.003, 2010.

Ruch, J., Anderssohn, J., Walter, T. R., and Motagh, M.: Caldera-scale inflation of the Lazufre volcanic area, South America: Evidence from InSAR, J. Volcanol. Geotherm. Res., 174, 337–344, https://doi.org/10.1016/j.jvolgeores.2008.03.009, 2008.

Ruch, J., Manconi, A., Zeni, G., Solaro, G., Pepe, A., Shirzaei, M., Walter, T. R., and Lanari, R.: Stress transfer in the Lazufre volcanic area, central Andes, Geophys. Res. Lett., 36, L22303, https://doi.org/10.1029/2009GL041276, 2009.

Samaniego, P., Rivera, M., Mariño, J., Guillou, H., Liorzou, C., Zerathe, S., Delgado, R., Valderrama, P., and Scao, V.: The eruptive chronology of the Ampato–Sabancaya volcanic complex (Southern Peru), J. Volcanol. Geotherm. Res., 323, 110–128, https://doi.org/10.1016/j.jvolgeores.2016.04.038, 2016.

Sandri, L., Thouret, J.-C., Constantinescu, R., Biass, S., and Tonini, R.: Long-term multi-hazard assessment for El Misti volcano (Peru), Bull. Volcanol., 76, 771, https://doi.org/10.1007/s00445-013-0771-9, 2014.

Schoenbohm, L. M. and Carrapa, B.: Miocene–Pliocene shortening, extension, and mafic magmatism support small-scale lithospheric foundering in the central Andes, NW Argentina, in: Geodynamics of a Cordilleran Orogenic System: The Central Andes of Argentina and Northern Chile, vol. 212, Geological Society of America, 167–180, https://doi.org/10.1130/2015.1212(09), 2015.

Seggiaro, R. and Apaza, F.: Geología del proyecto geotérmico Socompa, Serv. Geológico Min. Argentino. Inst. Geol. y Recur. Miner. Buenos Aires, 26, 2018.

Sempere, T., Hérail, G., Oller, J., and Bonhomme, M. G.: Late Oligocene-early Miocene major tectonic crisis and related basins in Bolivia, Geology, 18, 946, https://doi.org/10.1130/0091-7613(1990)018<0946:LOEMMT>2.3.CO;2, 1990.

~~Puestos de Control fronterizos. Website: Argentina.gob.ar.: https://www.argentina.gob.ar/senasa/que-es/control/puestos., last access: 6 July 2022.~~

~~Ranking de riesgo específico para volcanes activos de Chile 2019: https://www.sernageomin.cl/wp-content/uploads/2020/07/2Ranking-2019_Tabla_Final.pdf.~~

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Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

Formatted: Spanish (Spain)

SERNAGEOMIN: Servicio Nacional de Geología y Minería., Red Nac. Vigil. volcánica. Volcanes Act. y Monit. por cada región del país, Chile., 2021.

SERNAGEOMIN: Ranking de riesgo específico para volcanes activos de Chile 2023~~: https://rnvv.sernageomin.cl/wp-content/uploads/sites/2/~~, 2023~~/10/Ranking-2023_tabloide_20231012.pdf.~~

~~Servicio Nacional de Áreas Protegidas (Sernap) – Ministerio de Medio Ambiente y Agua – Estado Plurinacional de Bolivia. Website: SERNAP.: http://sernap.gob.bo/., last access: 12 August 2021.~~

~~Secretaría de Articulación Federal de la Seguridad - Subsecretaría de Gestión del Riesgo y Protección Civil, divided in Dirección Nacional de Operaciones de Protección Civil and Dirección Nacional de Prevención y Reducción del Riesgo de Desastres. Website: https://www.argentina.gob.ar/seguridad/gestion-del-riesgo-y-proteccion-civil., last access: 12 August 2021.~~

~~Siebert, L., Simkin, T., and Kimberly, P.: Volcanoes of the world, Univ. Calif. Press 2011, 568, 2011~~.

De Silva, S. and Francis, P.: Volcanoes of the Central Andes, Springer Verlag, Berlín, 216 p., Berlin, 216 pp., 1991.

~~de Silva, S. L.: Geochronology and stratigraphy of the ignimbrites from the 21°30′S to 23°30′S portion of the Central Andes of northern Chile, J. Volcanol. Geotherm. Res., 37, 93–131, https://doi.org/10.1016/0377-0273(89)90065-6, 1989.~~

~~De Silva, S. L. and Zielinski, G. A.: Global influence of the AD1600 eruptionofHuaynaputina,Peru, Nature, 393, 455–458, 1998.~~

~~Simkin, T. and Siebert, L.: Volcanoes of the World, Second ed. Smithson. Institution, Geosci. Tucson, 349, 1994.~~

Sparks, R. S. J., Folkes, C. B., Humphreys, M. C. S., Barfod, D. N., Clavero, J., Sunagua, M. C., McNutt, S. R., and Pritchard, M. E.: Uturuncu volcano, Bolivia: Volcanic unrest due to mid-crustal magma intrusion, Am. J. Sci., 308, 727–769, https://doi.org/10.2475/06.2008.01, 2008.

Spica, Z., Legrand, D., Mendoza, A. I., Dahn, T., Walter, T., Heimann, S., Froger, J. L., and Rémy, D.: Analysis of surface waves extracted from seismic noise for the Lastarria volcanic zone, Chile., Cities Volcanoes 7, Colima, México., 2012.

Stern, C.: Active Andean volcanism: its geologic and tectonic setting, Rev. geológica Chile, 31, 106–123, https://doi.org/10.4067/S0716-02082004000200001, 2004.

Szakács, A.: Redefining active volcanoes: a discussion, Bull. Volcanol., 56, 321–325, https://doi.org/10.1007/BF00326458, 1994.

~~Trenes Argentinos Cargas y Logística – Sociedad Anónima estatal. Website: Argentina.gob.ar.: https://www.argentina.gob.ar/transporte/trenes-argentinos-cargas, last access: 18 September 2021.~~

~~Trenes Argentinos Operadora Ferroviaria – Red ferroviaria de pasajeros regionales y de larga distancia: www.argentina.gob.ar/transporte/trenes-argentinos., last access: 18 September 2021.~~

~~Terminales Portuarias. Datos abiertos del Ministerio de Transporte. Website: Dirección de Observatorio Nacional de Transporte Argentina.: https://datos.transporte.gob.ar/dataset/terminales-portuarias., last access: 19 September 2021.~~

~~Thorpe~~Tassi, F., Aguilera, F., Vaselli, O., Medina, E., Tedesco, D., Delgado Huertas, A., Poreda, R~~.~~., and Kojima, S.: The ~~Tectonic Setting of~~ magmatic- and hydrothermal-dominated fumarolic system at the Active ~~Andean Volcanism, in: Andean~~

Formatted: Spanish (Spain)

Formatted: Spanish (Spain)

Formatted: Spanish (Spain)

~~Magmatism, Birkhäuser Boston, Boston, MA, 4–8~~Crater of Lascar volcano, northern Chile, Bull. Volcanol., 71, 171–183, https://doi.org/10.1007/~~978-1-4684-7335-3_1, 1984~~s00445-008-0216-z, 2009.

~~Thorpe, R. S., Potts, P. J~~Tassi, F., Aguilera, F., Vaselli, O., Darrah, T., and ~~Francis, P. W.: Rare Earth data and petrogenesis of andesite~~Medina, E.: Gas discharges from ~~the North Chilean Andes, Contrib. to Mineral. Petrol~~four remote volcanoes in northern Chile (Putana, Olca, Irruputuncu and Alitar): a geochemical survey, Ann. Geophys., 54, ~~65–78~~121–136, https://doi.org/10.~~1007/BF00370873, 1976~~4401/ag-5173, 2011.

Thorpe, R. S., Francis, P. W., and O'Callaghan, L. J.: Relative roles of source composition, fractional crystallization and crustal contamination in the petrogenesis of Andean volcanic rocks, Philos. Trans. R. Soc. London. Ser. A, Math. Phys. Sci., 310, 675–692, https://doi.org/10.1098/rsta.1984.0014, 1984.

Thouret, J~~.-C., Guillande, R., Huaman, D., Gourgaud, A., Salas, G., and Chorowicz, J.: Current activity of the Nevado Sabancaya stratovolcano, south Peru. Geological framework and volcanic hazard-zone mapping, Bull. - Soc. Geol. Fr., 165, 1994~~., Finizola, A., Fornari, M., Suni, J., and Frechen, M.: Geology of El Misti volcano near the city of Arequipa , Peru, Geol. Soc. Am. Bull., 113, 1593–1610, https://doi.org/10.1130/0016-7606(2001)1132.0.CO;2, 2001.

~~Thouret, J.-C., Davila, J., and Eissen, J.-P.: Largest explosive eruption in historical times in the Andes at Huaynaputina volcano, a.d. 1600, southern Peru, Geology, 27, 435, https://doi.org/10.1130/0091-7613(1999)027<0435:LEEIHT>2.3.CO;2, 1999.~~

Tilling, R. I.: Volcanism and associated hazards: the Andean perspective, Adv. Geosci., 22, 125–137, https://doi.org/10.5194/adgeo-22-125-2009, 2009.

~~Traversa, P., Lengliné, O., Macedo, O., Metaxian~~Vélez, M. ., Bustos, E., Euillades, L., Blanco, M., López, J. ~~P., Grasso, J. R., Inza~~F. S., Barbero, I., Berrocoso, M., Gil Martinez, A., and ~~Taipe, E.: Short term forecasting of explosions~~Viramonte, J. G.: Ground deformation at ~~Ubinas volcano, Perú~~the Cerro Blanco caldera: A case of subsidence at the Central Andes BackArc, J. ~~Geophys. Res. Solid~~South Am. Earth~~, 116, 15~~ Sci., 106, 102941, https://doi.org/10.~~1029/2010JB008180, 2011.~~ ~~Servicio Ferroviario Turístico "Tren a las Nubes" S.E. – pasajeros turístico. Website: Tren a las Nubes.: www.trenalasnubes.com.ar., last access: 20 September~~1016/j.jsames.2020.102941, 2021.

~~Tren Patagónico S.A. – pasajeros interurbanos y cargas. Website: Tren Patagonico Sitio Oficial.: www.trenpatagonico-sa.com.ar., last access: 19 September 2021.~~

~~Trenes Argentinos – Red Ferroviaria~~Viramonte, J., Godoy, S., Arnosio, M., Becchio, R., and Poodts, M.: El campo geotermal de ~~Pasajeros~~la caldera del ~~Area Metropolitana~~cerro Blanco: utilización de imágenes aster, Proc. Geol. Congr. Buenos Aires~~—pasajeros metropolitanos. Website:~~, Asoc. Geológica Argentina.~~gob.ar.: www.argentina.gob.ar/transporte/trenes-argentinos., last access: 18 September 2021.~~

~~Viejo Expreso Patagónico S.A. "~~La ~~Trochita" – pasajeros turístico. Website: La Trochita.: http://latrochita.org.ar/, last access: 19 September 2021.~~

~~Infraestructura Caminera Bolivia. Servicio Nacional de Caminos of Ministerio de Obras Públicas, Servicios y Vivienda.: https://www.udape.gob.bo/portales_html/portalSIG/atlasUdape1234567/atlas04_2003/HTML/ID25_M.HTM., last access: 17~~

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Formatted: Spanish (Spain)

Formatted: English (United Kingdom)

Formatted: English (United Kingdom)

~~September 2021.~~

~~United Nations Office for the Coordination of Humanitarian Affairs - Latin America and the Caribbean – ROLAC. Common Operational Datasets (CODs).: https://cod.unocha.org/., last access: 14 May 2021.~~

~~Vezzoli, L., Tibaldi, A., Renzulli, A., Menna, M., and Flude, S.: Faulting-assisted lateral collapses and influence on shallow magma feeding system at Ollagüe volcano (Central Volcanic Zone, Chile-Bolivia Andes), J. Volcanol. Geotherm. Res., 171, 137–159, https://doi.org/10.1016/j.jvolgeores.2007.11.015, 2008.~~

~~Portal oficial del Estado argentino. Direccion nacional de vialidad.: https://www.argentina.gob.ar/tags/direccion-nacional-de-vialidad., last access: 13 September 2021.~~

~~Viceministerio Defensa Civil – VIDECI. Website: Videci.: http://www.defensacivil.gob.bo/., last access: 12 August 2021.~~

~~Viramonte, J., Reynolds, J. H., Del Papa, C., and Disalvo, A.: The Corte Blanco garnetiferous tuff: A distinctive late Miocene marker bed in northwestern~~Plata, Argentina ~~applied to magnetic polarity stratigraphy in the Río Yacones, Salta Province, Earth Planet. Sci. Lett., 121, 519–531, https://doi.org/10.1016/0012-821X(94)90088-4, 1994~~., 2, 505–512, 2005.

Viramonte, J. G., Galliski, M. A., Araña Saavedra, V., Aparicio, A., Garcia Cacho, L., and Martín Escorza, C.: El finivolcanismo básico de la depresión de Arizaro, provincia de Salta., IX Congr. Geológico Argentino Actas III, 234–251, 1984.

Walker, B. A., Klemetti, E. W., Grunder, A. L., Dilles, J. H., Tepley, F. J., and Giles, D.: Crystal reaming during the assembly, maturation, and waning of an eleven-million-year crustal magma cycle: thermobarometry of the Aucanquilcha Volcanic Cluster, Contrib. to Mineral. Petrol., 165, 663–682, https://doi.org/10.1007/s00410-012-0829-2, 2013.

~~Walker, M., Head, M. J., Berkelhammer, M., Björck, S., Cheng, H., Cwynar, L., Fisher, D., Gkinis, V., Long, A., Lowe, J., Newnham, R., Rasmussen, S. O., and Weiss, H.: Formal ratification of the subdivision of the Holocene Series/Epoch (Quaternary System/Period): two new Global Boundary Stratotype Sections and Points (GSSPs) and three new stages/subseries, Episodes, 41, 213–223, https://doi.org/10.18814/epiiugs/2018/018016, 2018.~~

~~Ward, K. M., Porter, R. C., Zandt, G., Beck, S. L., Wagner, L. S., Minaya, E., and Tavera, H.: Ambient noise tomography across the Central Andes, Geophys. J. Int., 194, 1559–1573, https://doi.org/10.1093/gji/ggt166, 2013.~~

~~Maritime Safety Information: World port index. Website: Marine Safety Office.: https://msi.nga.mil/Publications/WPI., last access: 1 October 2021.~~

~~Wörner, G., Harmon, R. S., Davidson, J., Moorbath, S., Turner, D. L., McMillan, N., Nyes, C., Lopez-Escobar, L., and Moreno, H.: The Nevados de Payachata volcanic region (18°S/69°W, N. Chile), Bull. Volcanol., 50, 287–303, https://doi.org/10.1007/BF01073587, 1988.~~

~~Wörner, G., Hammerschmidt, K., Henjes-Kunst, F., Lezaun, J., and Wilke, H.: Geochronology (40Ar/39Ar, K-Ar and He-exposure ages) of Cenozoic magmatic rocks from Northen Chile (18°-22°S): implications for magmatism and tectonic evolution of the Central Andes, Rev. Geológica Chile, 205–240, 2000.~~

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