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~~ Altiplano of Bolivia, to the Puna 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. 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 highest risk volcanoes combining complementary strategies: i) a regional mapping based on volcanic hazard parameters and surrounding density of elements at risk 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. We identified 59 active and potentially active volcanoes that not only include the volcanic centres with the most intense and frequent volcanic eruptions (e.g., El Misti and Ubinas volcanoes, Peru) but also the highest density of exposed elements (e.g., the cities of Arequipa and Mequegua, Peru). VRR ~~is~~ was carried out for 19 out of the 59 volcanoes, active within the last 1,000 years or with unrest signs, highlighting those with the highest potential impact (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 four active volcanic zones in South America (Fig. 1). This zone ~~within~~ between 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 and northernmost Chile-Bolivia, 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~~up to circa 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 landforms, products, and magma compositions (e.g., Bertin et al., 2022a; Grosse et al., 2018, 2022), including catastrophic ~~cone~~ sector 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~~ international 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 hampered by the ~~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~~ deposits usually lack or contain only 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 borders, in between Argentina, Chile, Bolivia or Peru. Andean communities have interacted with these volcanic features for more than 11,000 years ~~even~~ well 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~~follow 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, and~~then,~~ they can be subdivided into "erupting" and "dormant" types based on their current state of activity.~~, while e~~ Extinct volcanoes have not had eruptions during the Holocene and can~~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~~absolute ages. "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 recently updated its volcanic ranking ~~with~~ of 87 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 based on 15 hazard and 10 exposure parameters (Elissondo and Farías, 2024). From these rankings only 26 (Chilean ranking) and 22 (Argentinian ranking) volcanic centres, as well as all 16 volcanoes of the Peruvian ranking, 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 proposed, expanding the work of 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 applied to Latin American volcanoes with activity recorded in the last 1,000 years (Guimarães et al., 2021).

3

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), while its evolution began in the earliest Jurassic in association with the opening of the Southern Atlantic Ocean (Stern, 2004). 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 Andesan ridge (Stern, 2004). Although many of the main features of the Andes were formed during the Miocene, neotectonic Quaternary 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 1,500 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). All the volcanoes in this zone are above 3,500 m a.s.l., constituting a high, remote,

4

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 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 composition in the CVZA, although basaltic andesites and occasional basalts occur. The most relevant volcanic hazards 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).
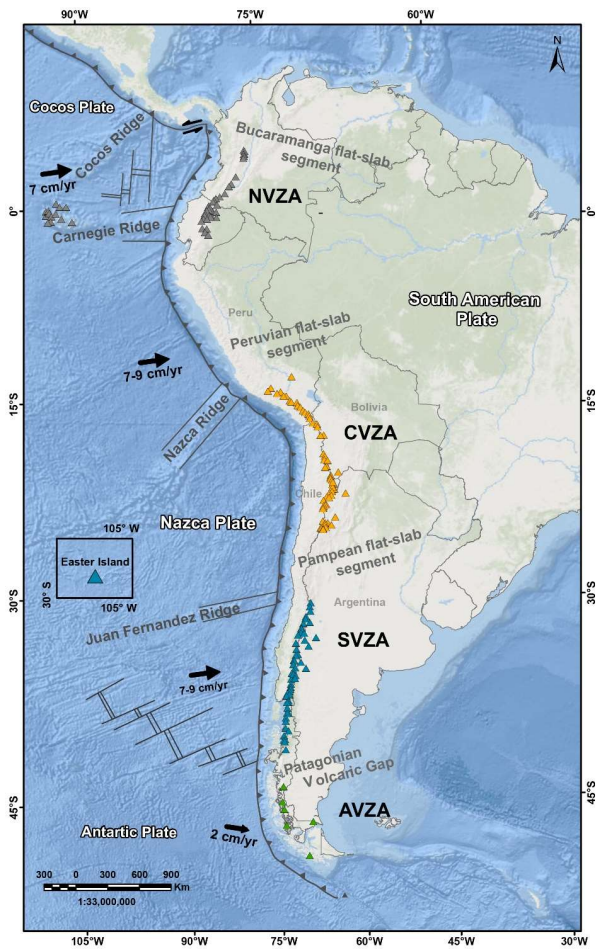
5

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). Layer 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 of the CVZA (i.e., Peru, Bolivia, Argentina and Chile). Four main steps were carried out: 1) compilation of active and potentially active volcanoes of the CVZA based on the existing catalogues of De Silva and Francis (1991), GVP (2013), Macedo et al. (2016), SERNAGEOMIN (2023), Elissondo and Farías () and Aguilera et al. (2022), including a detailed review of hazard and resilience parameters, 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 features and surrounding elements at risk for all the 59 identified active and potentially active volcanoes of the CVZA; 4) application of the VRR methodology (Nieto-Torres et al., 2021) to identify the highest risk volcanoes of the CVZA based on the estimation and scoring of hazard, exposure, vulnerability and resilience parameters. This last step focused on the 19 volcanoes having shown a volcanic activity during the past 1,000 years or records of the three signs of unrest (i.e., seismicity, 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. This has led to discrepancies in the CVZA volcano count evidenced in the number of potentially active eruptive centres identified by De Silva and Francis (1991) 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 six 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 nine in Argentina, 13 oin the Chile-Argentina border, 7 seven oin the Chile-Bolivia border, 2 two in Bolivia and 16 in Peru. In terms of types of volcanoes, 34 are stratovolcanoes, 15 are volcanic complexes, three are volcanic fields, one is a pyroclastic cone, four are dome complexes, 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 withof Pleistocene and two withof 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 intervals and/or poor constraints

7

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	N° 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

#	Name	Lat	Lon							
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

9

[*] 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, salt pans, farmlands, industrial areas). Each dataset is country-specific, 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 30 arc seconds (approximately 1 km at the equator). Obtained from the so-called top-down unconstrained modelling, this method misplaces the population in some locations showing the presence of people in uninhabited areas (WorldPop, 2023). A validation with satellite images was used to correct and reclassify the discrepancies with non-zero population to the range of 0-0.1 inhabitants per km^2. This data correction allowed us to obtain results of population density that were more consistent with the density and distribution of 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).

Transportation includes: i) road network, ii) rail network, iii) airports and air routes, iv) harbours, v) ferry terminals along rivers and lakes, and vi) border crossing check posts (Supplementary material 2). A taxonomy homogenization of the road network was required to reclassify in five categories as described in Table 2. In the case of rural paths, only connecting routes between rural centres (i.e., 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 analysed, particularly the hydrological characteristics, these facilities are essential.

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

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

Facilities 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). Facilities considered are divided into two groups: i) emergency facilities (e.g., civil protection headquarters, police stations, fire stations; see Supplementary Material 2) and ii) critical facilities. The first group consists of essential services to public safety and health; the second one includes strategic structures for social and economic sectors.

3.3 Regional mapping

The regional mapping consists in combining volcanic hazard 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, the number of eruptions and the maximum VEI during the Holocene have been represented as well as the age of 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

240 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, harbours, and border crossings) and linear features expressed in 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 3.

245 **3.4 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 wais carried out for the 19 active and potentially active volcanoes identified based on their activity during the past 1,000 years or records of three signs of unrest (i.e., seismicity, ground deformation and degassing). We apply the VRR-0 (2 factors), VRR-
250 1 (3 factors) and VRR-2 (4 factors) strategies of Nieto-Torres et al. (2021):

$$VRR - 0 \; (threat) = Hazard \times Exposure \; , \hspace{4cm} (1)$$

$$VRR - 1 = Hazard \times Exposure \; \times Vulnerability \; , \hspace{3cm} (2)$$

$$VRR - 2 = (Hazard \times Exposure \times Vulnerability)/(Resilience + 1) \; , \hspace{1.5cm} (3)$$

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

260 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 became available (e.g., historical eruption of Parinacota volcano, 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.
265 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 resilience). The maximum hazard score represents the highest intensity of each volcanic process; the maximum exposure score is the largest quantity of 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).

12

4. Results

4.1 Regional mapping of the CVZA

The regional maps resulting from the combination of the 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 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 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): 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. 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 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. 3) the Collahuasi mining district, representing one of the largest copper reserves in Chile and in the world, close to Irruputuncu and Olca-Paruma volcanoes, which have a low number of Holocene eruptions and low VEI (2) or not confirmed. 4) Calama city and San Pedro volcano, with a medium eruptive frequency (10 Holocene eruptions) and low VEI (2). 5) San Pedro de Atacama town, a popular tourist destination in Antofagasta region (Chile) close to Putana, Escalante-Sairecabur and Licancabur volcanoes (the first having 2 Holocene eruptions and VEI 2, and the last two with no information available); and 6) Sociedad Química y Minera de Chile (SQM), the world's biggest lithium producer close to Lascar volcano, 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).
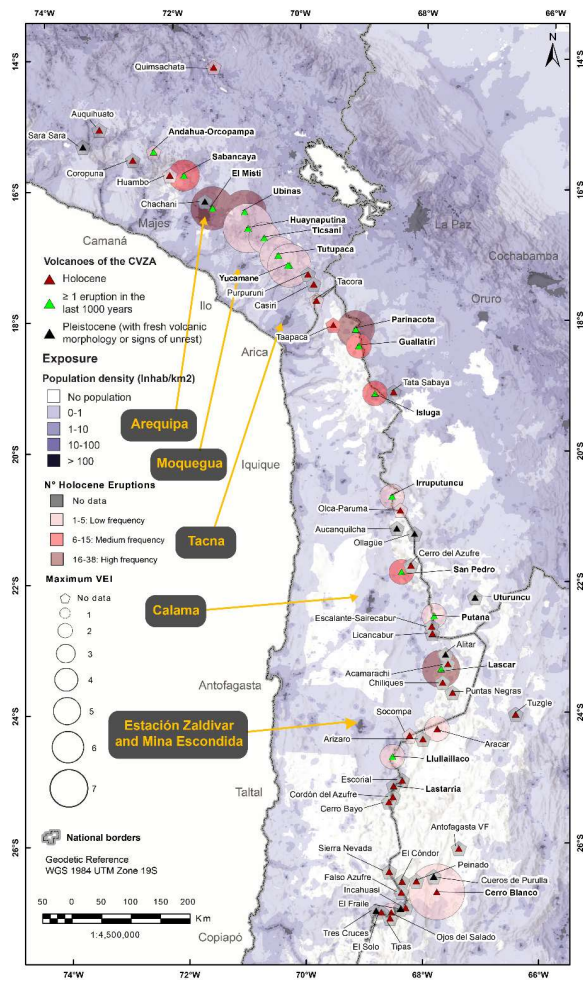
Figure 2: Regional map including the total CVZA active and potentially active volcanoes and population density, with the Maximum VEI during the Holocene and the number of Holocene eruptions of the CVZA volcanoes superimposed. Notice that the 19 volcanoes considered for the VRR analysis are in bold. Layer Sources: Esri, USGS, NOAA.
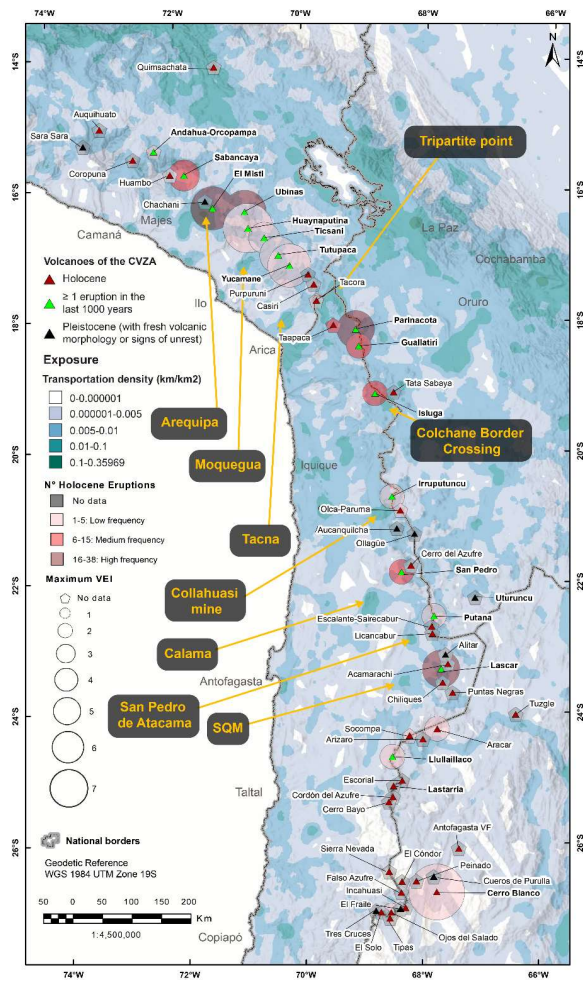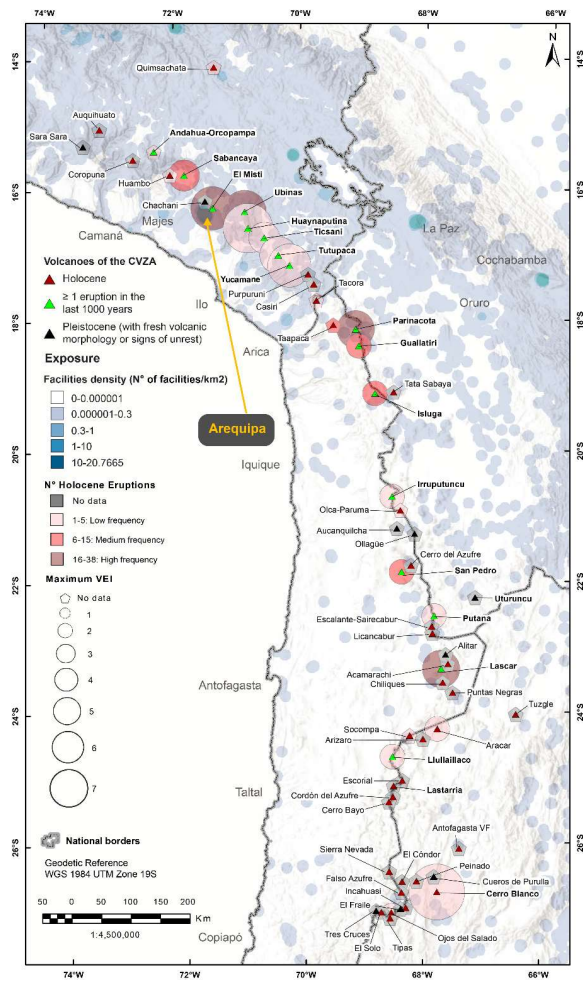
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Figure 3: Regional map including the total CVZA active and potentially active volcanoes and transportation density, with the Maximum VEI during the Holocene and the number of Holocene eruptions of the CVZA volcanoes superimposed. Notice that the 19 volcanoes considered for the VRR analysis are in bold. Layer Sources: Esri, USGS, NOAA.

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Figure 4: Regional map including the total CVZA active and potentially active volcanoes and facilities density, with the Maximum VEI during the Holocene and the number of Holocene eruptions of the CVZA volcanoes superimposed. Notice that the 19 volcanoes considered for the VRR analysis are in bold. Layer Sources: Esri, USGS, NOAA.

4.2 The Volcanic Risk Ranking

The 19 out of the 59 CVZA active and potentially active volcanoes that had an eruption during the last 1,000 years or have significant records of unrest signals were ranked based on the 4 four normalized factors of the VRR, i.e., hazard, exposure, vulnerability and resilience (Fig. 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).
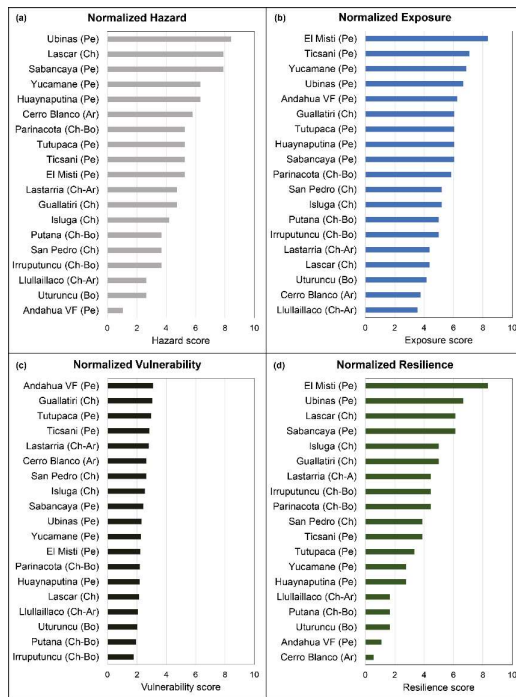
Figure 5: Factors of the volcanic risk ranking analysed separately. (a) hazard scoring; (b) exposure scoring; (c) vulnerability scoring; and (d) resilience scoring.

17

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~~ five highest VRR-1 scores (i.e., hazard, exposure, vulnerability) are 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).
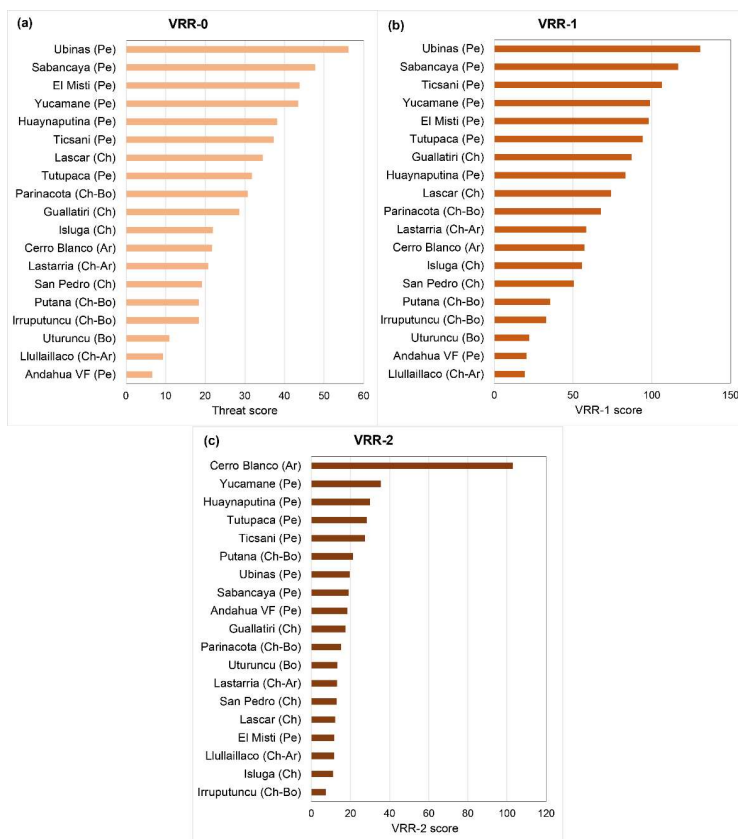
Figure 6: (a) The 2-factor (VRR-0), (b) 3-factor (VRR-1), and (c) 4-factor volcanic risk ranking (VRR-2) applied to the 19 CVZA selected volcanoes.

18

5 Discussion

5.1 Significance of regional mapping and VRR for the CVZA

340 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) (Figs. 2-4). As an example, the transport-density map highlights the areas having a high concentration of rural and urban infrastructure, which could be potentially impacted with economic consequences for~~m~~ the country. This is the case of the Collahuasi mining district in Chile

345 (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). Our regional map~~s~~ of the CVZA provide~~s~~ a first preliminary step to quickly identify target areas that require a more detailed risk analysis, making them useful~~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

350 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~~which cover the area~~s~~ most susceptible to the impact of the different types of hazards such as tephra fallout, pyroclastic density currents and lahars. In the case of volcanic fields and calderas, the exposure is analysed for elements inside the volcanic field and for the same radi~~ius~~ ~~but~~ starting from the field's boundary which is defined by the contour connecting ~~connection of~~ the outermost volcanic edifices

355 ~~that compose it~~. Differences in the hierarchy of the volcanoes evaluated within the results of the VRR-0, VRR-1 and VRR-2 are mostly due to population density and the diversity of critical infrastructures considered with the more densely populated areas obtaining higher~~that ensure more densely populated areas to have higher~~ scores in the threat ranking (i.e., VRR-0). The vulnerability factor in VRR-1 differentiates volcanic systems with equal or similar threat~~,~~ highlighting those associated with larger vulnerabilities (e.g., due to low redundancy and accessibility), while the resilience factor in VRR-2 help~~s~~ to identify

360 volcanoes with no or few mitigation and response measures. The variability between the results of the various VRR approaches (e.g., equations 1–3) confirm the importance of including hazard, exposure, vulnerability and resilience in an integrative ranking analysis 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.

365 From a hazard perspective, both the regional maps (Fig. 2-4) and the hazard factor of the VRR (Fig. 5a) allow to identify Ubinas (Peru), Lascar (Chile), Huaynaputina (Peru) and Cerro Blanco (Argentina~~Chile~~) as the most hazardous volcanoes. ~~However~~Although~~,~~ El Misti (Peru) and Parinacota (Chile) have a high eruptive frequency (22 and 38 events during the Holocene), they occupy only the 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

370 VRR represents the highest intensity of each volcanic process, not only eruptive frequency and maximum VEI as in the regional

19

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 maps since they have a medium to low eruptive frequenciesy (14 and 1 event, respectively); and maximum VEIs (3 and 5, respectively).

375 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 the better constrained eruptionseruptions that

380 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 only on volcanoes with eruptions in the last 1,000 yearsfocusing on the VRR analysis of the last 1,000 years of volcanic activity might exclude potentially

385 impactful volcanoes. For this reason, we also considered forconstrained this aspect by also integrating into the VRR analysis three additional volcanoes that show three signs of unrest: 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.

390 When hazard and exposure are considered, both regional mapping and VRR-0 highlight Ubinas, El Misti, and Huaynaputina as the volcanoes with the highest potential risk (Figs. 2-4 and 6a). However, Sabancaya and Yucamane appear on the 2nd and 4th positions of the threat score (VRR-0) and but 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, 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

395 radiius from the volcanic vent, which turns intomaking it a more exhaustive analysis.

The vulnerability factor, which is not considered for the regional mapping, helps to best distinguish volcanic systems with similar threat (i.e., VRR-0, 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

400 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. 6b) but having none or few resilience measures implemented (Fig. 5d) (Guimarães et al., 2021). In fact, 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

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405 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 scores, or those with few to no

410 mitigation and response measures implemented (e.g., Cerro Blanco, Argentina; Yucamane, Huaynaputina, Tutupaca, and Ticsani, Peru). Cerro Blanco (Argentina) scores as the highest risk volcano of the CVZA due to its low resilience (Fig. 6c).

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,

415 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, Ppriority risk reduction strategies that should be put in place or improved in order to increase resilience are listed below. 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

420 hazard maps, but it is important to make sure that the existent ones are up-to-date and available for the entire community. Second, the monitoring systems 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,; thisat is missing at all these 5 five highest-risk volcanoes (Cerro Blanco, Yucamane, Huaynaputina, Tutupaca, and Ticsani). Fourth, educational activities should be promoted to raise awareness in populations living around Ticsani, Yucamane, Huaynaputina, Tutupaca,

425 and Cerro Blanco; and existing ones should be supported and strengthened around Ubinas, Sabancaya and El Misti. Finally, local authorities might could invest in preparedness (e.g., evacuation plans and exercises or simulations for institutions and the 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, we have collected the threat and risk scores in a comparative diagram

430 shown in Fig. 7. At the time of our investigation, three of the four CVZA countries 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 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 consider the risk factors in different waysare all based on diverse ways of considering the risk factors. Consequently, we can find relative threat and risk

435 scores ranging from 0 to 250 (Fig. 7). In addition, each country evaluates only the volcanoes that concern their own territory whilst our VRR strategy considers volcanoes from the four CVZA countries. Regardless of the relative scoring, this difference

of approaches is evidenced in Fig. 7 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 (SERNAGEOMIN, 2023) and Argentinian and bordering volcanoes in yellow (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.~~
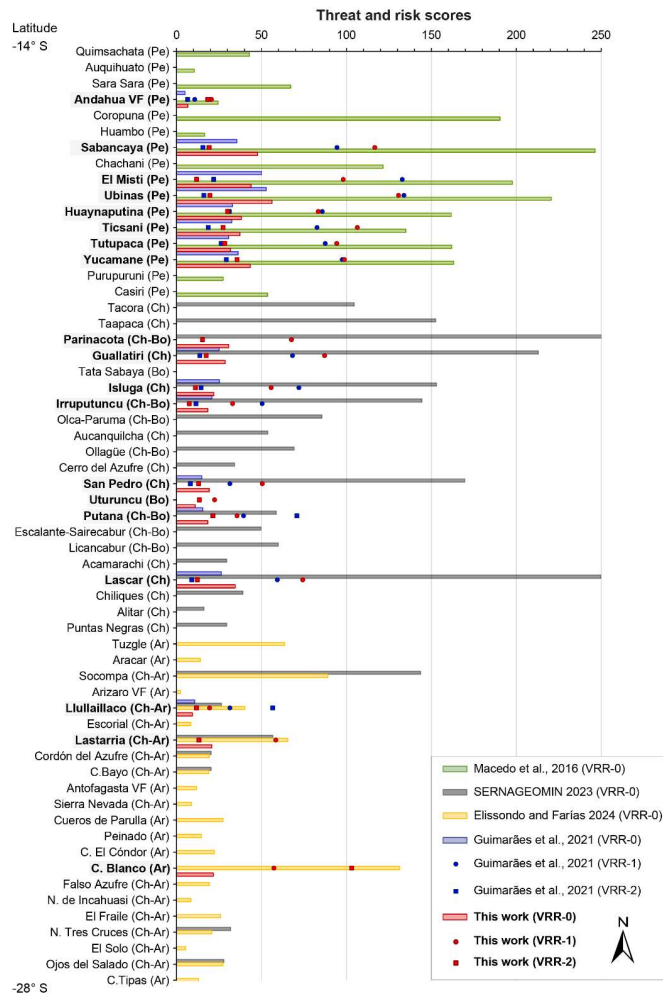
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Threat and risk scores

Figure 7: Comparison of existing volcanic threat and risk rankings. The CVZA volcanoes are organized by latitude, the volcanic systems in bold highlight the 19 analysed for the VRR in this work. Notice that bars represent threat rankings (i.e., VRR-0 (HxE)), circles represent the 3-factor VRR-1, and squares the 4-factor VRR-2. The threat ranking of INGEMMET (Macedo et al., 2016) in green, SERNAGEOMIN (SERNAGEOMIN, 2023) in grey, SEGEMAR (Elissondo and Farías, 2024) in yellow, the threat and risk rankings of Guimarães et al. (2021) in blue, and the ones of this work in red.

23

Comparing threat rankings in particular, we can point out that three of the five rankings share the same volcanoes in the top ~~5~~five, with slight differences in the order (Table 3, Fig. 7). The difference for the VRR-0 between this study and Guimarães et al. (2021) is related to the update of data used, and subsequently the scoring of some indicators such as the recurrence rate.

450 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 does not have records of ~~account for~~ eruptions during the last 1,000 years, nor ~~records of all~~the three signs of unrest. The Chilean and Argentinian threat rankings are not directly comparable since their ranking~~s~~ do~~es no~~'t consider volcanoes outside their territory and there is no existing ranking for Bolivian volcanoes.

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Table 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 appearing in different threat rankings.

	This work VRR-0	Guimarães et al. (2021) VRR-0	SERNAGEOMIN (2023)	Elissondo and Farias (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)

When comparing the existing threat rankings without the Peruvian volcanoes (Table 4), it is interesting to notice that the top-
460 ranked ~~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 Chil~~e~~ian or transboundary volcanoes, the top ~~3~~ three volcanoes are the same between our ranking and the one of SERNAGEOMIN. Then, the Cerro Blanco volcano, which is the top-ranked ~~one~~ Argentinian CVZA volcano, appears ~~at the 5th position~~fifth in our threat ranking. It was considered in our work due to the fact that it has shown the three signs of unrest. Except f~~ro~~rm this volcano, none of the volcanoes listed by Elissondo and Farias (20~~1~~24) appears in
465 the top five in the other rankings. This demonstrate~~s~~d 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)

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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 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

24

of ~~this work~~our ranking and in the 7th position of Guimarães et al. (2021), whilst Tutupaca is in the 5th ~~position of~~in Guimarães et al. (2021) and the 6th position ~~of this work~~in our ranking. Both volcanoes have the same hazard scores in both studies, however, Ticsani has a higher exposure score in our work, and hence, although its vulnerability is lower, ~~even if the vulnerability is lower~~ than Tutupaca, it scores higher ~~leading to a higher overall rank~~ in the VRR-1 produced in this work. The reasons for this are i) a higher population density identified within the 10, 30 and 100 km radii in our work; 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 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~~Larger differences ~~occur~~ are found when considering resilience (VRR-2 in Tables ~~4,~~ 5 and Fig. 7). Both studies share ~~3~~ three volcanoes in the top five, Yucamane, Huaynaputina and Tutupaca, although in different order~~s~~. 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~~ several parameters ~~when~~ used in 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 caldera eruption is one of the largest Holocene eruptions worldwide (Fernandez-Turiel et al., 2019). Whilst it was not considered by Guimarães et al. (2021), because it has not erupted~~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).

In the case of Putana, it has~~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 in contrast to Guimarães et al. (2021). The ~~biggest~~ largest differences for these two volcanoes are found in the vulnerability scoring given by the typology of buildings, its proximity to the Argentina-Chile border, the lack of

25

505 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).

5.3 Data limitations

It is important to notice the dynamic dimension of all risk factors and emphasize that the parameters of the rankings can be
510 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 both regional mapping or and 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,
515 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 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 Global Volcanism
520 Program database especially in relation to the eruptive history. For example, after the last update, San Pedro volcano is now listed as Pleistocene (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 not consistent, i.e., 6 six according to the GVP (2023), and at least 38 after the updated hazard map recently published by SERNAGEOMIN (Bertin et al., 2022b). Another case is Yucamane volcano, for which the GVP (2023) lists its last eruption
525 as 1320 BCE, which would leave this volcano out of our VRR analysis but according to INGEMMET its last eruption was 1787 CE (Macedo et al., 2016). Additionally, the timeliness of up-to-dateness data, in particular for the elements at risk and their vulnerability, is highly variable, influencing the accuracy of the analysis.

6 Conclusions

Regional mapping and volcanic risk rankings represent an important tools to identify volcanoes requiring a prioritization of
530 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 centres. However, this number could change in the future if additional information on the various volcanoes becomes available.

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26

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

- Huaynaputina and Cerro Blanco are the volcanoes with the highest eruption magnitude (VEI 6 and VEI 7, respectively) and the volcanoes with the highest eruption frequency are El Misti (22), Ubinas (26), Parinacota (38) and Lascar (37).
- Arequipa, Moquegua, and Tacna (Peru), Calama and the mining stations "Estación Zaldivar" and "Mina Escondida" (Chile) are associated with the highest population density 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 Sociedad Química y Minera de ChileSQM (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 most densely populated area, also associated with the highest density of transport infrastructure and facilities per km^2.

While the regional maps provides a visual assessment of potential volcanic impact at a regional scale, the VRR provides a more comprehensive regional analysis by integrating 4 four different risk factors. In this study, the VRR was focused on the 19 active or potentially active volcanoes that had eruptionerupted in the last 1,000 years and/or show significant signs of unrest. Results allow tohelp identifying the highest risk volcanoes and those that need to be prioritized in terms of implementing risk reduction strategies. In particular:

- The VRR-0, which considers hazard and exposure, highlights Ubinas, Sabancaya, El Misti, Yucamane and Huaynaputina as the most threatening volcanoes.
- The VRR-1, which considers hazard, exposure, and vulnerability, highlights Ubinas, Sabancaya, Ticsani, Yucamane, and El Misti as the highest-risk volcanoes,
- The VRR-2, which also includes resilience parameters, identifies Cerro Blanco, Yucamane, Huaynaputina, Tutupaca, and Ticsani as the highest-risk volcanoes.
- Given that volcanic hazard and exposure are difficult to modify and reduce, the implementation of risk reduction strategies might should focus on reducing vulnerability and increasing resilience, which are highlighted by the 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 a regional scale, which is especially valuable in the case of cross-border volcanoes. In fact, risk rankings are often carried out at

27

a 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 to carry out further studies at different scales, and to continuously update the presented regional VRR as new information becomes available~~that further studies are carried out at different scales and this regional VRR could be continuously updated as new information becomes available~~.

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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28

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