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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 identification of hazardous active volcanoes is challenging due to the limited accessibility. Here, we identify the riskiest volcanoes based on complementary strategies including i) a regional mapping based on volcanic hazard parameters and surrounding density of elements at risk combined with ii) the application of the recently developed Volcanic Risk Ranking methodology that integrates hazard, exposure and vulnerability as factors that increase risk, and resilience as a factor that reduces risk. The method identifies 59 active and potentially active volcanoes that not only highlights the volcanic centers with the most intense and frequent volcanic eruptions (e.g., El Misti and Ubinas volcanoes (Peru)) and the highest density of exposed elements (e.g., the cities of Arequipa and Mequegua (Peru)), but also those with the highest potential impact requiring risk mitigation actions (i.e., Cerro Blanco (Argentina), Yucamane, Huaynaputina, Tutupaca, and Ticsani (Peru)).

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, from very low to very high (Macedo et al., 2016). Chile and Argentina, recently updated their relative volcanic risk rankings with 87 and 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 exposure parameters were also considered including population, local and regional aviation, transportation and energy infrastructure.

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). 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 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).

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 (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 (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).

The CVZA is located between latitudes 14° and 28°S of the Andean cordillera, between the Peruvian and Pampean flat-slab segments (Fig. 1). Almost all the volcanoes in this zone are above 4,000 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/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 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 in the CVZA, although basaltic andesites and occasional basalts occur. The most relevant volcanic hazards in 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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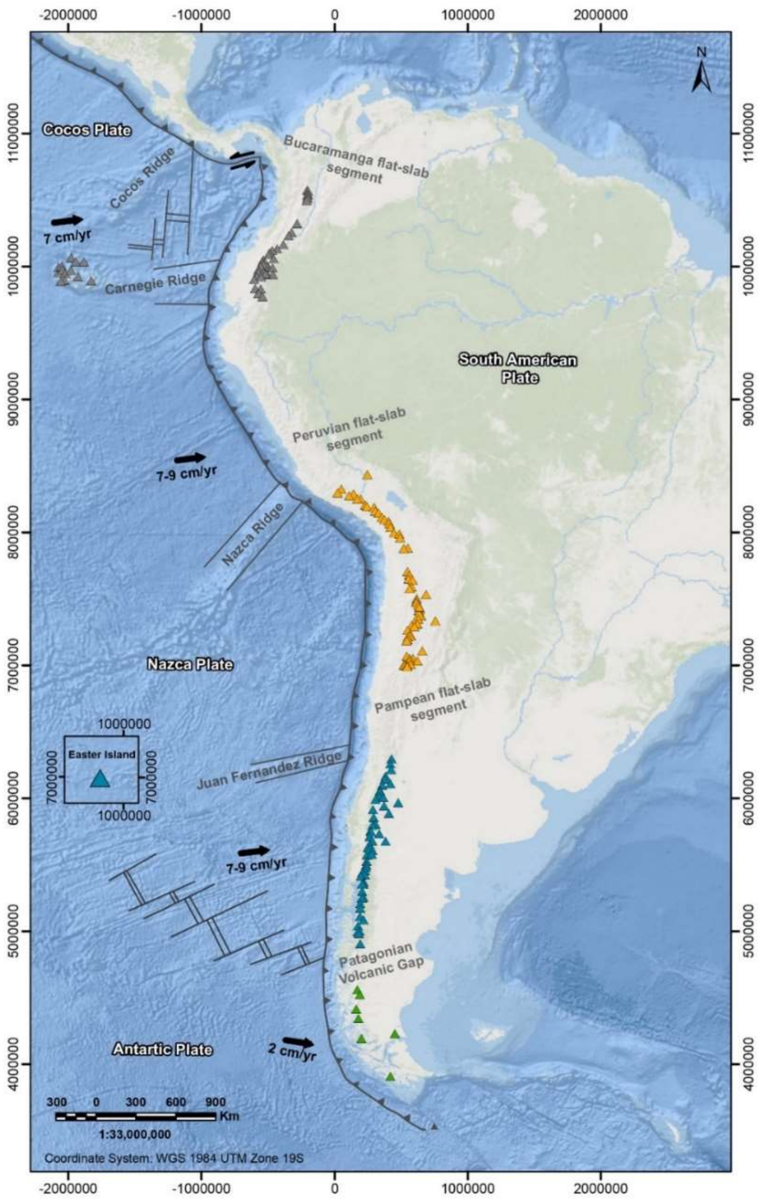

Figure 1: Location map showing the Northern Volcanic Zone of the Andes (NVZA) (grey triangles), Central Volcanic Zone of the Andes (CVZA) (yellow triangles), Southern Volcanic Zone of the Andes (SVZA) (blue triangles), and Austral Volcanic Zone of the Andes (AVZA) (green triangles). Modified from Stern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

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3 Methodology

This study includes the analysis of the four countries prone to be impacted by future volcanic activity in the CVZA (i.e., Peru, Bolivia, Argentina and Chile) for which four main steps were carried out: 1) update of the inventory of active and potentially active volcanoes of the CVZA based on the existing catalogs of De Silva and Francis (1991), GVP (2013), Macedo et al. (2016), SERNAGEOMIN (2023), Elissondo and Farías (2023) and Aguilera et al. (2022), and compilation of hazard and resilience parameters (Reyes-Hardy et al., 2023); 2) compilation of elements at risk; 3) regional mapping that includes both volcanic hazard parameters and surrounding elements at risk; 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 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 activity but currently showing 3 types 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 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).

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 pans, farmlands, industrial areas). Each dataset is country-specific, favoring official sources (e.g., ministries, national geographic institutes, national observatories, statistical institutes). Open datasets (e.g., HOT, 2020) were used to complete missing official information.
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

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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 from the so-called top-down unconstrained modelling (WorldPop, 2023). However, this method misplaces the population in some places indicating the presence of people in uninhabited areas (WorldPop, 2023). We corrected the error of the non-zero population using mainly satellite images and we reclassified the pixels in the range of 0-0.1 inhabitants per km^2. This correction of data allowed us to obtain results of population density more consistent with the distribution of population and residential buildings (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).

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 express, 2021; TACL, 2021; TAOF, 2021; HOT, 2020	ICAO, 2022	Puertos Argentina, 2019; Terminales Portuarias, 2021; Worldport, 2021	ICAO, 2022	SENASA, 2018; Fronteras Argentina, 2022
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

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Transportation includes: i) road network, ii) rail network, iii) airports and air routes, iv) harbors, v) ferry terminals along rivers and lakes, and vi) border crossing check posts (Table 1). The road network is classified in four 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 (i.e., critical exposed element) 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, 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.

	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 «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 are: i) emergency facilities (i.e., civil protection installations, police stations, fire stations, health sites, emergency operations centers and ranger stations, and heliports) (Table 3); and ii) critical facilities (i.e., schools and government offices).

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

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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 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. 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, and border crossings) and linear features expressed in kilometers 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.

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 the volcanoes having had activity in the past 1,000 years in addition to the volcanoes with Pleistocene or Holocene activity currently showing 3 types 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):

$$VRR(0)(threat) = Hazard \times Exposure \,, \quad (1)$$

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$$VRR(1) = Hazard \times Exposure \times Vulnerability\ , \tag{2}$$

$$VRR(2) = (Hazard \times Exposure \times Vulnerability)/(Res + 1)\ , \tag{3}$$

Vulnerability considers 4 dimensions (physical, systemic, social, economic), while resilience includes 2 dimensions (mitigation measures and response) (Nieto-Torres et al., 2021). The resilience factor is mathematically corrected in order for the formula to stay valid even in those 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 available (e.g., historical eruption of Parinacota volcano). The normalization is based on the maximum possible value for each of the evaluated factors (19, 48, 95 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 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.

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N°	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

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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 Parulla	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 CVZA 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 (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 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

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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 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), Antinaco (105 inhabitants) (see Supplementary material 2).

Six areas can be identified based on the density distribution of transport infrastructure (Fig. 3): First, 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, 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 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, the Collahuasi mining district (a large copper mine, which represents one of the largest copper reserves in Chile and the world), close to Irruputuncu and Olca-Paruma volcanoes (with a low number of Holocene eruptions and low VEI (2) or not confirmed); fourth, Calama city and San Pedro volcano (with a medium eruptive frequency (10 Holocene eruptions) and VEI (2)); fifth, San Pedro de Atacama town (a popular tourist destination in Antofagasta region, Chile) close to Putana, Escalante-Sairecabur and Licancabur volcanoes (with the former having 2 Holocene eruptions and VEI 2, and the last two with no information available); and sixth, SQM (Sociedad Química y Minera de Chile, the world's biggest lithium producer) close to Lascar volcano (with 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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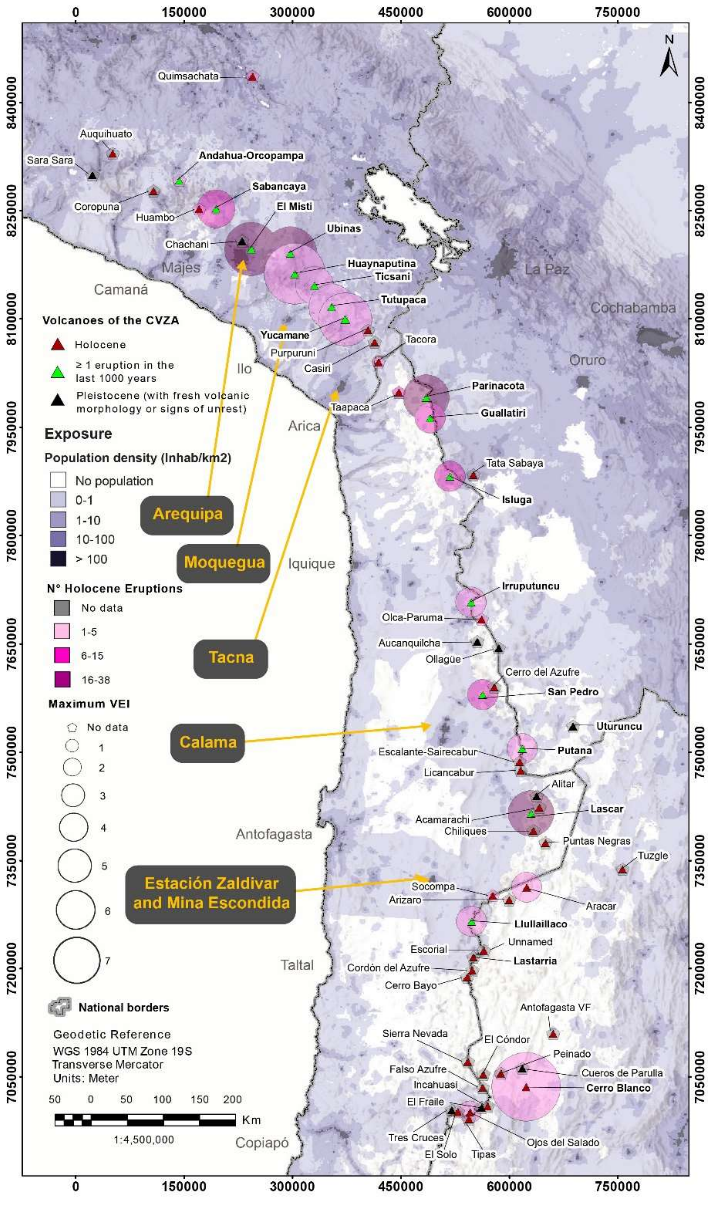

245 **Figure 2: Regional map including the total CVZA active volcanoes and population density, with the Maximum VEI during the Holocene and the number of Holocene eruptions of the CVZA volcanoes superimposed. Notice that volcano names having had activity in the past 1,000 years in addition to the volcanoes with Pleistocene or Holocene activity currently showing 3 types of unrest are in bold. Service Layer Credits: Sources: Esri, USGS, NOAA.**

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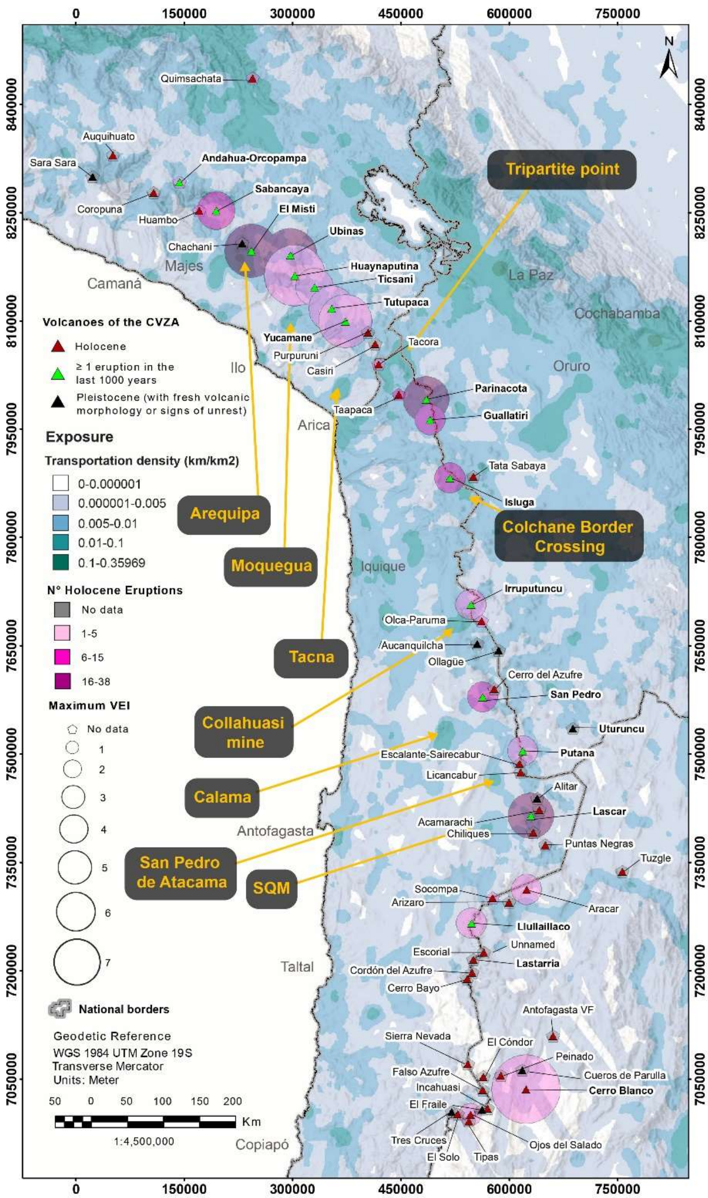

Figure 3: Regional map including the total CVZA active volcanoes with transportation density, with the Maximum VEI during the Holocene and the number of Holocene eruptions of the CVZA volcanoes superimposed. Notice that volcano names having had activity in the past 1,000 years in addition to the volcanoes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

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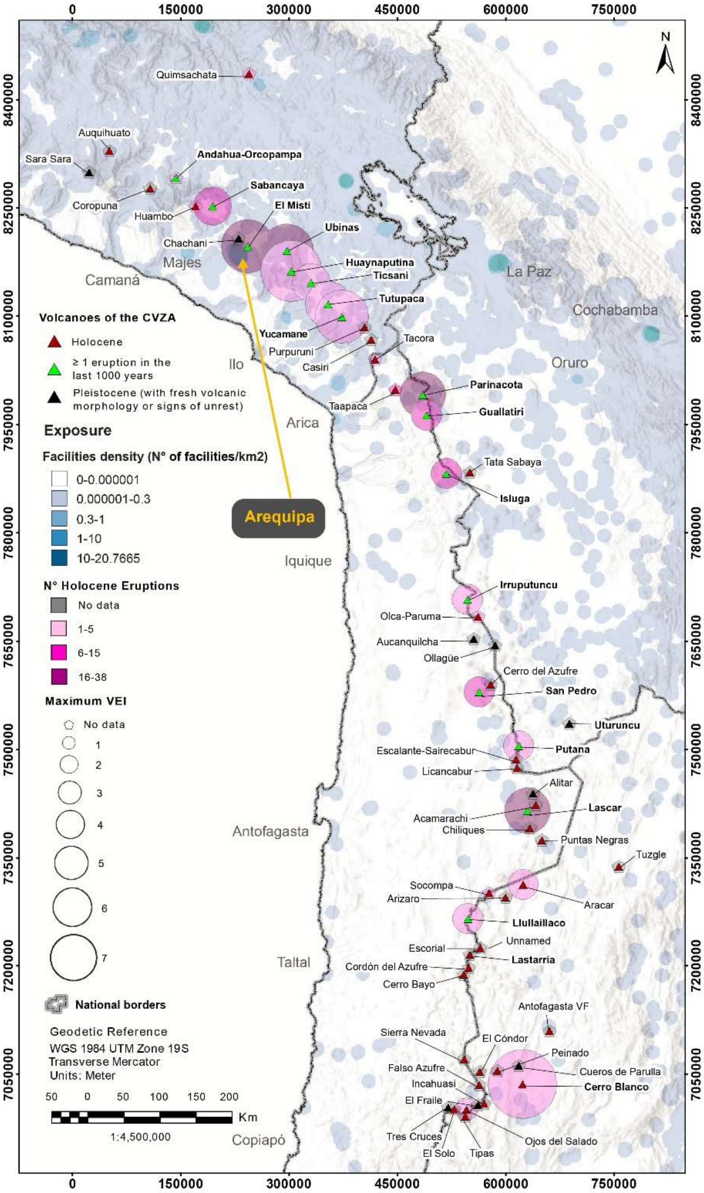

255 **Figure 4: Regional map including the total CVZA active volcanoes with facilities density, with the Maximum VEI during the Holocene and the number of Holocene eruptions of the CVZA volcanoes superimposed. Notice that volcano names having had activity in the past 1,000 years in addition to the volcanoes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

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4.3 The 2-factor, 3-factor and 4-factor Volcanic Risk Ranking

The 16 volcanoes that had an eruption in the last 1,000 years and the 3 volcanoes showing 3 signs of unrest were ranked based on the 4 normalized factors of the VRR, i.e., hazard, exposure, vulnerability and resilience (Fig. 5). 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).

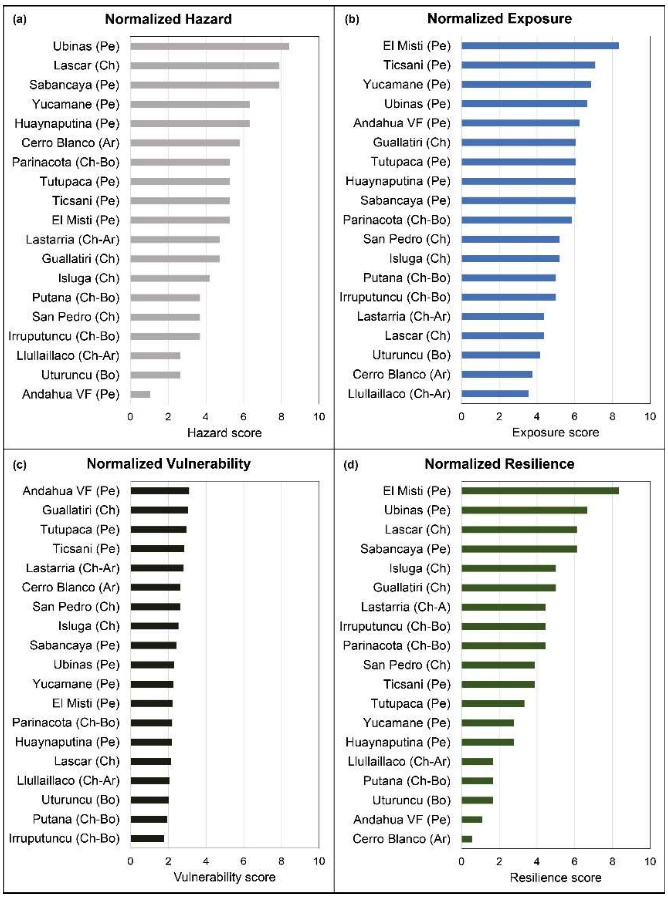

Figure 5: Factors of the volcanic risk ranking analyzed separately. (a) hazard scoring; (b) exposure scoring; (c) vulnerability scoring; and (d) resilience scoring.

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).

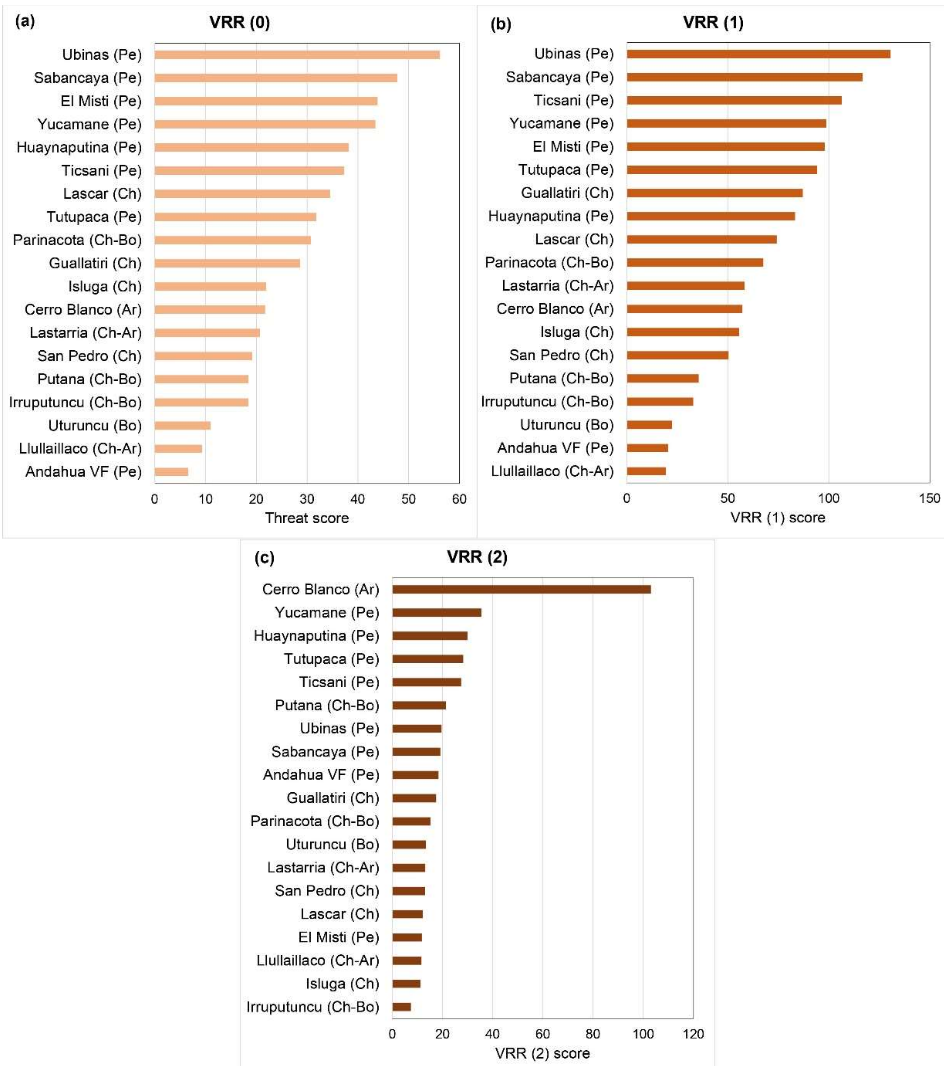

Figure 6: (a) The 2-factor, (b) 3-factor, and (c) 4-factor volcanic risk ranking applied to the 19 CVZA selected volcanoes.

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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.

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

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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. 2-4). In the case of the transport-density map, for example, it is possible to visualize areas having a high concentration of rural and urban infrastructure, which could also be potentially impacted with some economic consequences on the country. Such 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, regional maps do not provide the details at local scale (e.g., the type or quality of transport infrastructure and facilities). The regional map of the CVZA could be helpful for stakeholders as a first preliminary step to quickly identify target areas that require a more detailed

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risk analysis. The VRR methodology, on the other hand, provides a more spatially discretized and in-depth 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 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 10^{h} and 7th position on the VRR, respectively, even though they have a high eruptive frequency (22 and 38 events during the Holocene). On the contrary, Sabancaya and Yucamane (Peru) appear at the 3rd and 4th position on 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).

When hazard and exposure are combined, both approaches highlight Ubinas, El Misti, and Huaynaputina as the volcanoes with the highest potential risk (Fig. 2-4 and 6a). However, Sabancaya and Yucamane appear on the 2th 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 overlap 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 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), but having none or few resilience measures implemented (Fig. 5d) (Guimarães et al., 2021). In fact, while 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 resilience measures implemented (i.e., Cerro Blanco (Argentina), Yucamane, Huaynaputina, Tutupaca, and Ticsani (Peru))

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(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, 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 volcano of the CVZA (Fig. 6c).

5.3 Comparison with existing volcanic rankings

To visualize the different existing volcanic rankings easier, we have collected their threat and risk scores in a comparative diagram shown in Fig. 7. At the time of our investigation, three of the four bordering 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 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 own territory whilst the VRR strategy, comprising a regional scale, considers volcanoes from the four bordering countries of the CVZA. Regardless of the relative scoring, there is a general trend evidenced in Fig. 7, when 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) 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.

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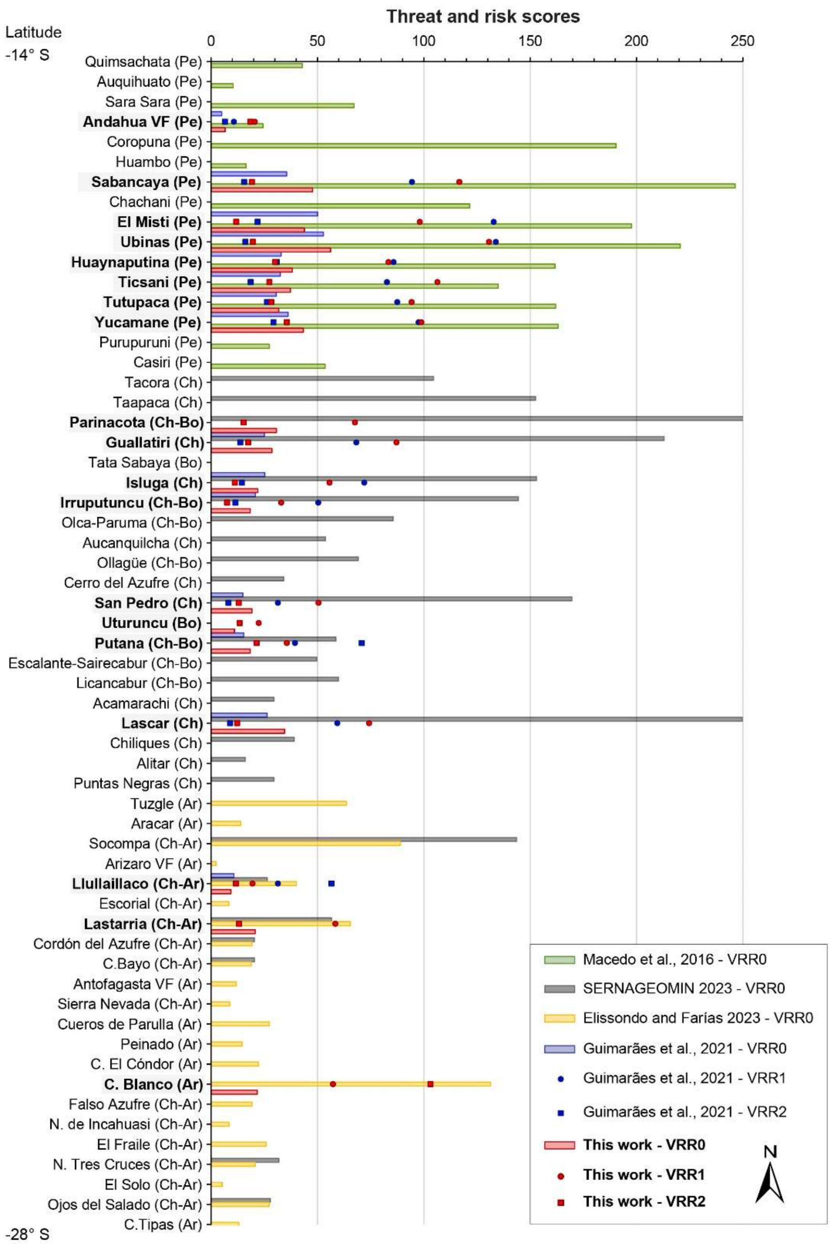

Figure 7: Comparison of existing volcanic threat and risk rankings. The CVZA volcanoes are organized by latitude, the volcanic systems in bold highlight the ones analyzed for the VRR in this work. Notice that bars represent threat rankings (i.e., VRR0 (HxE)) circles represent the 3-factor VRR1 and squares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

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green, SERNAGEOMIN (SERNAGEOMIN, 2023) in grey, SEGEMAR (Elissondo and Farías, 2023) in yellow, the threat and risk rankings of Guimarães et al. (2021) in a scale of blues, and the ones of this work in a scale of reds.

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, Fig. 7). The difference in order for the VRR(0) of this study and Guimarães et al. (2021) is related to the current update of available data, or the eruptive period considered. The difference with Macedo et al. (2016) is the absence of Coropuna volcano 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 eruptions during the last 1,000 years or no current signs of unrest are monitored. The Chilean and Argentinian threat rankings are not comparable since none of these Peruvian volcanoes are considered for being outside of their territory and regarding Bolivian volcanoes, they have not yet its own ranking.

Table 5. 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 in different threat rankings.

	This work VRR(0)	Guimarães et al. (2021) VRR(0)	SERNAGEOMIN (2023)	Elissondo and Farias (2023)	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 accounting for the vulnerability and resilience factors (VRR(1) and VRR(2)), only this work and Guimarães et al. (2021) can be compared (Table 6, 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, 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 and iii) the multiple economic activity source within 100 km for both volcanoes have been updated with respect to Guimarães et al. (2021).

Table 6. 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)

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The major differences occur when considering resilience (VRR(2) in Table 6 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).

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 respect to Guimarães et al. (2021). The biggest differences for these 2 volcanoes are found in the vulnerability factor, mainly due to 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 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). 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, we also recognize the limitations of the GVP database especially in relation to

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the eruptive history. For example, after their last update (GVP, 2023) San Pedro volcano now is listed as Pleistocene, whilst according with previous information it was Holocene (GVP, 2013), with 10 eruptive events and maximum VEI 2, also in agreement with SERNAGEOMIN. In the case of Parinacota the number of eruptions also disagree, i.e., 6 according to the GVP, and at least 38 after the updated hazard map of Parinacota recently published by SERNAGEOMIN (Bertin et al., 2022b). Another case is Yucamane, for which the GVP list 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 data, in particular for the elements at risk and their vulnerability, is quite variable and that affects the accuracy of the analysis.

6 Conclusions

Our analysis shows that the most comprehensive list of volcanoes of the CVZA comprises a total of 59 active and potentially active volcanic centers. The regional maps compiled for a visualization of hazard and exposure elements show that:

- El Misti, Ubinas, Huaynaputina, Parinacota, Lascar and Cerro Blanco are the volcanoes with the highest eruption magnitude (VEI 6, Huaynaputina; VEI 7, Cerro Blanco) or frequency (22, El Misti; 26, Ubinas; 38, Parinacota; 37, Lascar).
- Arequipa, Moquegua, and Tacna (Peru), Calama and the mining stations “Estación Zaldivar” and “Mina Escondida” (Chile) are associated with the highest 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.

While the regional map provides a fast visual assessment of potential volcanic impact at regional scale, the VRR provides a more comprehensive analysis by integrating various risk factors. Moreover, integrating all the 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 in the last 1,000 years. Results help identifying the riskiest volcanoes and those that need to be prioritized in terms of implementing risk reduction strategies. In particular:

- The 3-factor VRR (VRR (1), Eq.2) highlights Ubinas, Sabancaya, Ticsani, Yucamane, and El Misti as the riskiest volcanoes, while Cerro Blanco, Yucamane, Huaynaputina, Tutupaca, and Ticsani represent the riskiest volcanoes when the 4-factor VRR (VRR (2), Eq.3) is applied.

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- As hazard and exposure are difficult to modify and reduce, the implementation of risk mitigation measures should focus on reducing vulnerability and increasing resilience, especially for Cerro Blanco, Yucamane, Huaynaputina, Tutupaca, and Ticsani volcanoes.

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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