Appendix B – Region 15

Country and regional profiles of volcanic hazard and risk:

South America

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This download comprises the profiles for Region 15: South America only. For the full report and all regions see Appendix B Full Download. Page numbers reflect position in the full report. The following countries are profiled here:

Brown, S.K., Sparks, R.S.J., Mee, K., Vye-Brown, C., Ilyinskaya, E., Jenkins, S.F., and Loughlin, S.C. (2015) Country and regional profiles of volcanic hazard and risk. In: S.C. Loughlin, R.S.J. Sparks, S.K. Brown, S.F. Jenkins & C. Vye-Brown (eds) *Global Volcanic Hazards and Risk,* Cambridge: Cambridge University Press.

Region 15: South America

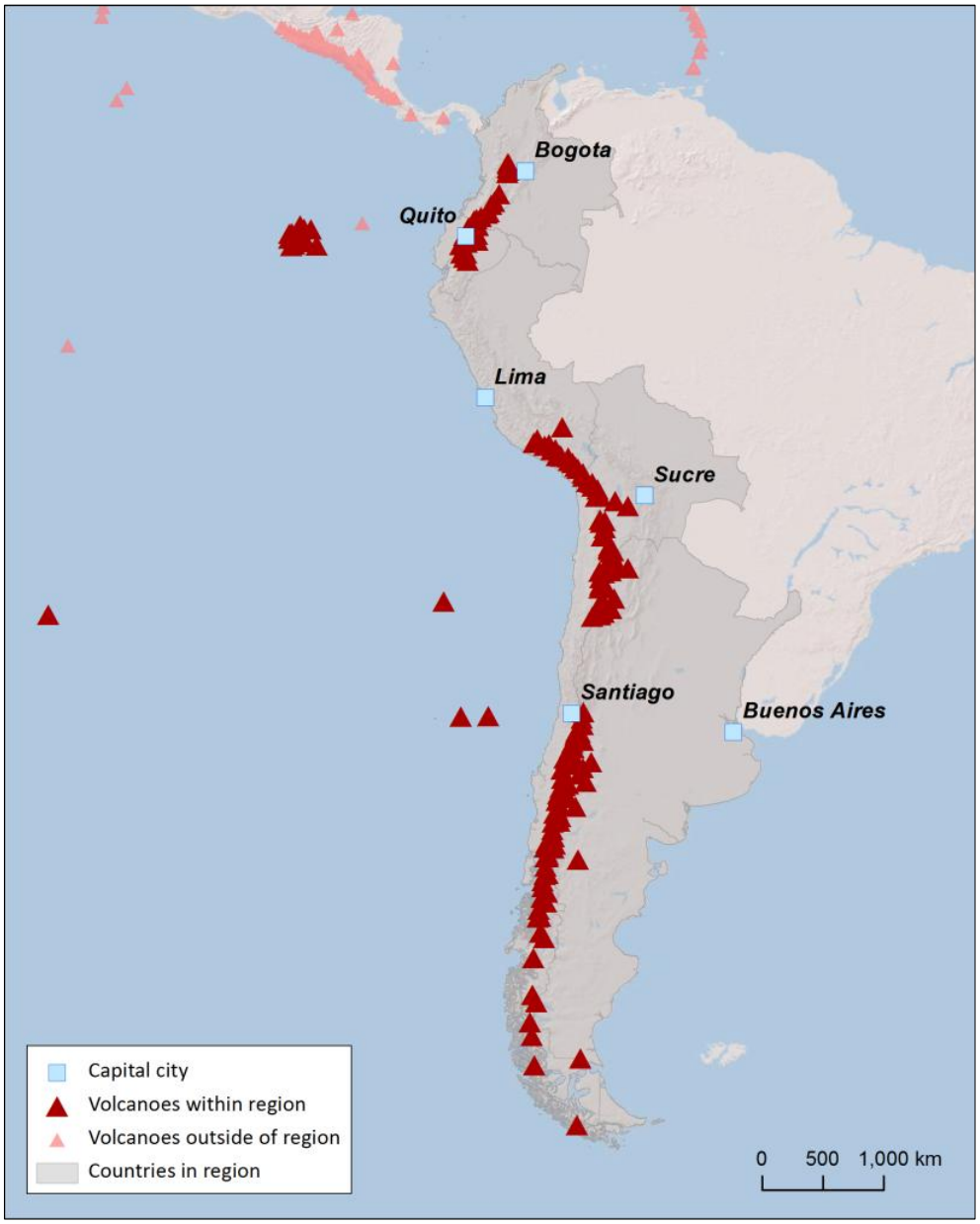

Figure 15.1 The distribution of Holocene volcanoes through the South America region. The capital cities of the constituent countries are shown.

Description

Region 15: South America comprises volcanoes throughout South America, from Colombia in the north to the tip of Chile in the south, and west to include the Galapagos Islands and Chilean islands in the Pacific Ocean. Six countries are represented here. All are included in this regional discussion, and individual profiles are provided.

Country	Number of volcanoes
Argentina	41
Bolivia	12
Chile	105
Colombia	15
Ecuador	35
Peru	17

Table 15.1 The countries represented in this region and the number of volcanoes. Volcanoes located on the borders between countries are included in the profiles of all countries involved. Note that countries may be represented in more than one region, as overseas territories may be widespread.

197 Holocene volcanoes are located in South America. Most of these volcanoes are in Chile. Volcanism here is largely related to the subduction of the Nazca Plate beneath the South American Plate.

A range of volcano types are present, though most are stratovolcanoes. The rock composition varies from basaltic to rhyolitic, but is most commonly andesitic.

Along with ranges of volcano morphologies and rock types, a range of activity styles and eruption magnitudes are recorded throughout the Holocene, with eruptions ranging from VEI 0 to 6. About 72% of eruptions have been small, at VEI 0 to 2, however about 12% of eruptions have been large explosive VEI ≥4 events. The only countries in this region with no Holocene record of VEI ≥4 eruptions are Argentina and Bolivia, though pyroclastic flows are recorded in eruptions at volcanoes on the border of Chile-Argentina and Chile-Bolivia. Four VEI 6 eruptions are recorded here. The two most recent were the 1280 eruption of Quilotoa in Ecuador in which pyroclastic flows and lahars reached the Pacific, and the 1600 eruption of Huaynaputina, Peru, in which pyroclastic flows reached 13 km and lahars reached 120 km.

Seventy-six volcanoes have historical records of 672 eruptions, 95% of which were recorded through direct observations. Areas where the population is sparse have fewer observed events and therefore a less comprehensive record. Pyroclastic flows and lahars are recorded in 12 and 15% of historical eruptions respectively. Lava flows are recorded in 20% of historical eruptions. Many of South America's volcanoes are ice-capped, and as such lahars and explosive eruptions may be frequent.

Lives have been lost in 5% of historical eruptions. The eruption of Nevado del Ruiz in Colombia in 1985 resulted in the greatest loss of life, with over 20,000 fatalities due to lahars. These were produced during a moderate VEI 3 eruption, which led to the melting of the summit ice-cap. Most volcanoes (72%) have low proximal populations, and as such are considered relatively low risk. However, the hazard is poorly constrained at many volcanoes here, with no hazard and risk classification at about 80% of the region's volcanoes. Eight Risk Level III volcanoes are located in this region, all in Ecuador and Colombia.

Most historically active volcanoes are monitored in this region, with an apparent concentration of monitoring at the Risk Level II and III volcanoes. Chile, Colombia, Ecuador and Peru all have specific monitoring institutions.

Volcano facts

Number of Holocene volcanoes	197
Number of Pleistocene volcanoes with M≥4 eruptions	38
Number of volcanoes generating pyroclastic flows	45 (217 eruptions)
Number of volcanoes generating lahars	32 (126 eruptions)
Number of volcanoes generating lava flows	49 (194 eruptions)
Number of eruptions with fatalities	34
Number of fatalities attributed to eruptions	33,230
Largest recorded Pleistocene eruption	The 2.2 Ma M8 Cerro Galán Ignimbrite from Cerro Galán is the largest recorded Quaternary explosive eruption in this region.
Largest recorded Holocene eruption	The largest recorded Holocene eruption in LaMEVE in this region in the 800 BP Quilotoa eruption at M6.4.
Number of Holocene eruptions	976 confirmed Holocene eruptions
Recorded Holocene VEI range	0 – 6 and unknown
Number of historically active volcanoes	76
Number of historical eruptions	672

Number of volcanoes	Primary volcano type	Dominant rock type
13	Caldera(s)	Andesitic (5), Dacitic (5), Rhyolitic (3)
129	Large cone(s)	Andesitic (87), Basaltic (15), Dacitic (21), Trachytic/Andesitic (1), Unknown (5)
7	Lava dome(s)	Andesitic (1), Dacitic (4), Rhyolitic (1), Unknown (1)
18	Shield(s)	Andesitic (1), Basaltic (17)
28	Small cone(s)	Andesitic (13), Basaltic (11), Dacitic (1), Unknown (3)
1	Subglacial	Dacitic (1)
1	Submarine	Unknown (1)

Table 15.2 The volcano types and dominant rock types of the volcanoes of this region according to VOTW4.0.

Eruption Frequency

VEI	Recurrence Interval (Years)
Small (< VEI 4)	1
Large (> VEI 3)	50

Table 15.3 Average recurrence interval (years between eruptions) for small and large eruptions in South America.

The eruption record indicates that on average small to moderate sized eruptions of VEI <4 occur in this region with an average recurrence interval (ARI) of about a year, whilst the ARI for large eruptions is longer, at about 50 years.

Eruption Size

Eruptions are recorded through South America of VEI 0 to 6, representing a range of eruption styles from gentle effusive events to large explosive eruptions. VEI 2 events dominate the record, with over 50% of all Holocene eruptions classed as such. 12% of eruptions here are explosive at VEI ≥4.

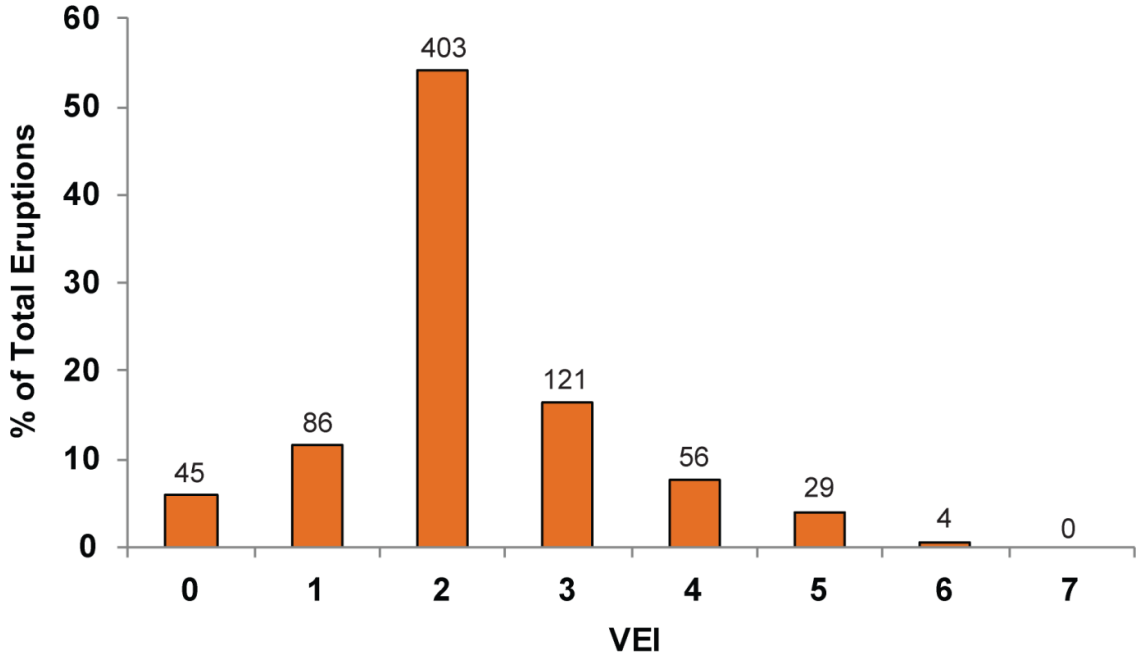

Figure 15.2 Percentage of eruptions in this region recorded at each VEI level; the number of eruptions is also shown. The percentage is of total eruptions with recorded VEI. A further 232 eruptions were recorded with unknown VEI.

Socio-Economic Facts

Total population (2011)	361,188,771
Gross Domestic Product (GDP) per capita (2005 PPP $)	4,499 – 15,501 (Mean 10,129)
Gross National Income (GNI) per capita (2005 PPP $)	4,444 – 15,347 (Mean 10,060)

Human Development Index (HDI) (2012)	0.675 – 0.819 (Medium to Very High, Mean 0.746 High)

Population Exposure

Number (percentage) of people living within 10 km of a Holocene volcano	1,252,806 (0.35 %)
Number (percentage) of people living within 30 km of a Holocene volcano	8,997,260 (2.49 %)
Number (percentage) of people living within 100 km of a Holocene volcano	35,346,223 (9.79 %)

Infrastructure Exposure

Number of airports within 100 km of a volcano	20
Number of ports within 100 km of a volcano	10
Total length of roads within 100 km of a volcano (km)	30,039
Total length of railroads within 100 km of a volcano (km)	3,118

Table 15.4 (Next page): Identity of the volcanoes in this region in each Hazard-PEI group. Those volcanoes with a sufficient record for determining a hazard score are deemed 'Classified' (top). Those without sufficient data are 'Unclassified' (bottom). The unclassified volcanoes are divided into groups: U-NHHR is Unclassified No Historic or Holocene Record: that is there are no confirmed eruptions recorded in the Holocene. U-HR is Unclassified with Holocene Record: that is there are confirmed eruptions recorded during the Holocene, but no historical (post-1500) events. U-HHR is Unclassified with Historic and Holocene record. The unclassified volcanoes in ***bold*** *have experienced unrest or eruptions since 1900 AD, and those in red have records of at least one Holocene VEI ≥4 eruption.*

CLASSIFIED	**Hazard III**		Azul, Cerro; Puyehue-Cordón Caulle; Osorno	Reventador; Sangay; Calbuco	Bravo, Cerro; Cayambe; Cotopaxi; Tungurahua	Nevado del Ruiz; Guagua Pichincha	Galeras; Atacazo	
	Hazard II		Fernandina; Yucamane; Láscar; Planchón-Peteroa; Chillán, Nevados de; Antuco; Copahue; Lonquimay; Llaima	Sabancaya; Ubinas; Villarrica	Tolima, Nevado del			
	Hazard I		Wolf; Negra, Sierra; Azul, Cerro; Guallatiri; Isluga; San Pedro; Huequi; Lautaro	Maipo	Puracé; Misti, El; Tupungatito; San José			
UNCLASSIFIED	**U – HHR**	Robinson Crusoe	Sumaco; Darwin; **Alcedo**; **Pinta**; **Marchena**; **Santiago**; Ticsani; **Irruputuncu**; Olca-Paruma; Putana; Llullaillaco; **Tinguiririca**; **Descabezado Grande**; Tromen; **Callaqui**; Quetrupillan; Huanquihue Group; **Mocho-Choshuenco**; Puntiagudo-Cordón Cenizos; Minchinmávida; Mentolat; **Hudson, Cerro**; **Arenales**; **Viedma**; **Reclus**; **Burney, Monte**; Fueguino	Huaynaputina; **Carrán-Los Venados**; **Chaitén**	**Huila, Nevado del**; **Doña Juana**; **Cumbal**; **Negro de Mayasquer, Cerro**; Antisana	Chacana		
	U- HR	Aliso	Ecuador; Taapaca; Parinacota; Socompa; **Ojos del Salado, Nevados**; Infiernillo; Longaví, Nevado de; Lanín; Antillanca Group; Cayutué-La Viguería; **Yanteles**; Corcovado; **Melimoyu**; Macá; Aguilera; Pali-Aike Volcanic Field	Soche; Huambo; Sollipulli; Caburgua-Huelemolle	Romeral; Chachimbiro; Chimborazo; Quimsachata; Andahua-Orcopampa	Santa Isabel; Machín; Azufral; Quilotoa	Cuicocha; Imbabura	Pululagua
	U- NHHR	San Félix; Unnamed; Blanca, Laguna	Genovesa; Auquihuato, Cerro; Sara Sara; Coropuna; Tutupaca; Casiri, Nevados; Tacora; Tambo Quemado; Tata Sabaya; Jayu Khota, Laguna; Nuevo Mundo; Pampa Luxsar; **Ollagüe**; Azufre, Cerro del; Sairecabur; Licancabur; Guayaques; Purico Complex; Colachi; Acamarachi; Overo, Cerro; **Chiliques**; Cordón de Puntas Negras; Miñiques; Tujle, Cerro; Caichinque; Tilocalar; Negrillar, El; Pular; Negrillar, La; Escorial; **Lastarria**; Cordón del Azufre; Bayo Gorbea, Cerro; Nevada, Sierra; Falso Azufre; Incahuasi, Nevado de; Solo, El; Copiapó; Tuzgle; Aracar; Unnamed; Antofagasta; Cóndor, El; Peinado; **Robledo**; Tipas; Palomo; Atuel, Caldera del; Risco Plateado; Calabozos; Maule, Laguna del; San Pedro-Pellado; Blancas, Lomas; Resago; Payún Matru; Domuyo; Cochiquito Volcanic Group; Puesto Cortaderas; Trolon; Mariñaqui, Laguna; **Tolguaca**; Tralihue; Pantojo, Cerro; Tronador; **Cuernos del Diablo**; Yate; Hornopirén; Apagado; Crater Basalt Volcanic Field; Palena Volcanic Group; Puyuhuapi; Cay; Río Murta	Petacas; Santa Cruz; San Cristóbal; Easter Island	Sotará; Illiniza; Chachani, Nevado; Nicholson, Cerro	Mojanda	Licto	
		PEI 1	**PEI 2**	**PEI 3**	**PEI 4**	**PEI 5**	**PEI 6**	**PEI 7**

Population Exposure Index

Number of Volcanoes	Population Exposure Index
1	7
5	6
8	5
23	4
18	3
137	2
5	1

Table 15.5 The number of volcanoes in South America classed in each PEI category.

Risk Levels

Number of Volcanoes	Risk Level
8	III
10	II
22	I
157	Unclassified

Table 15.6 The number of volcanoes in the South America region classified at each Risk Level.

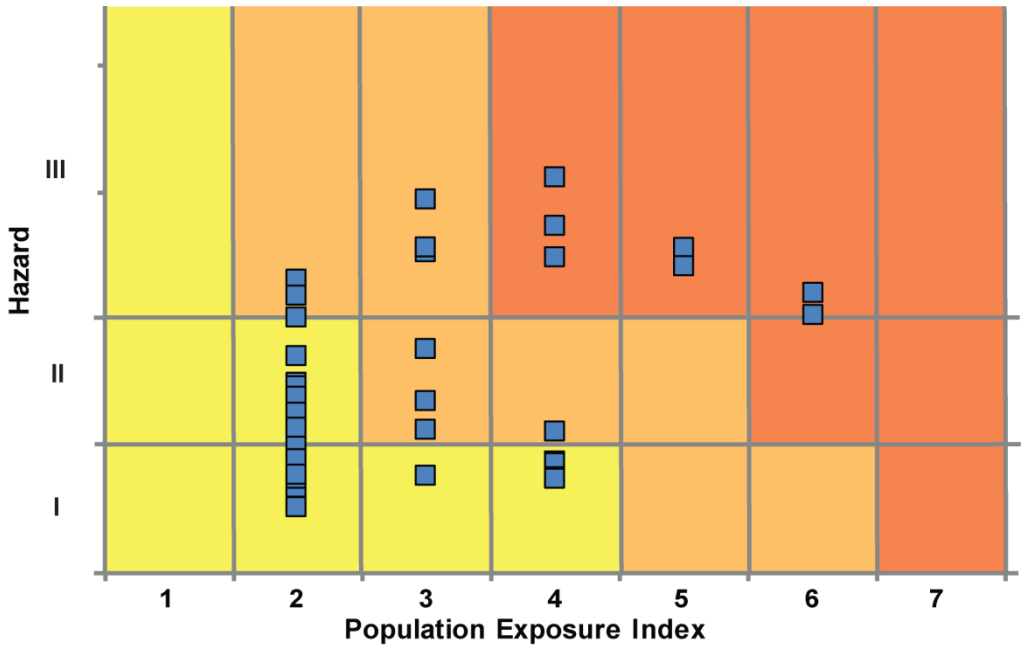

Figure 15.3 Distribution of the classified volcanoes of this region across Hazard and Population Exposure Index levels. The warming of the background colours illustrates increasing Risk levels from Risk Level I - III.

Regional Monitoring Capacity

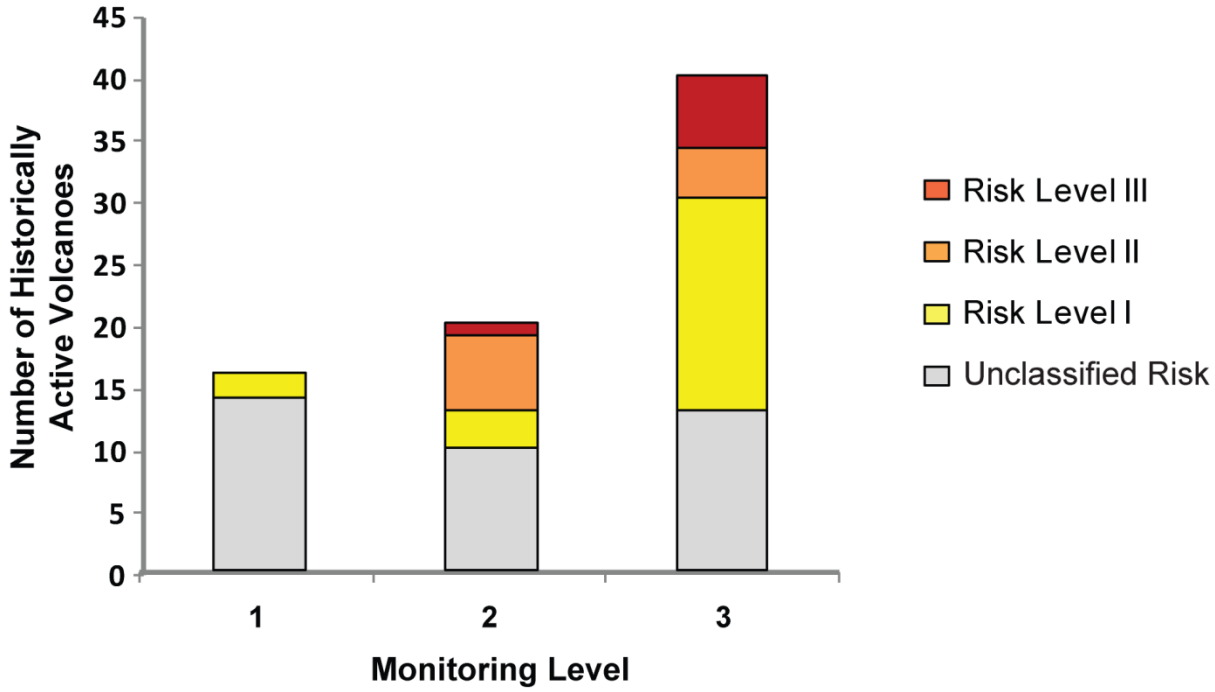

Figure 15.4 The monitoring and risk levels of the historically active volcanoes in South America. Monitoring Level 1 indicates no known dedicated ground-based monitoring; Monitoring Level 2 indicates that some ground-based monitoring systems are in place including ≤3 seismic stations; Monitoring Level 3 indicates the presence of a dedicated ground-based monitoring network, including ≥4 seismometers

Argentina

Description

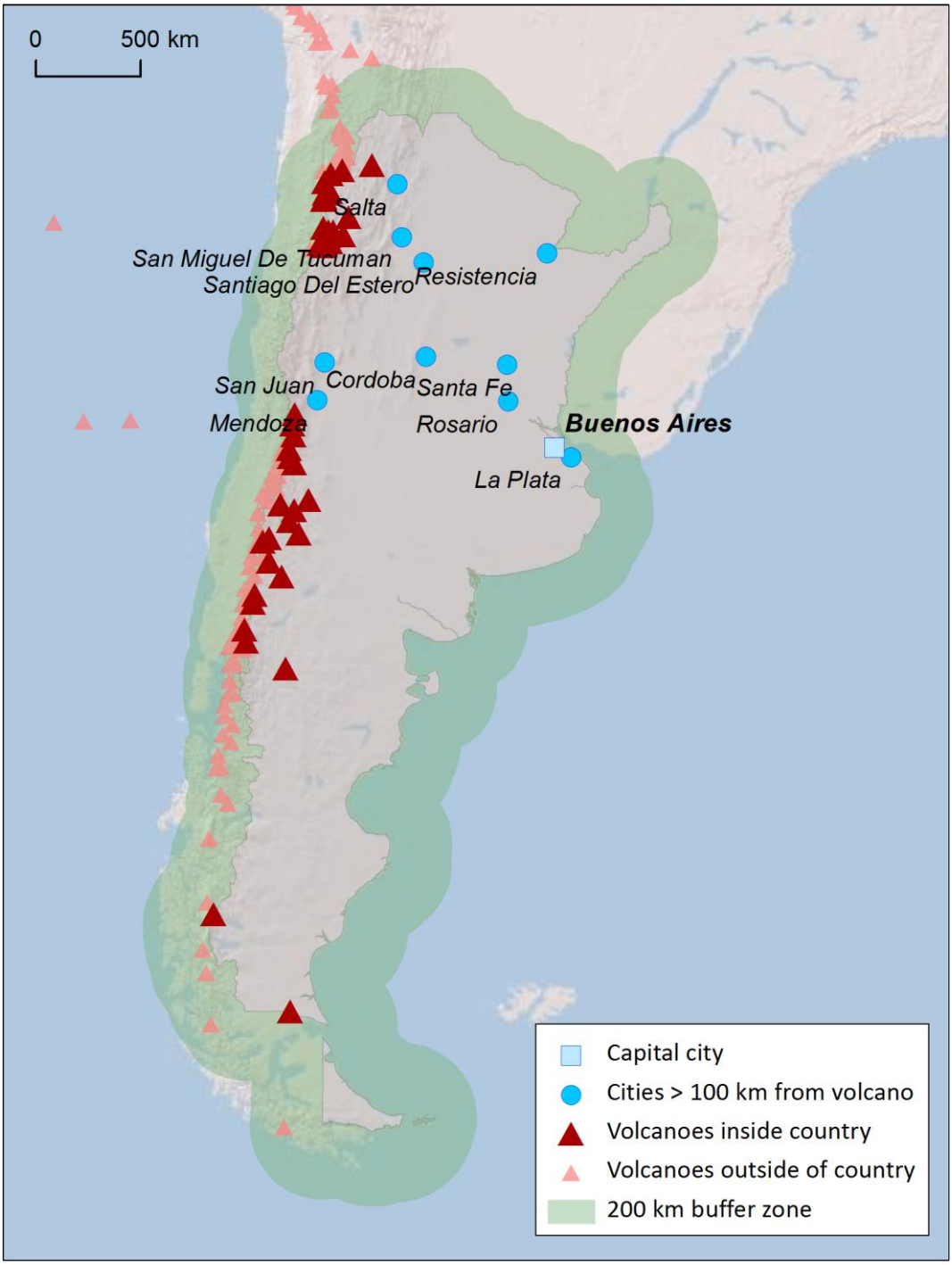

Figure 15.5 Location of Argentina's volcanoes, the capital and largest cities. A zone extending 200 km beyond the country's borders shows other volcanoes whose eruptions may directly affect Argentina.

Forty-one volcanoes are recorded in Argentina, including 19 on the border with Chile. Most of these volcanoes are located in the Andes, in western Argentina, dominantly in the centre and north of the

country. Volcanism here is largely due to the subduction of the Nazca Plate beneath the South American Plate. A range of volcano types are present here, though most are stratovolcanoes of dominantly andesitic composition.

Large explosive Pleistocene activity is recorded in Argentina, and 61 eruptions of Holocene age are recorded from 13 volcanoes. The remaining Holocene volcanoes have activity that is suspected to have occurred in the last 10,000 years. Of these Holocene eruptions, 47 are of historical age, occurring at 8 volcanoes. VOTW4.22 records Holocene eruptions of VEI 0 to 3, indicating a prevalence of mild to moderate activity. However, recent studies have identified two Holocene VEI ≥6 eruptions from Cerro Blanco-Robledo volcanic complex, with the caldera forming eruption being one of the largest Holocene eruptions in the central Andes at approximately 4500 BP (Baez et al., 2015). Just one eruption, that of Copahue in 2000, has a recorded historical pyroclastic flow. During this event pyroclastic flows, scoria and ash fall occurred and evacuations were ordered with damage occurring to property.

Many of the most populous cities in Argentina are located far to the east of the volcanic chain, and the elevation of much of the Andes means that local populations are small. Indeed, less than 2,000 people live within 10 km of a Holocene volcano in the whole of Argentina, and less than 2% of the total population live within 100 km of one or more volcanoes (under 700,000). Although the hazard classification at many of Argentina's volcanoes is complicated by large uncertainties, the small local populations mean that these volcanoes are considered relatively low risk to proximal populations. However, the dominant wind direction is such that ash will commonly be distributed west to east across much of Argentina from eruptions in the far west of the country.

The Chilean volcanoes beyond the border are also very important to the hazard consideration in Argentina. Explosive eruptions of these volcanoes can produce ash clouds with ash dispersal throughout Argentina. Indeed, the dominant wind direction here is west to east, leading to ash fall in Argentina in most Chilean eruptions (Viramonte et al., 2001). There are many examples of this (Figure 15.6). For example, the 2008 eruption of Chaitén produced ash fall beyond the Argentine coast (Folch et al., 2008, Durant et al., 2012) and the 2011 eruption of Cordón Caulle resulted in significant ash fall across three Argentine provinces (Río Negro, Neuguén and Chubut) (Collini et al., 2012). Both eruptions had negative impacts on farming (livestock) and agriculture, water transportation networks and air and ground transportation networks (Collini et al., 2012). See the profile for Chile for further discussion of the Chilean volcanoes.

Ash remobilisation can occur for years after an eruption due to wind and rain, and this can cause issues even in times of inactivity at the volcanoes, therefore ash distribution throughout the country must be understood, both from Argentine and Chilean volcanoes.

Authorities in Argentina, especially SEGEMAR (Servicio Geologico y Minero Argentino), Comisión Nacional de Riesgos, Ministerio de Ciencia Tecnología e Innovación Productiva (MINCyT) and the Argentine Space Agency (CONAE) collaborate with the Servicio Nacional de Geologia y Mineria (SERNAGEOMIN) in Chile for monitoring of the border volcanoes. Seismic and deformation monitoring is in place as are cameras for visual observations. Universidad Nacional de Río Negro in collaboration with Firenze University, maintain temporary seismic array for volcanic monitoring in several potential dangerous volcanoes (Copahue, Domuyo, Tromen). Universidad Nacional de Salta in collaboration with Universidad de Cadiz maintains a high resolution GPS network in the Cerro

Blanco-Robledo caldera comnplex for deformation monitoring. Servicio Meteorológico Nacional, Universidad Nacional de Salta, CONICET and CONAE in cooperation with VAAC Buenos Aires work to give early alerts and ash-fall dispersion forecasts. Alerts are released and evacuations ordered as unrest and eruption occurs. SERNAGEOMIN also monitor most volcanoes within Chile, releasing alerts that can be used in ash forecasts for Argentina.

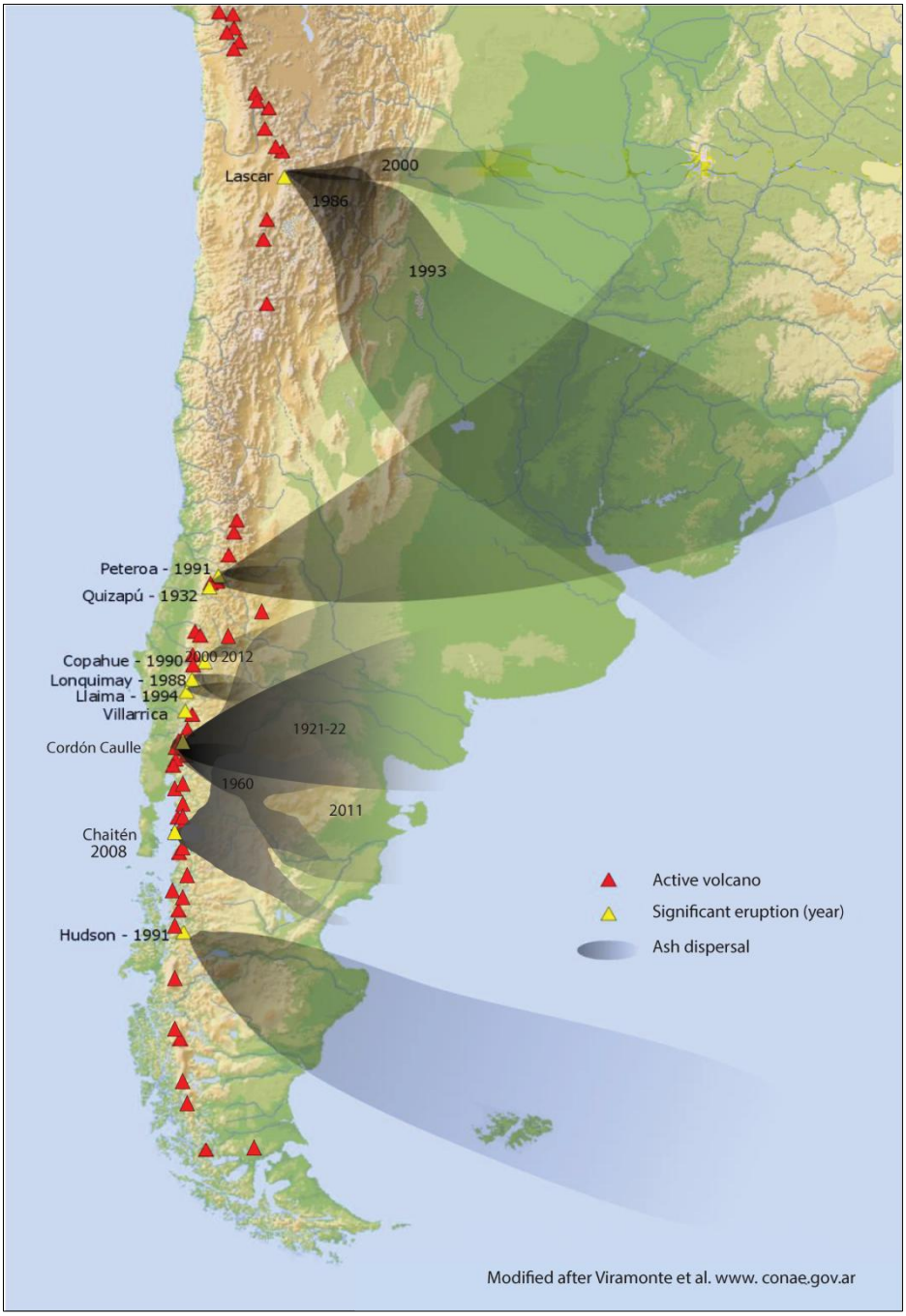

Figure 15.6 The active volcanoes of the central and southern Andes and ash dispersal across Argentina from recent eruptions of Chilean volcanoes. Modified after Viramonte et al. 2001.

References:

Baez, W., Arnosio, M., Chiodi, A., Ortiz-Yanes, A., Viramonte, J.G., Bustos, E., Giordano, G. and Lopez, J.F. (2015) Estratigrafía y evolución del Complejo Volcánico Cerro Blanco, Puna Austral, Argentina. Revista Mexicana de Ciencias Geológicas. rmcg.geociencias.unam.mx/revista/mrevista.php?idioma=E&numero=X

Collini, E., Soledad Osores, M., Folch, A. Viramonte, J.G., Villarosa, G. And Salmuni, G. (2012) Volcanic ash forecast during the June 2011 Cordon Caulle eruption. Natural Hazards, 66:2, 389-412.

Durant, A., Villarosa, G., Rose, W.I., Delmelle, P., Prata, A.J., Viramonte, J.G. (2012) Long-range volcanic ash transport and fallout during the 2008 eruption of Chaiten volcano, Chile. *Physics and Chemistry of the Earth,Parts A/B/C*, 45-46, 50-64.

Folch, A., Jorba, O., & J. Viramonte. 2008. Volcanic Ash Forecast- Application to the May 2008 Chaitén Eruption. *Natural Hazard and Earth System Sciences*. 8: 927-940

Viramonte, J.G., Peralta, C.M., Garrido, D. and Felpeto, A. (2001). Uso de sensores remotos para la mitigación de efectos causados por erupciones volcánicas : Elaboración de mapas de Riesgo volcánico y alertas para la aeronavegación: Un caso de estudio. www.conae.gov.ar/WEB_Emergencias/Links_del_Cuerpo_Principal/Volcanes/Informe%20Riesgo%20Volcanico.htm

Volcano Facts

Number of Holocene volcanoes	41, inclusive of 19 on the border with Chile
Number of Pleistocene volcanoes with M≥4 eruptions	6, inclusive of 3 on the border with Chile
Number of volcanoes generating pyroclastic flows	4
Number of volcanoes generating lahars	2
Number of volcanoes generating lava flows	6
Number of fatalities caused by volcanic eruptions	-
Tectonic setting	37 subduction zone, 4 intra-plate
Largest recorded Pleistocene eruption	The M8 eruption of the Cerro Galán Ignimbrite from Cerro Galán at 2.08 Ma.
Largest recorded Holocene eruption	Recent studies reveal that Cerro Blanco – Robledo caldera has had the most powerful Holocene eruption in ~4,500 BP and at VEI ≥6 (Baez et al., 2015).

Number of Holocene eruptions	61 confirmed eruptions. 14 uncertain and 2 discredited eruptions.
Recorded Holocene VEI range	0 – 3 in VOTW4.22, with VEI ≥6 indicated by recent studies (Baez et al., 2015).
Number of historically active volcanoes	8
Number of historic eruptions	47

Number of volcanoes	Primary volcano type	Dominant rock type
3	Caldera(s)	Andesitic (2), Rhyolitic (1)
28	Large cone(s)	Andesitic (13), Basaltic (4), Dacitic (7), Unknown (4)
1	Lava dome(s)	Dacitic (1)
1	Shield(s)	Basaltic (1)
7	Small cone(s)	Andesitic (3), Basaltic (4)
1	Subglacial	Dacitic (1)

Table 15.7 The number of volcanoes in Argentina, their volcano type classification and dominant rock type according to VOTW4.0.

Socio-Economic Facts

Total population (2012)	41,117,000
Gross Domestic Product (GDP) per capita (2005 PPP $)	15,501
Gross National Income (GNI) per capita (2005 PPP $)	15,347
Human Development Index (HDI) (2012)	0.811 (Very High)

Population Exposure

Capital city	Buenos Aires
Distance from capital city to nearest Holocene volcano	974.1 km
Total population (2011)	41,769,726
Number (percentage) of people living within 10 km of a Holocene volcano	1,809 (<1%)

Number (percentage) of people living within 30 km of a Holocene volcano	26,905 (<1%)
Number (percentage) of people living within 100 km of a Holocene volcano	618,387 (1.5%)

Ten largest cities, as measured by population and their population size:

Buenos Aires	13,076,300
Cordoba	1,428,214
Rosario	1,173,533
Mendoza	876,884
San Miguel De Tucuman	781,023
La Plata	694,167
Salta	512,686
Santa Fe	468,632
San Juan	447,048
Resistencia	387,158

Infrastructure Exposure

Number of airports within 100 km of a volcano	2
Number of ports within 100 km of a volcano	1
Total length of roads within 100 km of a volcano (km)	4,638
Total length of railroads within 100 km of a volcano (km)	278

Volcanoes in Argentina occur along the western border of the country, on the border with Chile. Volcanoes here are located in three main groups, in the north, centre and south. Many of the border volcanoes here have 100 km radii that extend into Chile, and likewise the radii of Chilean volcanoes extend into western Argentina. The capital, Buenos Aires, lies in the east of the country at nearly 1000 km distance to the nearest Holocene volcano, and most of the largest cities in the country lie far east of the volcanic chain. Only the southernmost Palei-Aike volcano is located near the coast exposing ports and an airport here. An extensive road and rail network lies within the radii of the volcanoes throughout the country.

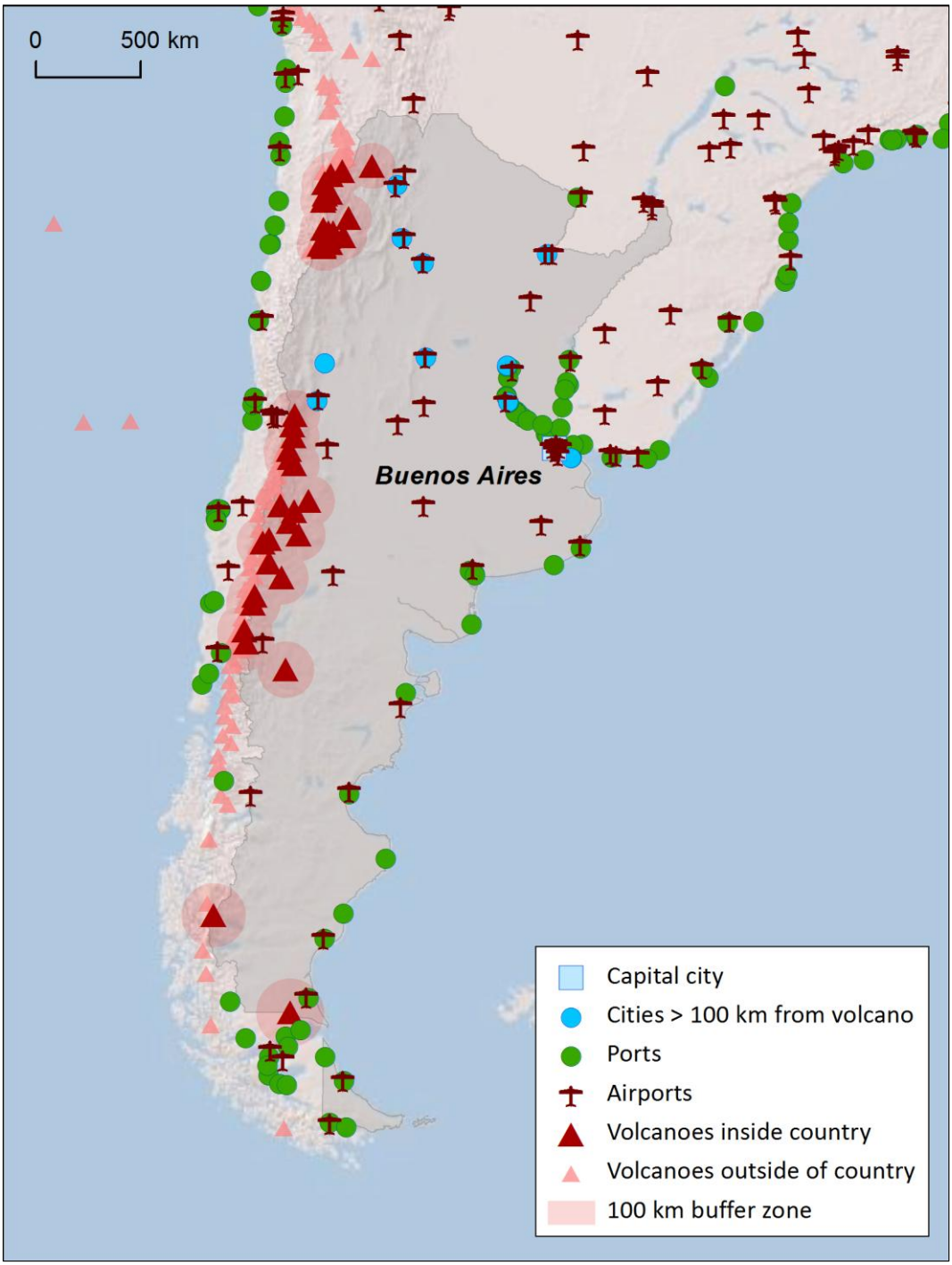

Figure 15.7 The location of Argentina's volcanoes and the extent of the 100 km zone surrounding them. Ports, airports and the major cities are just some of the infrastructure that may be exposed to volcanic hazards.

Hazard, Uncertainty and Exposure Assessments

There are varying levels of information available in the eruption records of Argentina's volcanoes. Just four out of 41 have sufficient detail to define the hazard through the calculation of the VHI. These are classified at Hazard Levels I and II.

Of the unclassified volcanoes, 28 have no confirmed eruptions in the Holocene record. Nine have a Holocene record, including historical events at Llullaillaco, Tromen, Huanquihue Group and Viedma. The latter has recorded eruptions since 1900 AD. Unrest has been recorded at a further three unclassified volcanoes.

The PEI in Argentina is classed as low to moderate, with most volcanoes having a PEI of 2. All classified volcanoes here are classed at Risk Level I. Given the low population, all unclassified volcanoes would be classed at Risk Levels I and II, were the hazard known.

CLASSIFIED	**Hazard III**							
	Hazard II		Copahue					
	Hazard I			Maipo	Tupungatito; San José			
UNCLASSIFIED	**U – HHR**		Llullaillaco; Tromen; Huanquihue Group; **Viedma**					
	U- HR		Socompa; **Nevados Ojos del Salado**; Infiernillo; Lanín; Pali-Aike Volcanic Field; **Cerro Blanco-Robledo complex***					
	U-NHHR	Blanca, Laguna	Escorial; **Lastarria**; Cordón del Azufre; Bayo Gorbea, Cerro; Nevada, Sierra; Falso Azufre; Incahuasi, Nevado de; Solo, El; Tuzgle; Aracar; Unnamed; Antofagasta; Cóndor, El; Peinado; Tipas; Atuel, Caldera del; Risco Plateado; Payún Matru; Domuyo; Cochiquito Volcanic Group; Puesto Cortaderas; Trolon; Tralihue; Pantojo, Cerro; Tronador; Crater Basalt Volcanic Field					
		PEI 1	**PEI 2**	**PEI 3**	**PEI 4**	**PEI 5**	**PEI 6**	**PEI 7**

*Table 15.8 Identity of Argentina's volcanoes in each Hazard-PEI group. Those volcanoes with a sufficient record for determining a hazard score are deemed 'Classified' (top). Those without sufficient data are 'Unclassified' (bottom). The unclassified volcanoes are divided into groups: U-NHHR is Unclassified No Historic or Holocene Record: that is there are no confirmed eruptions recorded in the Holocene. U-HR is Unclassified with Holocene Record: that is there are confirmed eruptions recorded during the Holocene, but no historical (post-1500) events. U-HHR is Unclassified with Historic and Holocene record. The unclassified volcanoes in **bold** have experienced unrest or eruptions since 1900 AD, and those in red have records of at least one Holocene VEI ≥4 eruption.*

**Note that Robledo had no eruptions recorded in VOTW4.22, but recent studies have identified a large explosive Holocene at this volcano (Baez et al., 2015) and so its entry has been adjusted here from U-NHHR to U-HR.*

Volcano	Population Exposure Index	Risk Level
San José	4	I
Tupungatito	4	I
Maipo	3	I
Copahue	2	I

Table 15.9 Classified volcanoes of Argentina ordered by descending Population Exposure Index (PEI). Risk levels determined through the combination of the Hazard Level and PEI are given. Risk Level I – 4 volcanoes; Risk Level II – 0 volcanoes; Risk Level III – 0 volcanoes.

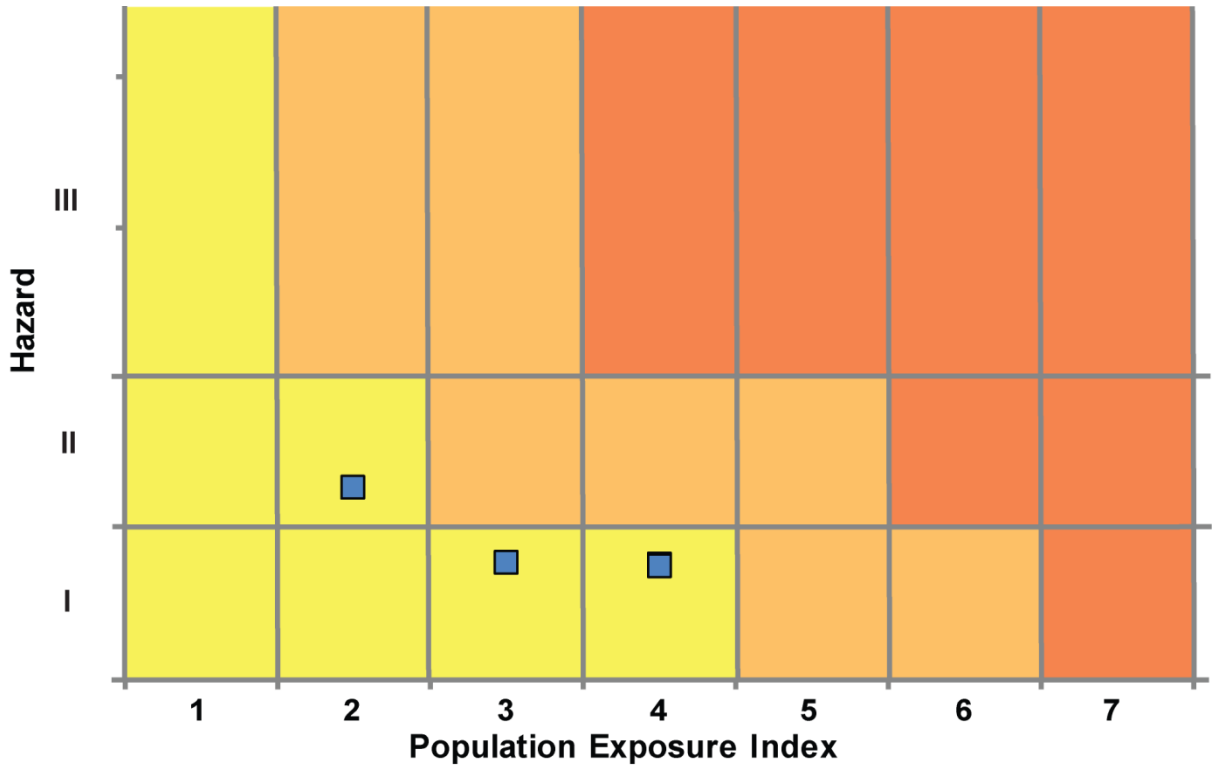

Figure 15.8 Distribution of Argentina's classified volcanoes across Hazard and Population Exposure Index levels. The warming of the background colours illustrates increasing Risk levels from Risk Level I - III.

National Capacity for Coping with Volcanic Risk

Eight volcanoes in Argentina, inclusive of those on the border with Chile, have records of historical activity. Four are classified at Risk Level I (Tupungatito, San José, Maipo, Copahue) and four are unclassified with a PEI of 2 (Llullaillaco, Tromen, Huanquihue Group and Viedma). At the time of the writing of this report, no information is available to indicate that dedicated ground-based monitoring is in place the four unclassified volcanoes. However, SERNAGEOMIN in Chile operate monitoring systems at four of the border volcanoes, with seismic and deformation monitoring at Copahue, Maipo, Tupungatito and San José.

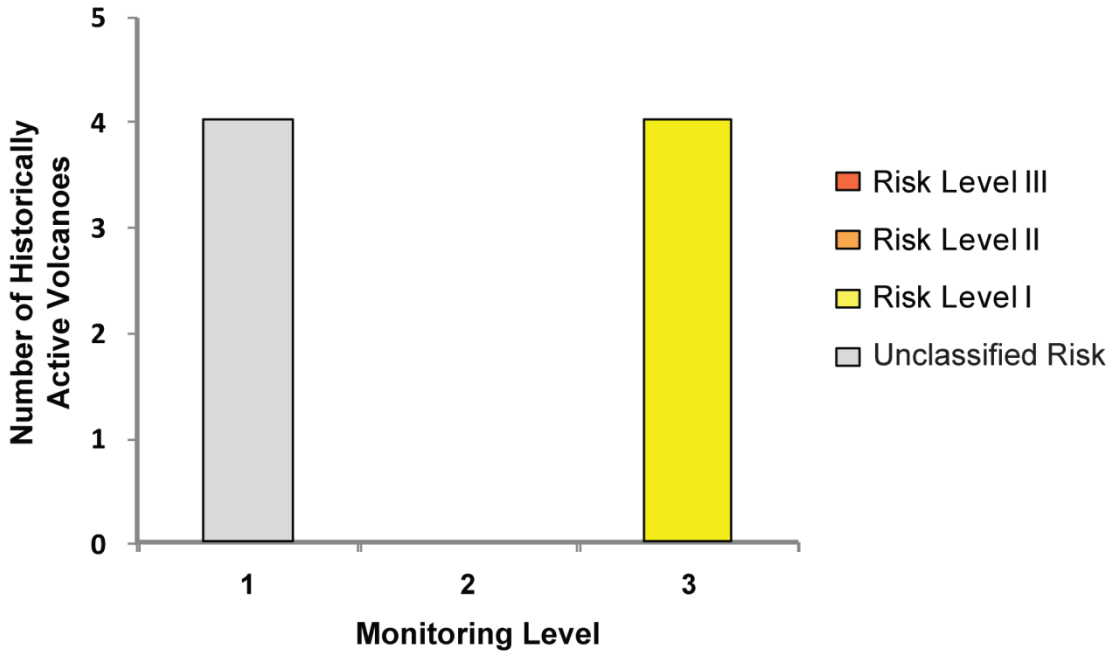

Figure 15.9 The monitoring and risk levels of the historically active volcanoes in Argentina. Monitoring Level 1 indicates no known dedicated ground-based monitoring; Monitoring Level 2 indicates that some ground-based monitoring systems are in place including ≤3 seismic stations; Monitoring Level 3 indicates the presence of a dedicated ground-based monitoring network, including ≥4 seismometers.

Bolivia

Description

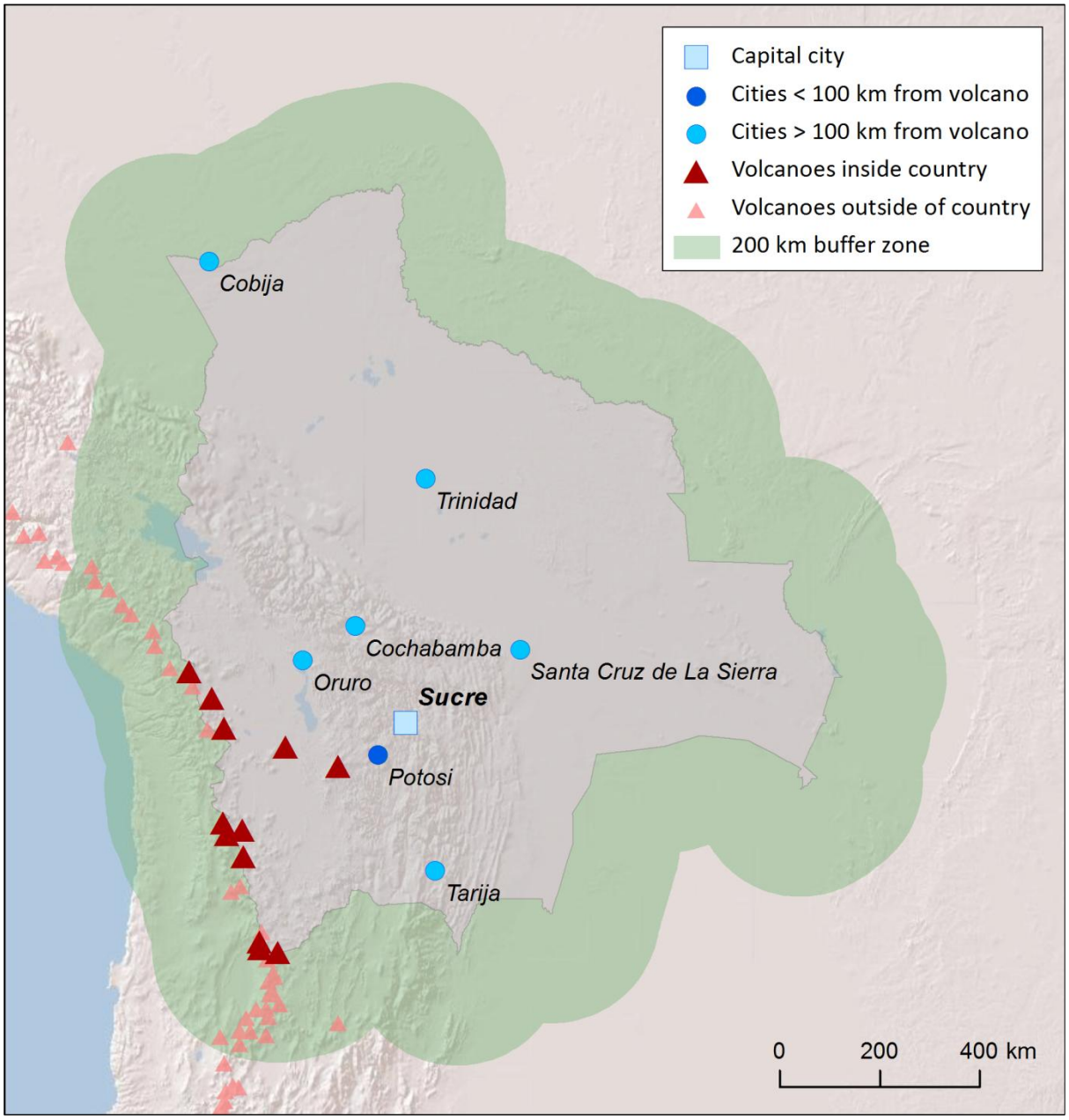

Figure 15.10 Location of Bolivia's volcanoes, the capital and largest cities. A zone extending 200 km beyond the country's borders shows other volcanoes whose eruptions may directly affect Bolivia.

Twelve Holocene volcanoes are located in Bolivia, including seven on the border with Chile. Volcanism here is largely due to the subduction of the Nazca Plate beneath the South American Plate. A variety of volcano forms have developed here, with stratovolcanoes being the most common. The composition varies from basaltic to rhyolitic, though andesitic compositions are most common.

Very large explosive eruptions are recorded back into the Pleistocene, but the Holocene record is sparse, with just seven confirmed eruptions. Two of these were recorded historically, in 1865 at Olca-Paruma, and in 1995 at Irruputuncu. This latter eruption is the largest recorded in the Holocene, at just VEI 2.

The sparse nature of the eruptive record suggests that the hazard (the VHI) is poorly constrained however the volcanoes of Bolivia are remote, with the most populous cities located to the east. Only a small number of people live in close proximity to Holocene volcanoes in Bolivia, with about 3,000 in total within 10 km, and less than 500,000 within 100 km of these volcanoes. As such, current understanding suggests that these volcanoes are of relatively low risk.

There is no official monitoring institution in Bolivia, however SERNAGEOMIN in Chile monitors the border volcanoes. Two part-time scientists at the Universidad Mayor de San Andres undertaken volcanic research in Bolivia, and they advise that there are no current response protocols in place for developing unrest or eruption, largely due to the remote nature of the volcanoes. They suggest that infrastructure is at risk, with highways (the Oruro-Pisiga and Patacamaya-Tambo Quemado highway), railways (the Arica line) and an electricity generating station near Nuevo Mundo highlighted as being exposed.

Volcano Facts

Number of Holocene volcanoes	12, inclusive of 7 on the border with Chile
Number of Pleistocene volcanoes with M≥4 eruptions	-
Number of volcanoes generating pyroclastic flows	1
Number of volcanoes generating lahars	-
Number of volcanoes generating lava flows	1
Number of fatalities caused by volcanic eruptions	-
Tectonic setting	Subduction zone
Largest recorded Pleistocene eruption	The M7.2 eruption of Laguna Colorado, at 1.9 Ma.
Largest recorded Holocene eruption	The VEI 2 eruption of Irruputuncu in 1995 AD.
Number of Holocene eruptions	7 confirmed eruptions. 2 uncertain eruptions.
Recorded Holocene VEI range	0 – 2
Number of historically active volcanoes	2
Number of historic eruptions	2

Number of volcanoes	Primary volcano type	Dominant rock type
1	Caldera(s)	Rhyolitic (1)
7	Large cone(s)	Andesitic (7)
2	Lava dome(s)	Dacitic (2)
2	Small cone(s)	Andesitic (1), Basaltic (1)

Table 15.10 The number of volcanoes in Bolivia, their volcano type classification and dominant rock type according to VOTW4.0.

Socio-Economic Facts

Total population (2012)	10,523,000
Gross Domestic Product (GDP) per capita (2005 PPP $)	4,499
Gross National Income (GNI) per capita (2005 PPP $)	4,444
Human Development Index (HDI) (2012)	0.675 (Medium)

Population Exposure

Capital city	Sucre
Distance from capital city to nearest Holocene volcano	152.1 km
Total population (2011)	10,118,683
Number (percentage) of people living within 10 km of a Holocene volcano	3,098 (<1%)
Number (percentage) of people living within 30 km of a Holocene volcano	29,479 (<1%)
Number (percentage) of people living within 100 km of a Holocene volcano	465,904 (4.6%)

Largest cities, as measured by population and their population size:

Santa Cruz de La Sierra	1,364,389
Cochabamba	900,414
La Paz	812,799
Sucre	224,838
Oruro	208,684
Tarija	159,269
Potosi	141,251

Trinidad	84,259
Cobija	26,585

Infrastructure Exposure

Number of airports within 100 km of a volcano	0
Number of ports within 100 km of a volcano	0
Total length of roads within 100 km of a volcano (km)	908
Total length of railroads within 100 km of a volcano (km)	282

The volcanoes are situated in a chain along much of the western border of Bolivia and Chile. The 100 km radii of these volcanoes fully encompasses this border, and extends into Chile, Peru and Argentina. Similarly, the border volcanoes in these countries have 100 km radii that extend into Bolivia. The capital, Sucre, lies at over 150 km from the nearest Holocene volcano. The volcanoes in Bolivia are relatively remote, but with numerous small settlements and an extensive road network lying within their 100 km radii.

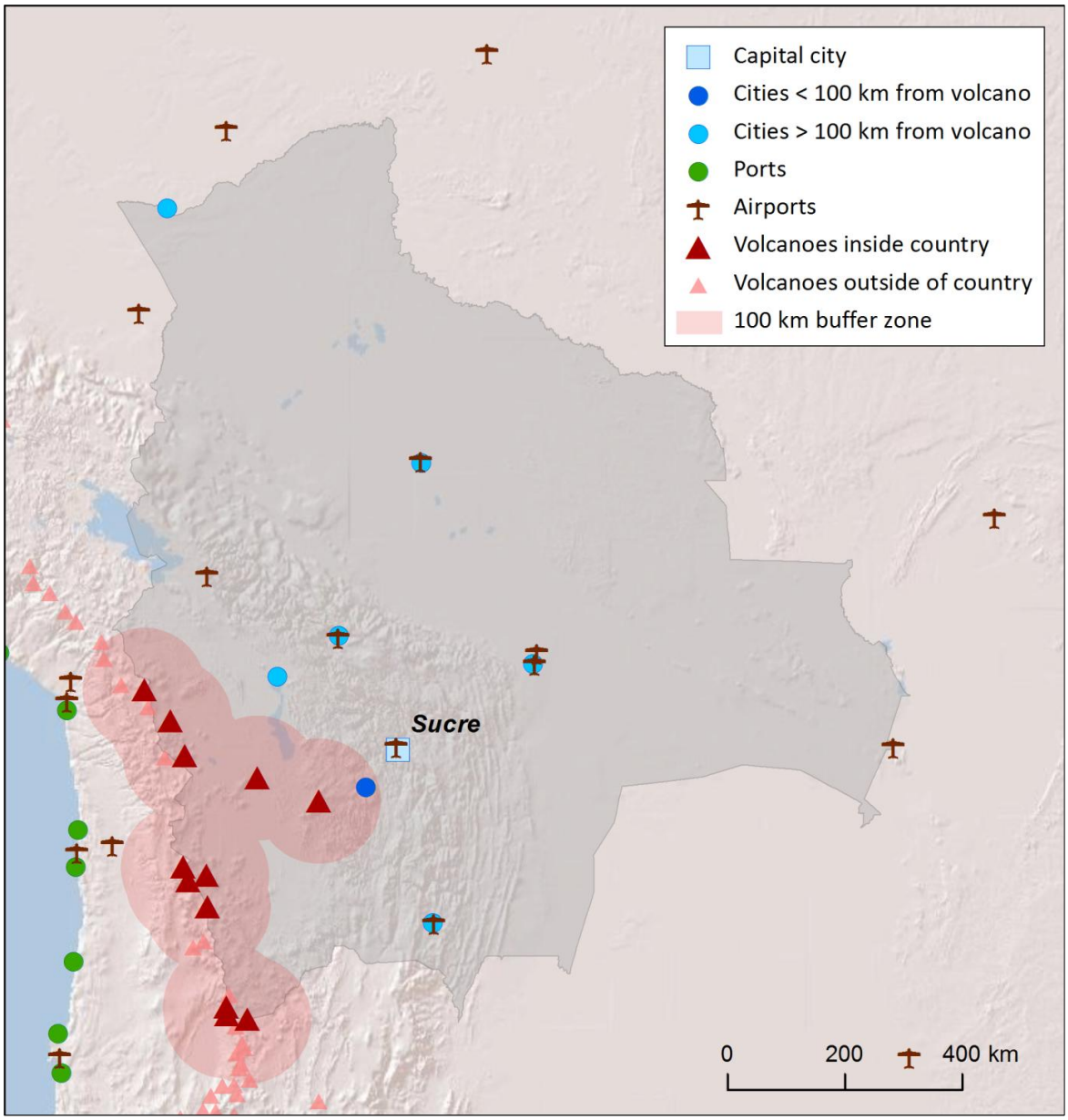

Figure 15.11 The location of Bolivia's volcanoes and the extent of the 100 km zone surrounding them. Ports, airports and the major cities are just some of the infrastructure that may be exposed to volcanic hazards.

Hazard, Uncertainty and Exposure Assessments

The eruption records for Bolivia's volcanoes lack sufficient detail to determine hazard levels through the calculation of the VHI. These volcanoes are therefore unclassified. Indeed, of the twelve volcanoes here, just three have a confirmed Holocene record of eruptions, including historical activity at Irruputuncu and Olca-Paruma. Eruptions and unrest have been recorded at these two volcanoes since 1900 AD, respectively.

The PEI at all Bolivian volcanoes is low at PEI 2. The absence of a hazard classification prevents determination of risk levels, however this low local populations suggests risk levels of I and II.

CLASSIFIED	**Hazard III**							
	Hazard II							
	Hazard I							
UNCLASSIFIED	**U – HHR**		**Irruputuncu**; **Olca-Paruma**					
	U- HR		Parinacota					
	U-NHHR		Tambo Quemado; Tata Sabaya; Jayu Khota, Laguna; Nuevo Mundo; Pampa Luxsar; **Ollagüe**; Sairecabur; Licancabur; Guayaques					
		PEI 1	**PEI 2**	**PEI 3**	**PEI 4**	**PEI 5**	**PEI 6**	**PEI 7**

*Table 15.11 Identity of Bolivia's volcanoes in each Hazard-PEI group. Those volcanoes with a sufficient record for determining a hazard score are deemed 'Classified' (top). Those without sufficient data are 'Unclassified' (bottom). The unclassified volcanoes are divided into groups: U-NHHR is Unclassified No Historic or Holocene Record: that is there are no confirmed eruptions recorded in the Holocene. U-HR is Unclassified with Holocene Record: that is there are confirmed eruptions recorded during the Holocene, but no historical (post-1500) events. U-HHR is Unclassified with Historic and Holocene record. The unclassified volcanoes in **bold** have experienced unrest or eruptions since 1900 AD, and those in red have records of at least one Holocene VEI ≥4 eruption.*

National Capacity for Coping with Volcanic Risk

Two volcanoes on the Bolivia-Chile border have historical records of activity. Monitoring undertaken by SERNAGEOMIN in Chile is described at both these volcanoes, however the details are unknown.

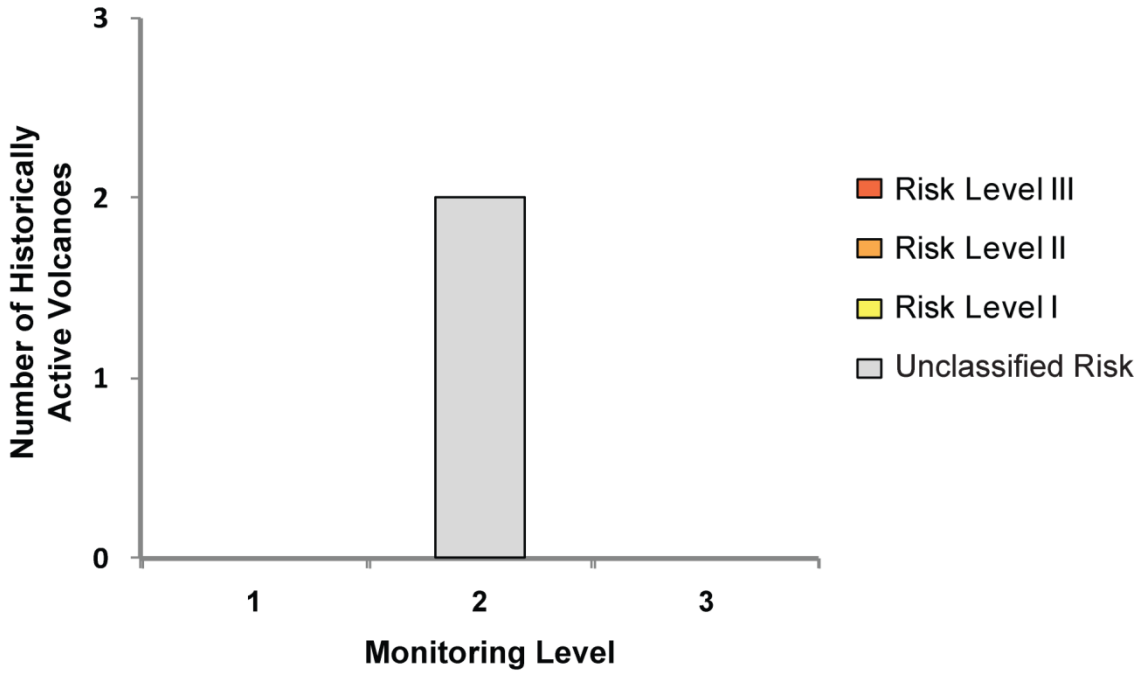

Figure 15.12 The monitoring and risk levels of the historically active volcanoes in Bolivia. Monitoring Level 1 indicates no known dedicated ground-based monitoring; Monitoring Level 2 indicates that some ground-based monitoring systems are in place including ≤3 seismic stations; Monitoring Level 3 indicates the presence of a dedicated ground-based monitoring network, including ≥4 seismometers.

Chile

Description

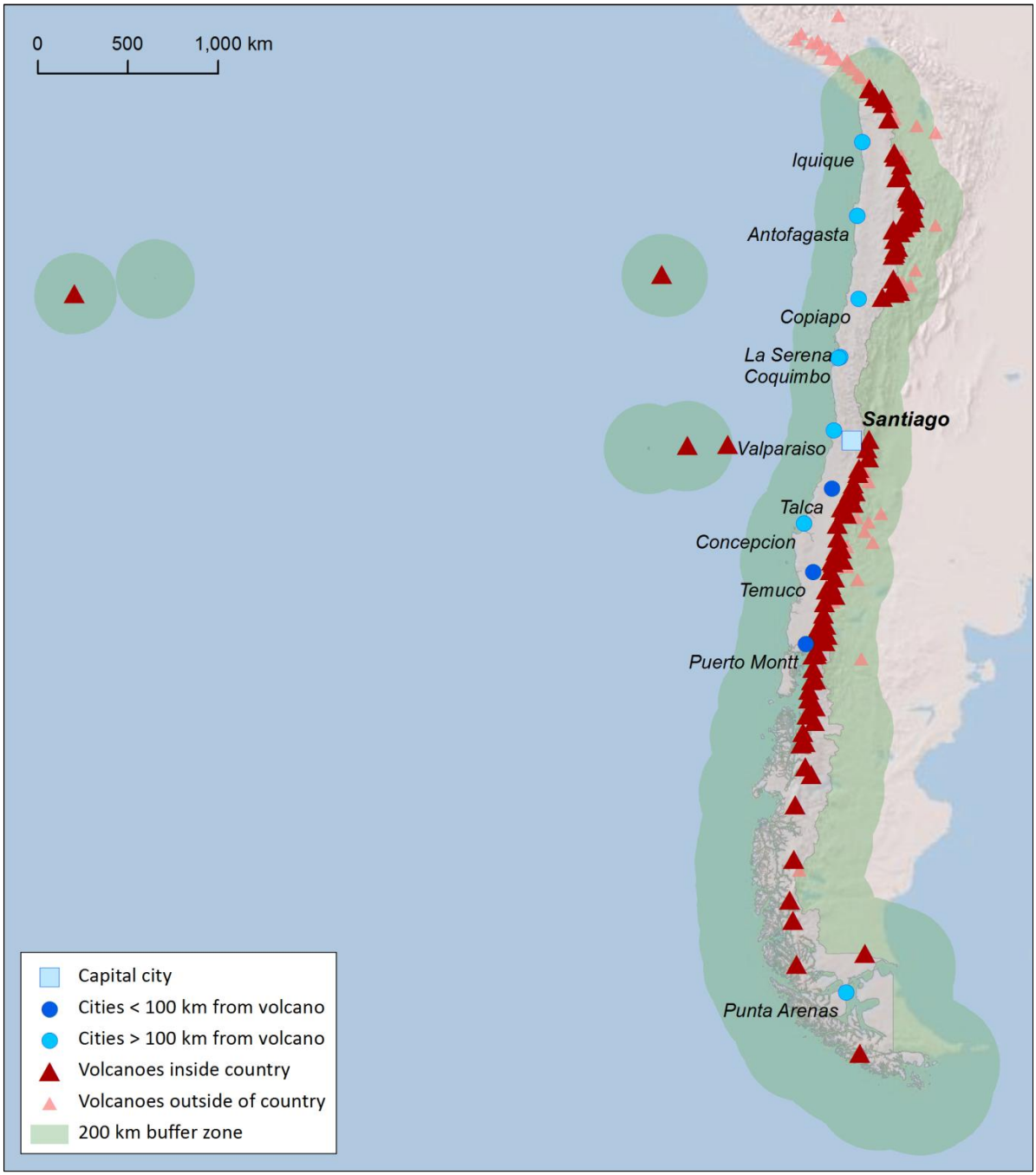

Figure 15.13 Location of Chile's volcanoes, the capital and largest cities. A zone extending 200 km beyond the country's borders shows other volcanoes whose eruptions may directly affect Chile.

There are 105 volcanoes in Chile, including nearly 30 on the borders within Argentina, Bolivia and Peru. Several groups of volcanoes are present, with scattered remote volcanoes in the very far south, a large concentration of volcanic centres south of Santiago and north of Copiapo, and Chilean

islands in the Pacific Ocean. Volcanism through Chile is primarily due to the subduction of the Nazca Plate beneath the South American Plate and intra-plate processes in the Pacific.

A range of volcano types are present throughout Chile, though stratovolcanoes are most common with about three quarters of volcanoes here being classified as such. The rock type also varies, from basaltic to rhyolitic, however andesitic compositions are most common.

Large explosive Pleistocene activity is recorded in Chile at 20 volcanoes. The largest Pleistocene eruptions were of magnitude 7.4, with three eruptions of this size at Calabozos caldera about 150,000, 300,000 and 800,000 years ago. Holocene activity has occurred here and hot springs are still active within the caldera.

Holocene activity in Chile has included 476 confirmed eruptions from 56 volcanoes. The remaining volcanoes have activity of suspected Holocene age. Holocene activity has comprised a range of activity styles and sizes, with eruptions from VEI 0 to 6, though only about 5% of these were VEI ≥4.

Historically, 40 volcanoes are recorded producing 357 eruptions. Of these, 8 were VEI ≥4, though pyroclastic flows are recorded in 16 eruptions. Lava flows have more commonly been recorded and 14% of eruptions have resulted in lahars. The largest historical eruption in Chile occurred at Cerro Azul in 1916. This VEI 5 eruption ejected 9.5 cubic kilometres of tephra and was one of the world's largest eruptions in the 20th century.

Only a small total population is situated within 10 km of one or more Holocene volcanoes in Chile, however this grows considerably at 30 km and to about 10.6 million at 100 km, accounting for about 63% of the population. Ten historic eruptions have resulted in loss of life, at Lonquimay, Llaima, Villarrica, Carran-Los Venados, Chaiten and Cerro Hudson.

The Red de Vigilancia Volcanic (Volcano monitoring network) and the Observatorio Volcanologico de Los Andes del Sur (OVDAS) are part of the Servicio Nacional de Geologia y Mineria (SERNAGEOMIN). This body is government funded, and was founded in 1996. The main objective of these groups is to establish monitoring systems and monitor the most dangerous volcanoes in Chile (based on the frequency of activity, proximity to population centres and vulnerability of public and private infrastructure) in order to provide information to the relevant authorities.

Monitoring is undertaken at many volcanoes using seismic networks, cameras, deformation and gas measurements. Success of the network has been proven in the eruption of Puyehue-Cordon Caulle and alerts at Hudson and Copahue. Resources and plans are available for responding to developing unrest and eruption at current un- or under-monitored volcanoes.

Scientific, technical and support staff are present at the monitoring institution, and about 20% of these have experience of responding to activity, however large amounts of data are gathered and further scientific experience and support is required for full analysis.

Regular technical meetings are held in the event of increased activity and an informal response protocol is followed, including alerting the regional VAAC. The Oficina Nacional de Emergencia del Ministerio del Interior y Seguridad Pública (ONEMI) coordinates emergency response. OVDAS communicates hazard assessments and alerts to ONEMI who use a civil protection alert system.

A relative threat ranking is produced by SERNAGEOMIN for the volcanoes of Chile. This is similar to the NVEWS method and VHI, using hazard indicators taken from the records and coupling these with exposure factors. The relative threat is the sum of the hazard × sum of exposure. This ranking system indicates that Villarrica and Llaima have the largest relative threat ranking, with these volcanoes being the most frequently active here with 126 historical eruptions between them coupled with large populations within 100 km.

A questionnaire was completed by SERNAGEOMIN as part of this study. This indicated that a number of volcano records in VOTW4.0 require updating, with some volcanoes considered Holocene age in VOTW4.0 but designated as Pleistocene age by SERNAGEOMIN. This highlights the value of close collaboration between the volcanological community to ensure up-to-date and sustainable data systems. Updates will be considered by the Smithsonian Institution.

See also:

SERNAGEOMIN: www.sernageomin.cl/volcan-observatorio.php

Volcano Facts

Number of Holocene volcanoes	105, inclusive of 19 on the border with Argentina, 7 on the border with Bolivia and 1 on the border with Peru
Number of Pleistocene volcanoes with M≥4 eruptions	20, inclusive of 3 on the border with Argentina
Number of volcanoes generating pyroclastic flows	19
Number of volcanoes generating lahars	13
Number of volcanoes generating lava flows	25
Number of fatalities caused by volcanic eruptions	?473
Tectonic setting	101 Subduction zone, 3 Intra-plate, 1 Rift zone
Largest recorded Pleistocene eruption	The Loma Seca Tuff, units S, V and L from Calabozos are all recorded at M7.4 at 150 ka, 300 ka and 800 ka respectively.
Largest recorded Holocene eruption	The M6.3 H1/T2 eruption from Cerro Hudson at 7710 BP.
Number of Holocene eruptions	476 confirmed eruptions. 74 uncertain and 9 discredited eruptions.
Recorded Holocene VEI range	0 – 6 and unknown
Number of historically active volcanoes	40

Number of historic eruptions	357

Number of volcanoes	Primary volcano type	Dominant rock type
6	Caldera(s)	Andesitic (3), Dacitic (2), Rhyolitic (1)
78	Large cone(s)	Andesitic (51), Basaltic (12), Dacitic (12), Unknown (3)
2	Lava dome(s)	Andesitic (1), Dacitic (1)
3	Shield(s)	Basaltic (3)
15	Small cone(s)	Andesitic (5), Basaltic (7), Dacitic (1), Unknown (2)
1	Submarine	Unknown (1)

Table 15.12 The number of volcanoes in Chile, their volcano type classification and dominant rock type according to VOTW4.0.

Socio-Economic Facts

Total population (2012)	17,479,000
Gross Domestic Product (GDP) per capita (2005 PPP $)	15,272
Gross National Income (GNI) per capita (2005 PPP $)	14,987
Human Development Index (HDI) (2012)	0.819 (Very High)

Population Exposure

Capital city	Santiago
Distance from capital city to nearest Holocene volcano	80.5 km
Total population (2011)	16,888,760
Number (percentage) of people living within 10 km of a Holocene volcano	21,030 (<1%)
Number (percentage) of people living within 30 km of a Holocene volcano	208,768 (1.2%)
Number (percentage) of people living within 100 km of a Holocene volcano	10,623,259 (62.9%)

Ten largest cities, as measured by population and their population size:

Santiago	4,837,295
Antofagasta	309,832
Valparaiso	282,448
Temuco	238,129

Iquique	227,499
Concepcion	215,413
Talca	197,479
Puerto Montt	160,054
La Serena	154,521
Copiapo	129,280

Infrastructure Exposure

Number of airports within 100 km of a volcano	10
Number of ports within 100 km of a volcano	8
Total length of roads within 100 km of a volcano (km)	16,196
Total length of railroads within 100 km of a volcano (km)	2,139

The numerous volcanoes of Chile are located primarily along the country's eastern border with Argentina, Bolivia and Peru, and as such the 100 km radii of these volcanoes extend into these neighbouring countries. Similarly, volcanoes near the borders in these countries have radii extending into Chile, exposing the infrastructure here. Several volcanoes are situated in the Pacific off the coast of Chile. The capital, Santiago, lies within 100 km of the historically active Tupungatito and San José volcanoes, hence considerable critical infrastructure is exposed here. Being a relatively narrow stretch of land, much of southern Chile lies within 100 km of Holocene volcanoes, and many ports are exposed here. A very extensive road and rail network is exposed throughout the country, and many of the country's largest cities lie within 100 km.

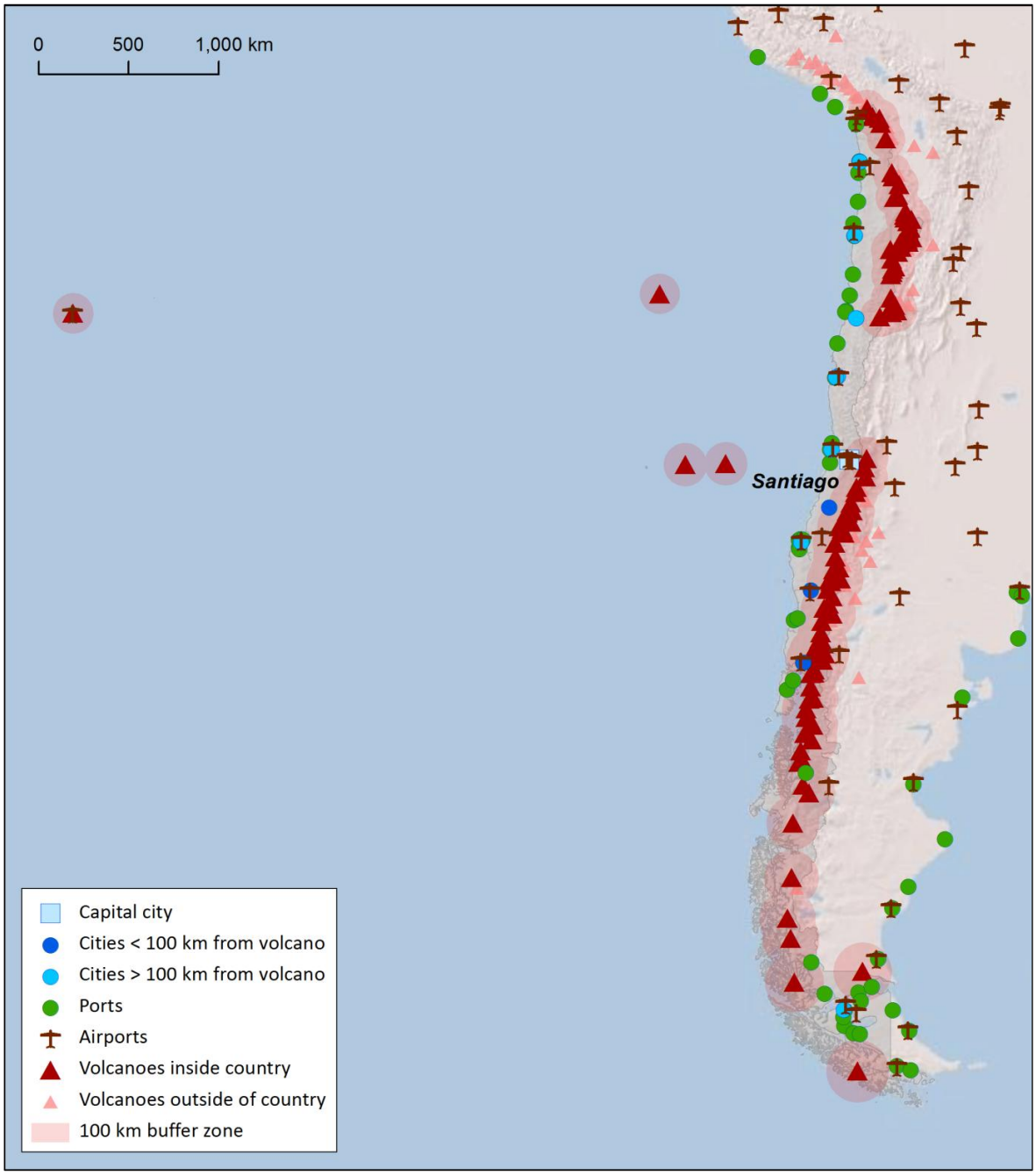

Figure 15.14 The location of Chile's volcanoes and the extent of the 100 km zone surrounding them. Ports, airports and the major cities are just some of the infrastructure that may be exposed to volcanic hazards.

Hazard, Uncertainty and Exposure Assessments

There are varying levels of information available in the eruption records of Chile's volcanoes. About 20% of the volcanoes here (20 out of 105) have sufficient detail to define the hazard through the calculation of the VHI. These are classified across all three hazard levels, with most being classed at Hazard Levels I and II. Four volcanoes are classed at Hazard Level III, all with Holocene records of eruptions of VEI 4 and 5 and all with records of explosive volcanism accompanied by the production of pyroclastic flows.

Of the unclassified volcanoes, 49 have no records of confirmed Holocene age eruptions. 36 volcanoes have a Holocene eruption record, of which 20 have erupted historically (post-1500 AD) including eruptions since 1900 AD at 11 volcanoes. Unrest is described at nine unclassified volcanoes since 1900 AD. Seven unclassified volcanoes have Holocene records of large explosive VEI ≥4 eruptions.

The PEI ranges from 1 to 4, low to moderate, in Chile, with an overwhelming majority at PEI 2. The classified volcanoes are therefore Risk Levels of I and II. Although the risk levels cannot be defined for the unclassified volcanoes due to the absence of hazard details, these would all also be clased at Risk Level I and II.

CLASSIFIED	**Hazard III**		Cerro Azul; Puyehue-Cordón Caulle; Osorno	Calbuco				
	Hazard II		Láscar; Planchón-Peteroa; Chillán, Nevados de; Antuco; Copahue; Lonquimay; Llaima	Villarrica				
	Hazard I		Guallatiri; Isluga; San Pedro; Huequi; Lautaro	Maipo	Tupungatito; San José			
UNCLASSIFIED	**U – HHR**	Robinson Crusoe	**Irruputuncu**; **Olca-Paruma**; Putana; Llullaillaco; **Tinguiririca**; **Descabezado Grande**; **Callaqui**; Quetrupillan; **Mocho-Choshuenco**; Puntiagudo-Cordón Cenizos; Minchinmávida; Mentolat; **Cerro Hudson**; **Arenales**; **Reclus**; **Monte Burney**; Fueguino	**Carrán-Los Venados**; **Chaitén**				
	U- HR		Taapaca; Parinacota; Socompa; **Nevados Ojos del Salado**; Longaví, Nevado de; Lanín; Antillanca Group; Cayutué-La Viguería; **Yanteles**; Corcovado; **Melimoyu**; Macá; Aguilera; Pali-Aike Volcanic Field	Sollipulli; Caburgua-Huelemolle				
	U-NHHR	San Félix; Unnamed	Tacora; **Ollagüe**; Azufre, Cerro del; Sairecabur; Licancabur; Guayaques; Purico Complex; Colachi; Acamarachi; Overo, Cerro; **Chiliques**; Cordón de Puntas Negras; Miñiques; Tujle, Cerro; Caichinque; Tilocalar; Negrillar, El; Pular; Negrillar, La; Escorial; **Lastarria**; Cordón del Azufre; Bayo Gorbea, Cerro; Nevada, Sierra; Falso Azufre; Incahuasi, Nevado de; Solo, El; Copiapó; Palomo; Calabozos; Maule, Laguna del; San Pedro-Pellado; Blancas, Lomas; Resago; Mariñaqui, Laguna; **Tolguaca**; Pantojo, Cerro; Tronador; **Cuernos del Diablo**; Yate; Hornopirén; Apagado; Palena Volcanic Group; Puyuhuapi; Cay; Río Murta	Easter Island				
		PEI 1	**PEI 2**	**PEI 3**	**PEI 4**	**PEI 5**	**PEI 6**	**PEI 7**

*Table 15.13 Identity of Chile's volcanoes in each Hazard-PEI group. Those volcanoes with a sufficient record for determining a hazard score are deemed 'Classified' (top). Those without sufficient data are 'Unclassified' (bottom). The unclassified volcanoes are divided into groups: U-NHHR is Unclassified No Historic or Holocene Record: that is there are no confirmed eruptions recorded in the Holocene. U-HR is Unclassified with Holocene Record: that is there are confirmed eruptions recorded during the Holocene, but no historical (post-1500) events. U-HHR is Unclassified with Historic and Holocene record. The unclassified volcanoes in **bold** have experienced unrest or eruptions since 1900 AD, and those in red have records of at least one Holocene VEI ≥4 eruption.*

Volcano	Population Exposure Index	Risk Level
Tupungatito	4	I
San José	4	I
Villarrica	3	II
Calbuco	3	II
Maipo	3	I
Azul, Cerro	2	II
Puyehue-Cordón Caulle	2	II
Osorno	2	II
Guallatiri	2	I
Isluga	2	I
San Pedro	2	I
Láscar	2	I
Planchón-Peteroa	2	I
Chillán, Nevados de	2	I
Antuco	2	I
Copahue	2	I
Lonquimay	2	I
Llaima	2	I
Huequi	2	I
Lautaro	2	I

Table 15.14 Classified volcanoes of Chile ordered by descending Population Exposure Index (PEI). Risk levels determined through the combination of the Hazard Level and PEI are given. Risk Level I – 15 volcanoes; Risk Level II – 5 volcanoes; Risk Level III – 0 volcanoes.

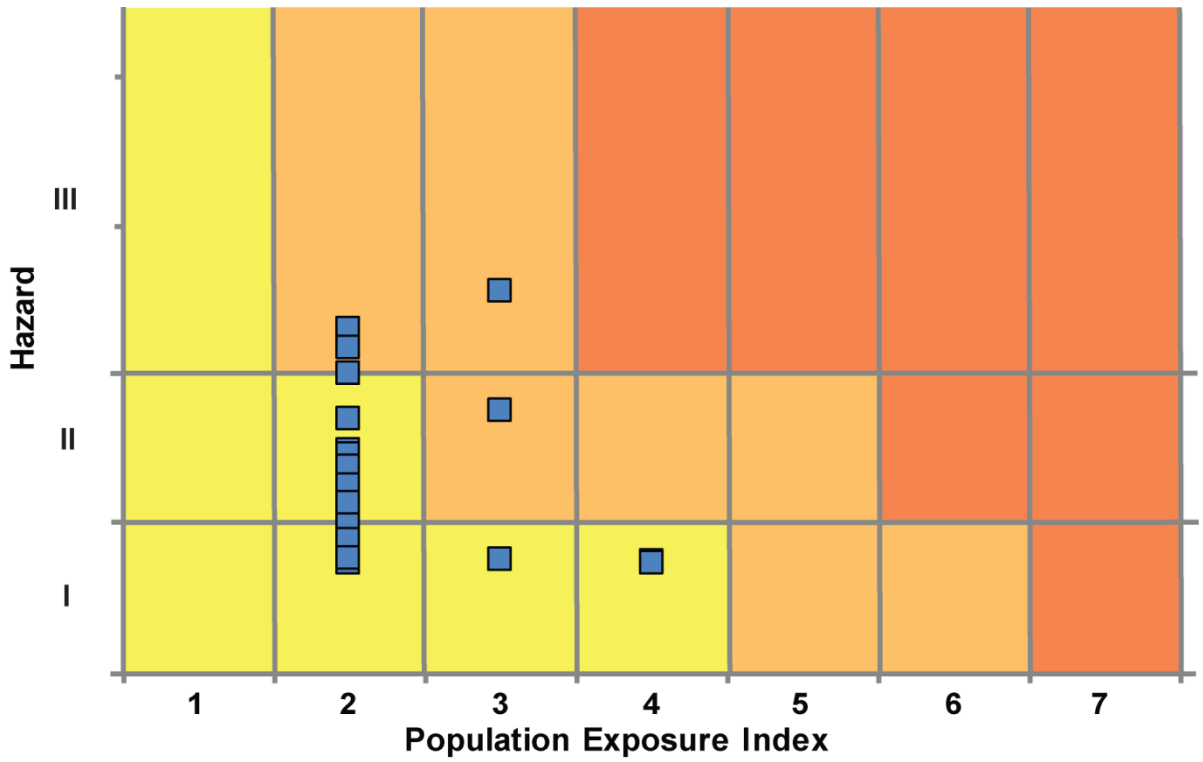

Figure 15.15 Distribution of Chile's classified volcanoes across Hazard and Population Exposure Index levels. The warming of the background colours illustrates increasing Risk levels from Risk Level I - III.

National Capacity for Coping with Volcanic Risk

Forty volcanoes have records of historical activity in Chile. These volcanoes are primarily classed at Risk Level I. All Risk Level II historical volcanoes are monitored by SERNAGEOMIN using seismic stations as a minimum. Many volcanoes also have deformation monitoring.

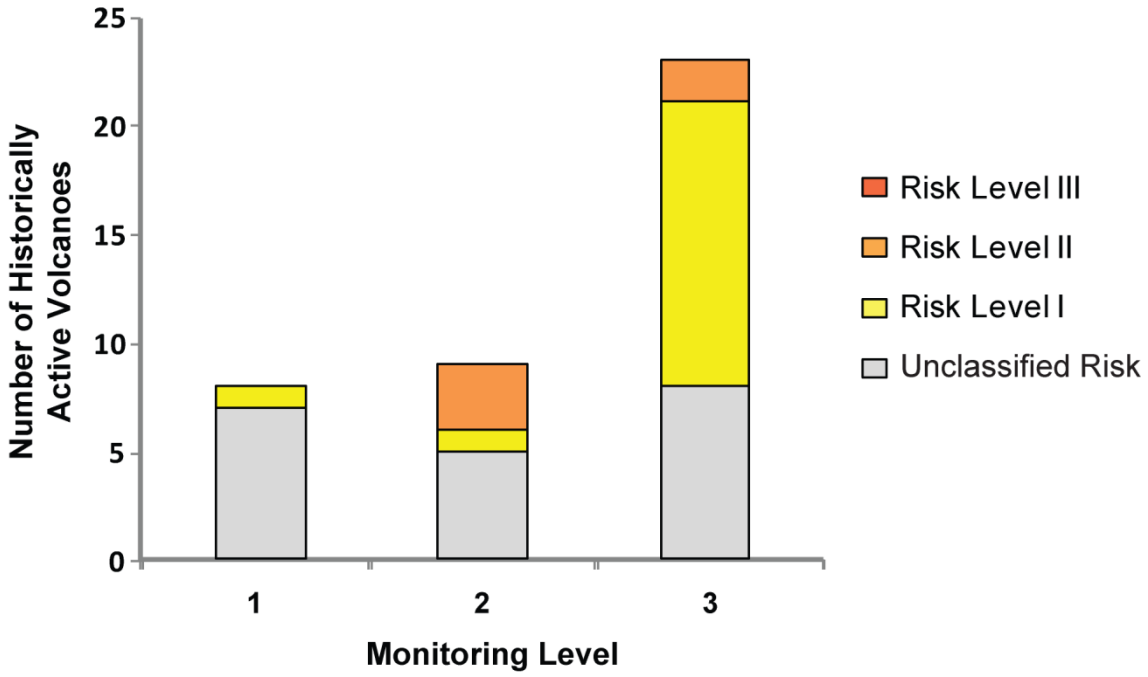

Figure 15.16 The monitoring and risk levels of the historically active volcanoes in Chile. Monitoring Level 1 indicates no known dedicated ground-based monitoring; Monitoring Level 2 indicates that some ground-based monitoring systems are in place including ≤3 seismic stations; Monitoring Level 3 indicates the presence of a dedicated ground-based monitoring network, including ≥4 seismometers.

Colombia

Description

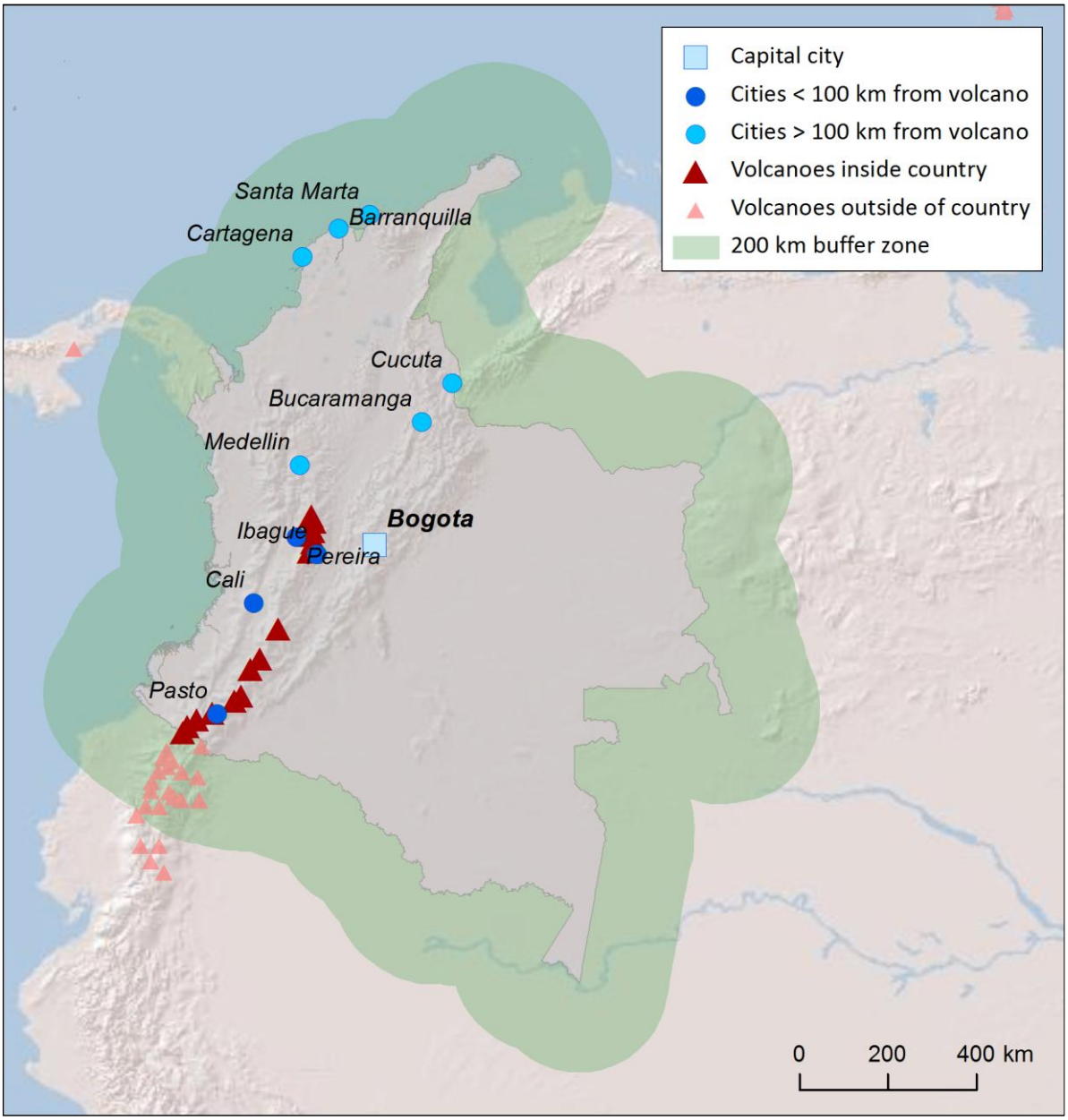

Figure 15.17 Location of Colombia's volcanoes, the capital and largest cities. A zone extending 200 km beyond the country's borders shows other volcanoes whose eruptions may directly affect Colombia.

Fifteen Holocene volcanoes are distributed through the northern Andes in western Colombia to the Ecuador border, paralleling the Pacific coastline. These volcanoes are related to the subduction of the Nazca Plate beneath the South American Plate.

All Holocene volcanoes in Colombia form edifices typically associated with explosive-type activity, including stratovolcanoes and complex volcanoes, with the exception of the Petacas lava dome and

Santa Isabel shield. The Colombian volcanoes are dominantly andesitic in composition. The explosive record continues into the Pleistocene, with three Colombian volcanoes hosting M/VEI ≥4 eruptions in this period.

There are 125 confirmed eruptions recorded in the Holocene, at VEI 1 to 5, indicating a range of activity from mild to strongly explosive. Eight volcanoes have a Holocene record of producing pyroclastic flows, and six are associated with lahars. Nine of the Colombian volcanoes have 79 eruptions recorded in historical times.

Many of Colombia's most populous cities are located on or towards the northern coast, away from volcanoes, however the cities of Cali, Ibague, Pasto and Pereira lie within 100 km of one or more Holocene volcanoes, with the latter three over-looked by Machin, Galeras and the Ruiz-Tolima chain. Numerous eruptions of Nevado del Ruiz, Nevado del Huila, Puracé and Galeras have resulted in evacuations and property damage. Fatalities are recorded in nine eruptions of these volcanoes and Doña Juana.

The assessment of hazard is complicated by sparse eruptive histories at over half of Colombia's volcanoes, resulting in hazard levels with large associated uncertainties hence just five volcanoes have a hazard level classified here. Nevado del Ruiz, Galeras and Cerro Bravo are classed with the highest hazard in Colombia based on detailed eruptive histories. Coupled with the high proximal population, these volcanoes are classed at Risk Level III.

Both Galeras and Nevado del Ruiz have caused loss of life. Machín has not caused any fatalities but has shown recent unrest, and its geological record indicates the potential for violent and destructive explosive eruptions. In 1993, a sudden intense but small magnitude explosive eruption of Galeras killed nine people, including six volcanologists who were in the inner crater or on its rim. A far larger disaster, the largest in South America's history, was the 1985 eruption of Nevado del Ruiz. Though only VEI 3, the eruption generated pyroclastic flows that melted the volcano's glacier cap and caused lahars. The mudflows descended the western flanks, flowing along the Río Lagunillas valley. The town of Armero, located on the banks of Río Lagunillas 48 km from the volcano, was completely buried. Though the death toll is uncertain, it is estimated that 21,000 of the 29,000 residents of Armero were killed, along with others elsewhere bringing the total loss of life to between 23,000 and 26,000.

Further eruptions with human impacts have occurred very recently at Galeras volcano. An eruption starting on 25th August 2010 spread ash as far as 30 km to the northwest; 7,000 people were advised to evacuate though few left their homes. Activity did not increase after this until January 2011.

Eruptions at a number of the northernmost volcanoes in Ecuador may directly affect Colombia as they lie within 100 km of the border. Similarly, Galeras, Cumbal and Azufral lie within 100 km of Ecuador.

Following the 1985 Nevado del Ruiz tragedy, the Colombian Government took steps to strengthen the monitoring and response mechanisms for Colombian volcanoes. These measures included making INGEOMINAS responsible for the monitoring of volcanoes and provision of scientific advice.

The Servicio Geologico Colombiano (INGEOMINAS) operate three volcano observatories in Colombia: Observatorio Pasto (responsible for Galeras, Cumbal, Chiles, Cerro Negro, Las Animas, Doña Juana and Azufral); Observatorio Manizales (responsible for Nevado del Ruiz, Cerro Machin, Cerro Bravo, Nevado Santa Isabel, and Nevado Tolima); and Observatorio Popayan (responsible for Nevado del Huila, Sotará and Puracé). INGEOMINAS operate a monitoring network at Colombia's active volcanoes and the status of the volcanoes is communicated publically and is available online.

See also:

INGEOMINAS - www.sgc.gov.co/

Volcano Facts

Number of Holocene volcanoes	15, inclusive of one on the border with Ecuador
Number of Pleistocene volcanoes with M≥4 eruptions	3
Number of volcanoes generating pyroclastic flows	8
Number of volcanoes generating lahars	6
Number of volcanoes generating lava flows	3
Number of fatalities caused by volcanic eruptions	?25,567
Tectonic setting	Subduction zone
Largest recorded Pleistocene eruption	The El Boqueron Ancestral caldera collapse eruption of 580 ka at Nevado del Tolima and the 560 ka Coba Negra caldera forming eruption of Galeras are both recorded at M6.2.
Largest recorded Holocene eruption	The M5.5 R8 eruption of Nevado del Ruiz at 2.8 ka.
Number of Holocene eruptions	125 confirmed eruptions. 10 uncertain eruptions.
Recorded Holocene VEI range	1 – 5 and unknown
Number of historically active volcanoes	9
Number of historic eruptions	79

Number of volcanoes	Primary volcano type	Dominant rock type
13	Large cone(s)	Andesitic (9), Dacitic (4)
1	Lava dome(s)	Unknown (1)
1	Shield(s)	Andesitic (1)

Table 15.15 The number of volcanoes in Colombia, their volcano type classification and dominant rock type according to VOTW4.0.

Socio-Economic Facts

Total population (2012)	47,783,000
Gross Domestic Product (GDP) per capita (2005 PPP $)	8,861
Gross National Income (GNI) per capita (2005 PPP $)	8,711
Human Development Index (HDI) (2012)	0.719 (High)

Population Exposure

Capital city	Bogatá
Distance from capital city to nearest Holocene volcano	138.6 km
Total population (2011)	44,725,543
Number (percentage) of people living within 10 km of a Holocene volcano	451,010 (1%)
Number (percentage) of people living within 30 km of a Holocene volcano	3,236,251 (7.2%)
Number (percentage) of people living within 100 km of a Holocene volcano	13,408,843 (30%)

Ten largest cities, as measured by population and their population size:

Bogota	7,102,602
Cali	2,392,877
Medellin	1,999,979
Barranquilla	1,380,425
Cartagena	952,024
Cucuta	721,398
Bucaramanga	571,820
Pereira	440,118
Santa Marta	431,781
Ibague	421,685

Infrastructure Exposure

Number of airports within 100 km of a volcano	2
Number of ports within 100 km of a volcano	0
Total length of roads within 100 km of a volcano (km)	3,159
Total length of railroads within 100 km of a volcano (km)	420

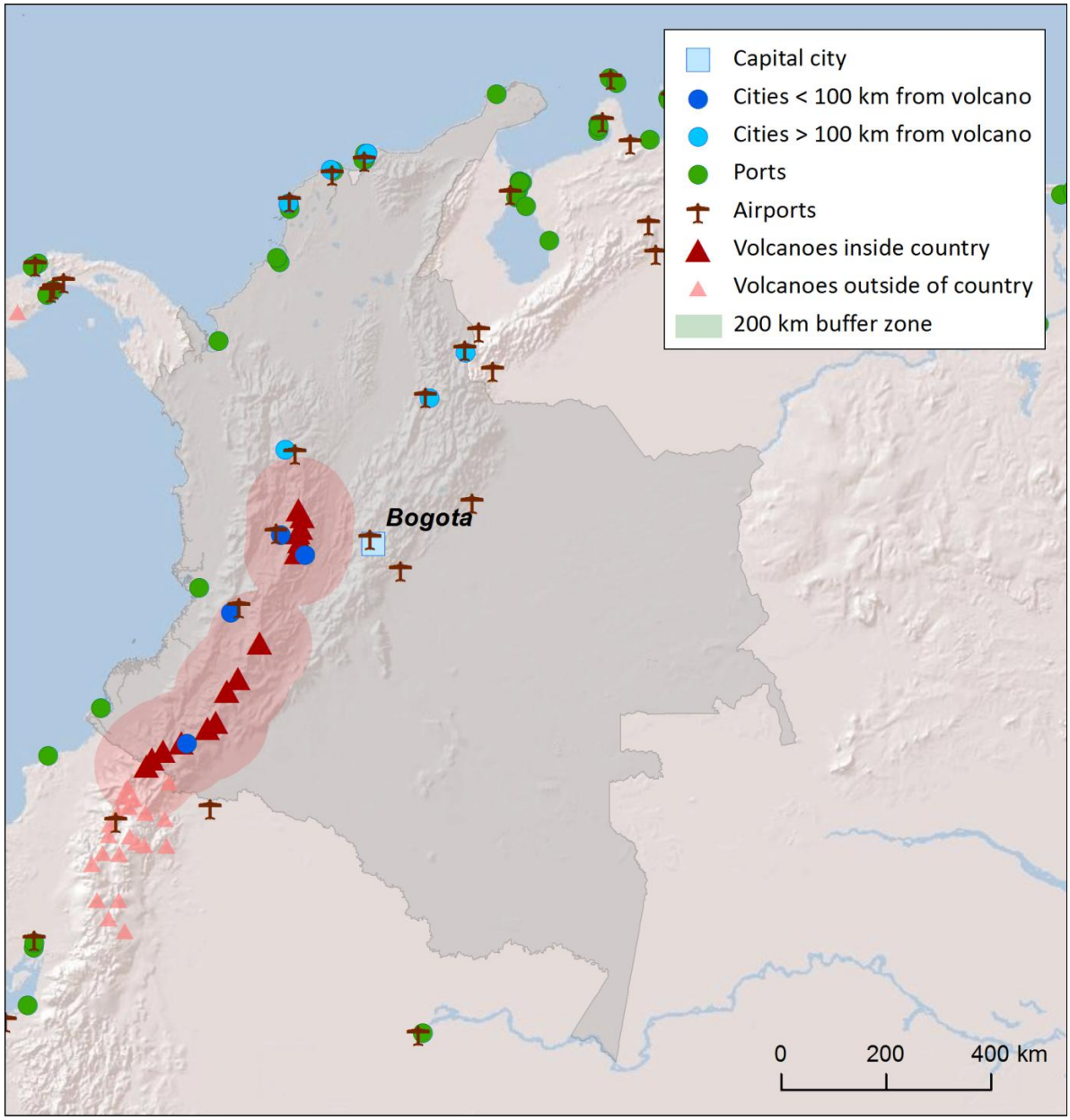

Figure 15.18 The location of Colombia's volcanoes and the extent of the 100 km zone surrounding them. Ports, airports and the major cities are just some of the infrastructure that may be exposed to volcanic hazards.

The volcanoes in Colombia are located in the west of the country from the border with Ecuador to just north of the capital, Bogata. The southernmost volcanoes, Galeras, Cumbal and Azufral lie close to the Ecuador border, and their 100 km radii extend into Ecuador, exposing infrastructure here.

Similarly, six of the northernmost of Ecuador's volcanoes have 100 km radii which extend into Colombia. Four of the largest cities in Colombia are situated within 100 km of Holocene volcanoes, including Pasto, Cali, Ibague and Pereira, exposing much of the critical infrastructure here. The capital, Bogata, lies within 140 km of several Holocene volcanoes, including the historically active Nevado del Ruiz and Nevado del Tolima.

Hazard, Uncertainty and Exposure Assessments

The volcanoes in Colombia are classed at Hazard Levels I to III. Ten of the 15 Colombian volcanoes have insufficient data available in their eruption records to adequately calculate a hazard score without very large uncertainties. The highest hazard levels are found at Nevado del Ruiz, Galeras and Cerro Bravo.

Of the unclassified volcanoes, three, Azufral, Machín and Sotará have had recorded periods of unrest above background levels since 1900. Both Azufral and Machín have Holocene eruption records but no historical eruptions. Four Colombian volcanoes: Nevado del Huila, Doña Juana, Cumbal and Cerro Negro de Mayasquer are unclassified, but have historical records of activity including post-1900 eruptions.

CLASSIFIED	**Hazard III**				Cerro Bravo	Nevado del Ruiz	Galeras	
	Hazard II				Nevado del Tolima			
	Hazard I				Puracé			
UNCLASSIFIED	**U – HHR**				Nevado del Huila, Doña Juana, Cumbal, Cerro Negro de Mayasquer			
	U- HR				Romeral	Santa Isabel, **Machín,** **Azufral**		
	U- NHHR			Petacas	**Sotará**			
		PEI 1	**PEI 2**	**PEI 3**	**PEI 4**	**PEI 5**	**PEI 6**	**PEI 7**

*Table 15.16 Identity of Colombia's volcanoes in each Hazard-PEI group. Those volcanoes with a sufficient record for determining a hazard score are deemed 'Classified' (top). Those without sufficient data are 'Unclassified' (bottom). The unclassified volcanoes are divided into groups: U-NHHR is Unclassified No Historic or Holocene Record: that is there are no confirmed eruptions recorded in the Holocene. U-HR is Unclassified with Holocene Record: that is there are confirmed eruptions recorded during the Holocene, but no historical (post-1500) events. U-HHR is Unclassified with Historic and Holocene record. The unclassified volcanoes in **bold** have experienced unrest or eruptions since 1900 AD, and those in red have records of at least one Holocene VEI ≥4 eruption.*

Volcano	Population Exposure Index	Risk Level
Galeras	6	III
Ruiz, Nevado del	5	III
Bravo, Cerro	4	III
Tolima, Nevado del	4	II
Puracé	4	I

Table 15.17 Classified volcanoes of Colombia ordered by descending Population Exposure Index (PEI). Risk levels determined through the combination of the Hazard Level and PEI are given. Risk Level I – 1 volcano; Risk Level II – 1 volcano; Risk Level III – 3 volcanoes.

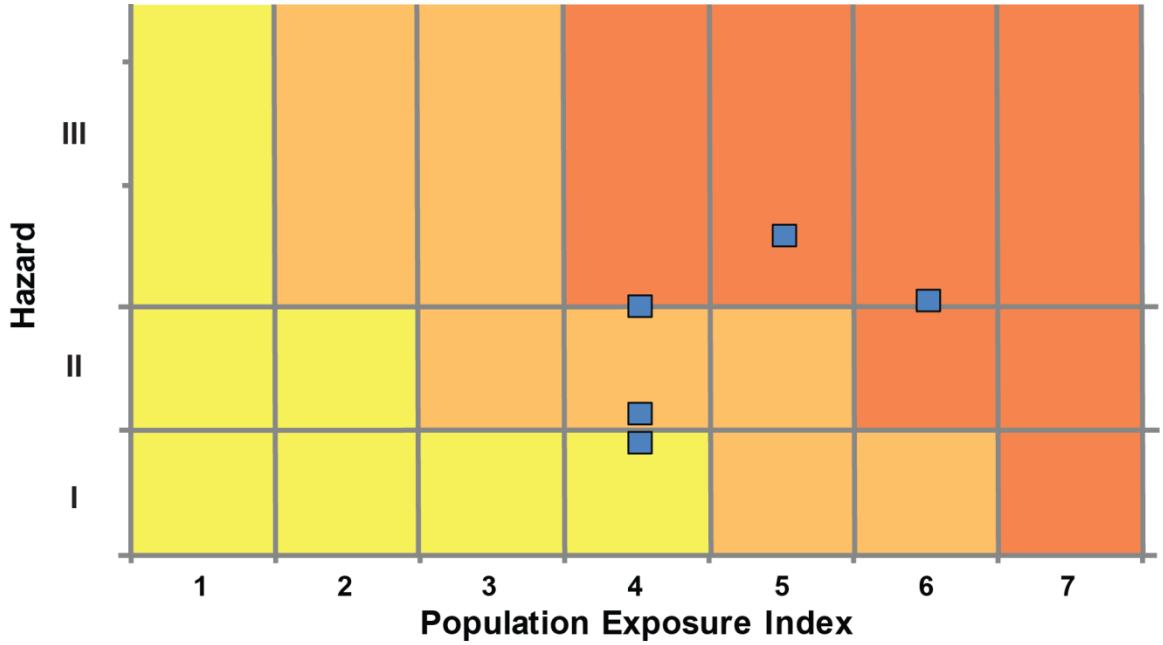

Figure 15.19 Distribution of Colombia's classified volcanoes across Hazard and Population Exposure Index levels. The warming of the background colours illustrates increasing Risk levels from Risk Level I - III.

All Colombian volcanoes have moderate to high PEI levels at PEI 3 to 6. The highest PEI is found at Galeras, which has over 120,000 living just within 10 km. Combined with a Hazard Level of III, Galeras is classed as a Risk Level III volcano. Of the classified volcanoes, just one volcano, Puracé is deemed Risk Level I, whilst one, Nevado del Tolima, is classed at Risk Level II.

National Capacity for Coping with Volcanic Risk

Nine volcanoes in Colombia have recorded historical activity. Of these, all have dedicated ground-based monitoring systems operated by INGEOMINAS. Seven volcanoes are classed here at Monitoring Level 3, with seismic networks in operation and additional deformation and or gas monitoring. The three volcanoes with the highest risk classification here are continuously monitored at this level.

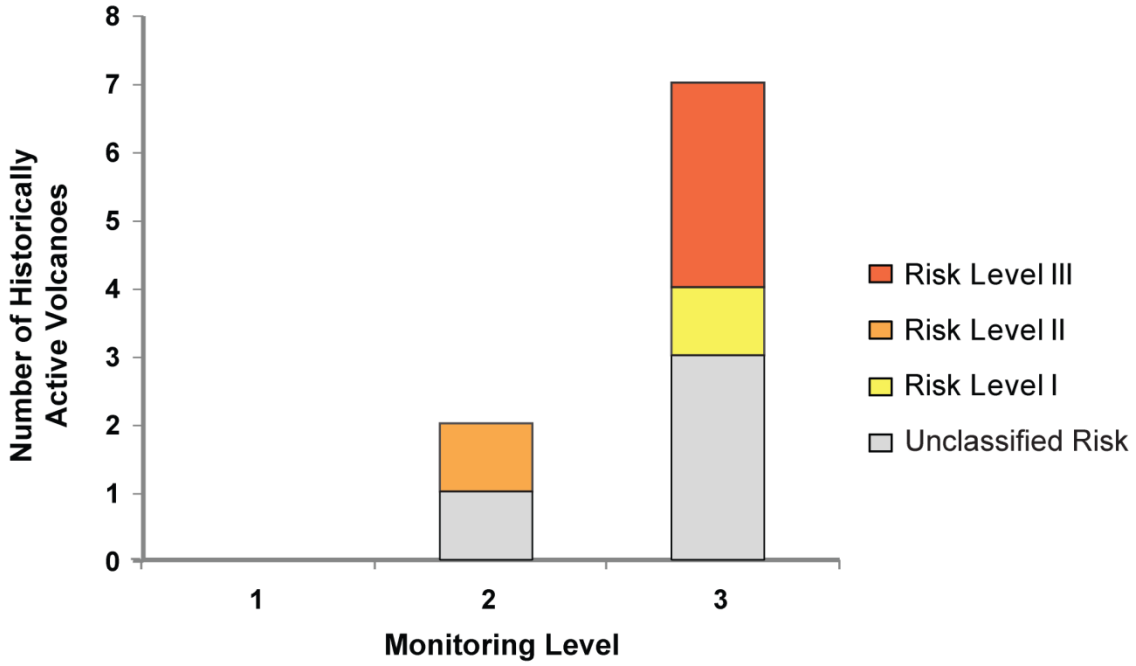

Figure 15.20 The monitoring and risk levels of the historically active volcanoes in Colombia. Monitoring Level 1 indicates no known dedicated ground-based monitoring; Monitoring Level 2 indicates that some ground-based monitoring systems are in place including ≤3 seismic stations; Monitoring Level 3 indicates the presence of a dedicated ground-based monitoring network, including ≥4 seismometers.

Ecuador and the Galapagos

Description

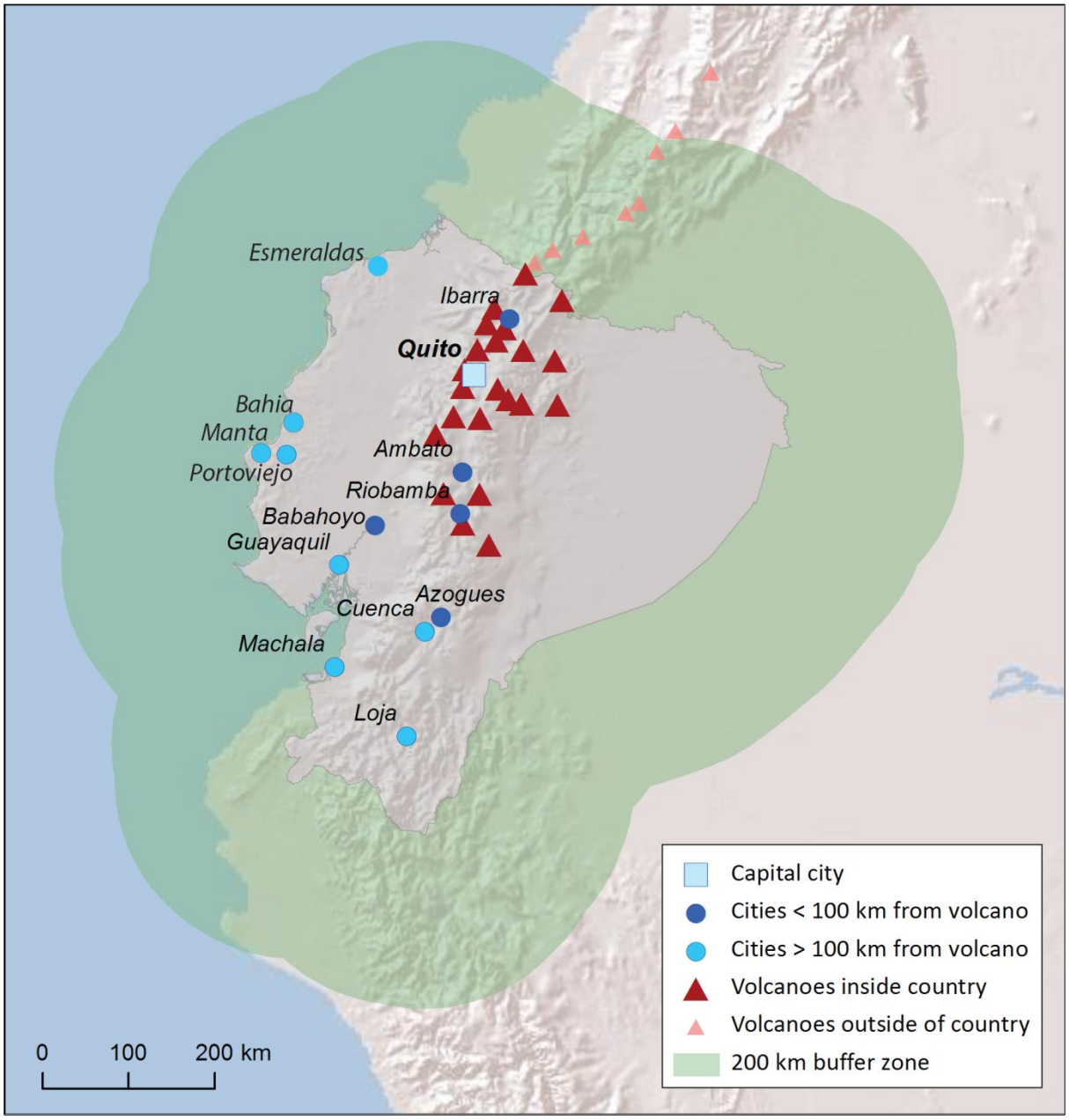

Figure 15.21 Location of Ecuador's volcanoes, the capital and largest cities. A zone extending 200 km beyond the country's borders shows other volcanoes whose eruptions may directly affect Ecuador.

Thirty-five volcanoes of Holocene age are identified in Ecuador. This includes volcanoes on mainland Ecuador and in the Galapagos Islands, nearly 1000 km to the west. Volcanism in mainland Ecuador is related to the subduction of the Nazca Plate beneath the South American Plate, whilst Galapagos volcanism is due to intra-plate hotspot volcanism and the Galapagos spreading centre. Volcanoes of the Galapagos are predominantly basaltic shields, while in mainland Ecuador the composition is more felsic and andesitic stratovolcanoes are most common.

Twenty-eight of the volcanoes have 311 confirmed Holocene eruptions, the remaining volcanoes have suspected Holocene activity. With records of activity ranging in size from VEI 0 to 6, a range of activity styles is indicated, from mild effusions of lavas to large explosive events. The largest Holocene eruption on record is the ~1280 AD eruption of Quilotoa at VEI 6 / M6.4. This event generated extensive pyroclastic flows, ash fall and lahars. A larger eruption (M6.9) is recorded in the Pleistocene at 211 ka, with the Ash Flow of the Chalupas Caldera. Numerous Pleistocene eruptions of VEI/M ≥4 are recorded in Ecuador, and 43 large explosive eruptions of this size are recorded in the Holocene.

Since 1500 AD, 197 eruptions are recorded at nineteen volcanoes. Of these, 11 were VEI 4 indicating that large explosive eruptions are relatively frequent in Ecuador. The dominantly andesitic composition and stratovolcano morphology indicates typical explosive activity. The altitude of the volcanoes in Ecuador means that many of the volcanoes are capped with snow or glaciers. This increases the propensity to cause hazardous lahars as even small eruptions can result in the melting of ice caps. Indeed eight volcanoes in Ecuador have a Holocene record of lahar triggering.

The most frequently active volcanoes here are Cotopaxi, Reventador and Tungurahua, while Sangay is continuously active since 1628, but poses little threat since it is isolated from population centres.

The Galapagos Island volcanoes are exclusively shield volcanoes. With a small population of just over 20,000, the main hazard they pose is largely environmental, but also to wildlife, such as slow moving giant tortoises, as a result of lava flows and ash fall. One exception to this is Fernandina, which has erupted explosively on numerous occasions producing pyroclastic flows and debris avalanches. No fatalities are recorded as a result of eruptions of Fernandina.

Much of central and northern mainland Ecuador lies within 100 km of one or more Holocene volcanoes, and six of the most populous cities in the country fall in this zone. The capital, Quito, lies within 100 km of many volcanoes, and within about 12 km of the historically active Guagua Pichincha. This volcano had a VEI 4 eruption in 1660 resulting in extensive ash fall and ash accumulation in the capital. Pyroclastic flows and surges were channelled mainly to the west as the caldera is breached in this direction. This breach will still likely act to channel flows to the west, however surges in particular are not always constrained by topography and can reach small communities such as Lloa, but have never jumped the topographic barrier into the Quito basin.

The presence of many cities within 100 km of the Holocene volcanoes exposes a large proportion of the population to direct volcanic hazards, with 50% of Ecuador's population residing within 100 km of one or more Holocene volcano.

The assessment of hazard at many of Ecuador's volcanoes is complicated by incomplete or sparse eruption records and publication of this information in "grey literature" that is difficult to access, hence the assignment of hazard levels is associated with large degrees of uncertainty.

Fatalities have resulted from eruptions of Reventador, Guagua Pichincha, Cotopaxi, Tungurahua, Sangay and Cerro Azul. Greatest loss of life as a result of volcanism in Ecuadorian territories occurred in 1640, following an eruption of Tungurahua. Though some uncertainty surrounds the eruption record, it is believed an approximately VEI 3 eruption caused pyroclastic flows and a small sector collapse that destroyed a village and its 5,000 inhabitants. Eruptions of Cotopaxi in 1742, 1768, and

1877 have also significantly added to the death toll from volcanoes in Ecuador, with roughly 1,200 deaths as a result of lahars attributable to these three eruption periods.

The Instituto Geofisico of the Escuela Politécnica Nacional (IGEPN) is responsible for the study, monitoring and hazard assessment of Ecuador's volcanoes. Sixteen volcanoes are monitored with at least one broadband seismic instrument and one or more continuously operating GPS staton. Tungurahua, Cotopaxi, Guagua Pichincha, Reventador, Cuicocha and Antisana volcanoes are monitored with a broad suite of geophysical instruments and because of the completeness of their real-time networks are considered to b in an "A" category. Ten other volcanoes: Atacazo, Pululagua, Imbabura, Chachimburo, Cerro Negro, Cayambe, Soche, Sangay, Chimborazo and Quilotoa all have at least one or more broadband seismic and deformation-detecting stations. The IGEPN provides advice and information regarding volcanic activity and presents this information online, accessible to the public. Reports are regularly issued summarising volcanic activity and early warnings before a notable increase in eruptive activity is given on this web, via calls, over local radio stations and through social media. Close collaborations exist with the Secretariat for Risk Management. Before and during volcanic crises IGEPN scientists communicate and provide hazard assessments to local, regional and national authorities. At Tungurahua volcano, which has been erupting since 1999, a volunteer volcano observers group (Vigias) has been very successful in providing in situ observations of eruptive activity, via a radio system to the local observatory IGEPN scientists.

From here we provide the information for mainland Ecuador and the Galapagos Islands separately.

See also:

Servicio Nacional de Sismologia y Vulcanologia: www.igepn.edu.ec/

Mainland Ecuador

Volcano Facts

Number of Holocene volcanoes	22, inclusive of one on the border with Colombia
Number of Pleistocene volcanoes with M≥4 eruptions	7
Number of volcanoes generating pyroclastic flows	14
Number of volcanoes generating lahars	8
Number of volcanoes generating lava flows	7
Number of fatalities caused by volcanic eruptions	?5,690
Tectonic setting	22 Subduction zone
Largest recorded Pleistocene eruption	The M6.9 Chalupas Ash Flow eruption of Chalupas at 211 ka.
Largest recorded Holocene eruption	The M6.4 eruption of Quilotoa about 700 years ago.
Number of Holocene eruptions	229 confirmed eruptions
Recorded Holocene VEI range	0 – 6 and unknown
Number of historically active volcanoes	10 according to VOTW4.22 (Cotopaxi, Reventador, Tungurahua, Guagua Pichincha, Cayambe, Sangay, Chacana, Antisana, Sumaco and Cerro Negro de Mayasquer). Activity at the latter three volcanoes is ambiguous.
Number of historic eruptions	131

Number of volcanoes	Primary volcano type	Dominant rock type
4	Caldera(s)	Dacitic (3), Rhyolitic (1)
17	Large cone(s)	Andesitic (13), Basaltic (1), Dacitic (3)
1	Small cone(s)	Andesitic (1)

Table 15.18 The number of volcanoes in Ecuador, their volcano type classification and dominant rock type according to VOTW4.0.

Socio-Economic Facts

Total population (2012)	15,520,000
Gross Domestic Product (GDP) per capita (2005 PPP $)	7,443
Gross National Income (GNI) per capita (2005 PPP $)	7,471
Human Development Index (HDI) (2012)	0.724 (High)

Population Exposure

Capital city	Quito
Distance from capital city to nearest Holocene volcano	12.2 km
Total population (2011)	15,007,343
Number (percentage) of people living within 10 km of a Holocene volcano	750,552 (5%)
Number (percentage) of people living within 30 km of a Holocene volcano	4,352,168 (29%)
Number (percentage) of people living within 100 km of a Holocene volcano	7,393,692 (49.3%)

Ten largest cities, as measured by population and their population size (2010, from UN data, data.un.org):

Guayaquil	2,278,691
Quito	1,607,734
Cuenca	329,928
Machala	231,260
Manta	217,553
Portoviejo	206,682
Loja	170,280
Ambato	165,185
Esmeraldas	154,035
Riobamba	146,324

Infrastructure Exposure

Number of airports within 100 km of a volcano	6 (Tulcan, Quito, Lago Agrio, Latacunga, Macas, Tena)
Number of ports within 100 km of a volcano	0
Total length of roads within 100 km of a volcano (km)	3,727
Total length of railroads within 100 km of a volcano (km)	0

In mainland Ecuador the 100 km radii of the volcanoes covers much of central and northern parts of the country, and the radii of six of the northernmost volcanoes extend into Colombia. Similarly, the three southernmost volcanoes of Colombia have 100 km radii which extend into Ecuador. Six of the largest cities in Ecuador are situated within 100 km of Holocene volcanoes, including the capital, Quito, hence much of the critical infrastructure of the country is exposed, including three airports and an extensive road network. Critical infrastructure such as two trans-Andean oil pipelines, four major hydroelectric installations, Quito's water supply from Antisana and Chacana volcanoes, as well as critical bridges are also exposed.

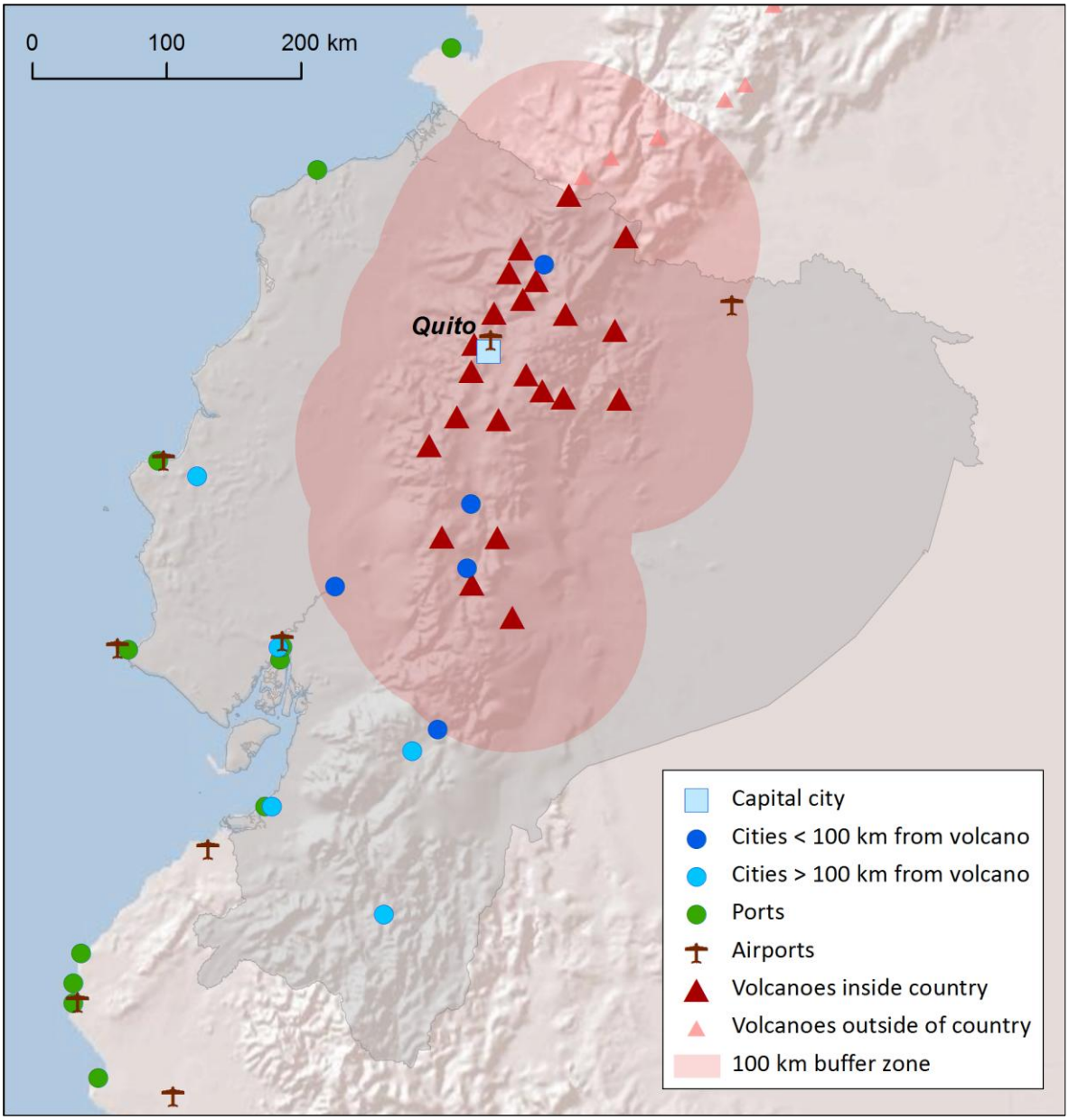

Figure 15.22 The location of Ecuador's volcanoes and the extent of the 100 km zone surrounding them. Ports, airports and the major cities are just some of the infrastructure that may be exposed to volcanic hazards.

Hazard, Uncertainty and Exposure Assessments

There are varying levels of information available in the eruption records of mainland Ecuador's volcanoes. Seven volcanoes out of 23 have sufficient detail to define the hazard through the calculation of the VHI. All of these are classified at Hazard Level III, with Holocene records of VEI ≥3 eruptions and records of explosive eruptions with the production of pyroclastic flows.

Of the unclassified volcanoes, three have no confirmed Holocene eruptions on record. The remaining 12 volcanoes have a Holocene eruptive record, with historical events at four volcanoes including post-1900 AD eruptions at Cerro Negro de Mayasquer. Four unclassified volcanoes have a Holocene record of large VEI ≥4 eruptions.

The size of the proximal populations at Ecuador's volcanoes ranges from small to large, generating PEIs of 1 to 7. Moderate and high PEIs dominate. This range results in a range of risk levels when combined with the Hazard Levels, from II to III at the classified volcanoes. Although here we consider threat to life measured by population exposure, infrastructure exposure such as the water supply to Quito is also vital. This, for example, is supplied from the PEI4 Antisana volcano, which if it were to erupt would have grave consequences for Quito's water supply.

CLASSIFIED	**Hazard III**			Reventador; Sangay	Cayambe; Cotopaxi; Tungurahua	Guagua Pichincha	Atacazo	
	Hazard II							
	Hazard I							
UNCLASSIFIED	**U – HHR**		Sumaco		**Cerro Negro de Mayasquer;** Antisana	Chacana		
	U- HR	Aliso		Soche	Chachimbiro; Chimborazo	Quilotoa	Cuicocha; **Imbabura**	Pululagua
	U- NHHR				Illiniza	Mojanda	Licto	
		PEI 1	**PEI 2**	**PEI 3**	**PEI 4**	**PEI 5**	**PEI 6**	**PEI 7**

*Table 15.19 Identity of Mainland Ecuador's volcanoes in each Hazard-PEI group. Those volcanoes with a sufficient record for determining a hazard score are deemed 'Classified' (top). Those without sufficient data are 'Unclassified' (bottom). The unclassified volcanoes are divided into groups: U-NHHR is Unclassified No Historic or Holocene Record: that is there are no confirmed eruptions recorded in the Holocene. U-HR is Unclassified with Holocene Record: that is there are confirmed eruptions recorded during the Holocene, but no historical (post-1500) events. U-HHR is Unclassified with Historic and Holocene record. The unclassified volcanoes in **bold** have experienced unrest or eruptions since 1900 AD, and those in red have records of at least one Holocene VEI ≥4 eruption.*

Volcano	Population Exposure Index	Risk Level

Atacazo	6	III
Guagua Pichincha	5	III
Tungurahua	4	III
Cotopaxi	4	III
Cayambe	4	III
Reventador	3	II
Sangay	3	II

Table 15.20 Classified volcanoes of Mainland Ecuador ordered by descending Population Exposure Index (PEI). Risk levels determined through the combination of the Hazard Level and PEI are given. Risk Level I – 0 volcanoes; Risk Level II – 2 volcanoes; Risk Level III – 5 volcanoes.

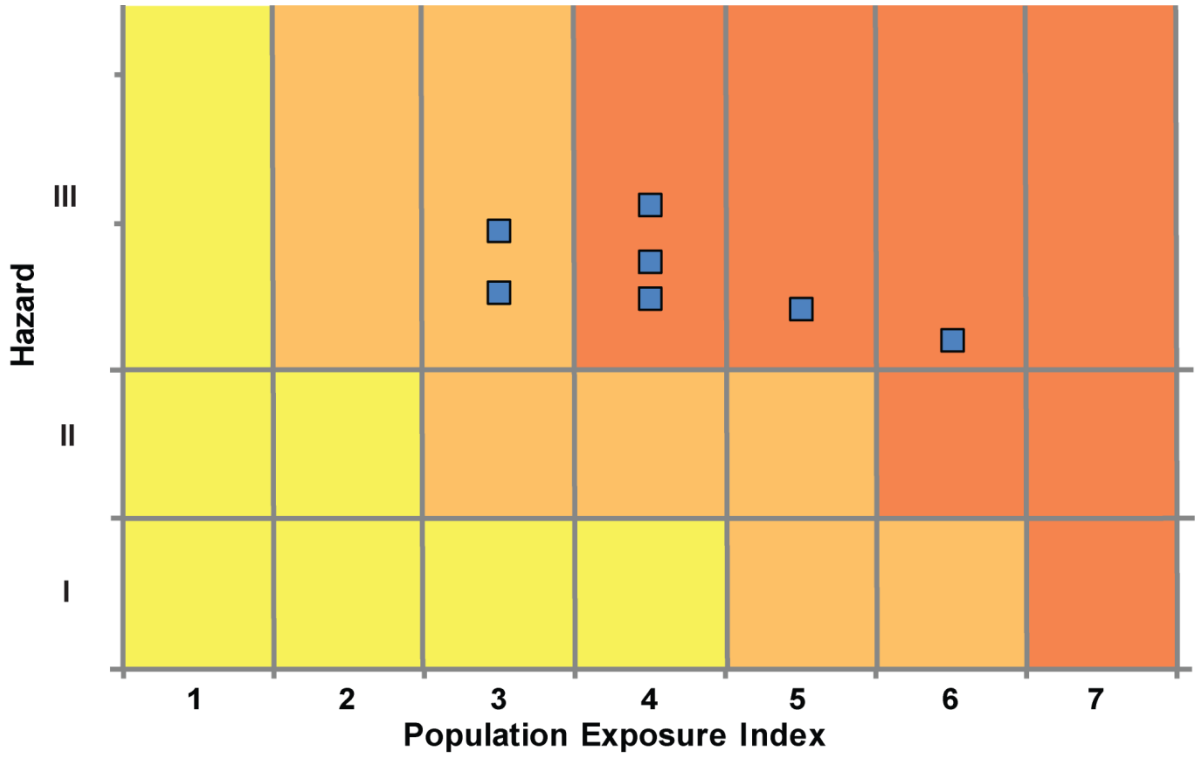

Figure 15.23 Distribution of mainland Ecuador's classified volcanoes across Hazard and Population Exposure Index levels. The warming of the background colours illustrates increasing Risk levels from Risk Level I - III.

National Capacity for Coping with Volcanic Risk

Ten volcanoes in mainland Ecuador have recorded historical activity. These volcanoes are distributed across all three monitoring levels with half of the volcanoes being classed at Monitoring Level 3. All Risk Level III volcanoes are monitored at Level 3, with the exception of Cayambe which also has both seismic and deformation monitoring. The Risk Level III volcanoes, Tungurahua, Guagua Pichincha and Cotopaxi all have multiple monitoring systems in place inclduing continuous seismic and deformation monitoring.

Monitoring is undertaken by the Instituto Geofisico EPN. Note that this institute also uses Monitoring Levels 1 - 3 to describe levels of monitoring at Ecuador's volcanoes, but these are different levels to those used here.

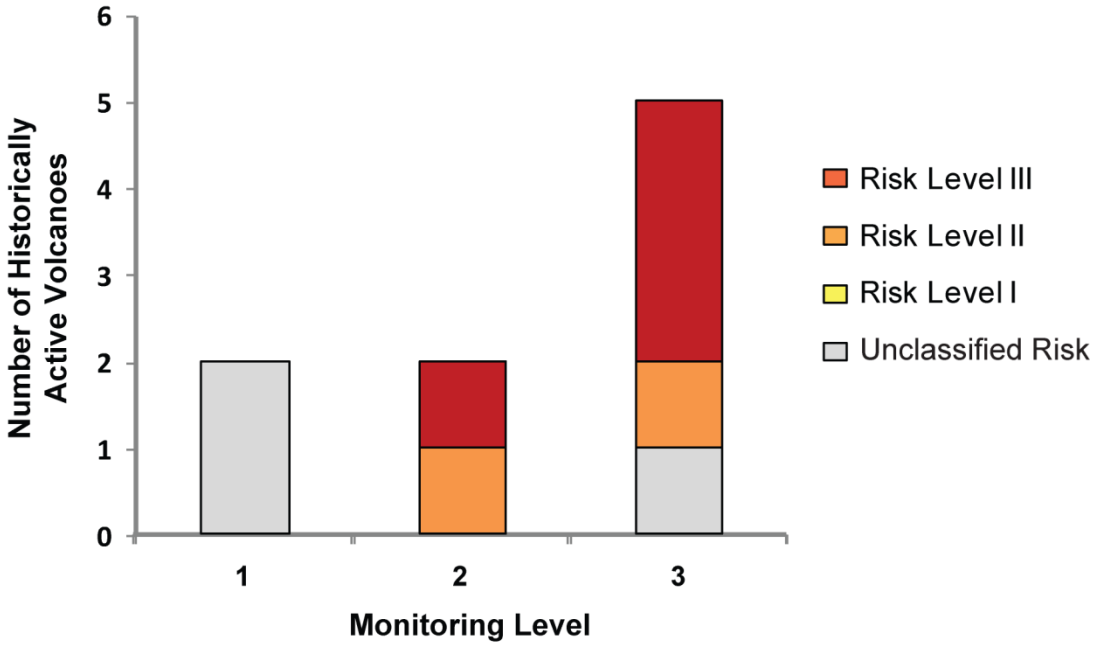

Figure 15.24 The monitoring and risk levels of the historically active volcanoes in mainland Ecuador. Monitoring Level 1 indicates no known dedicated ground-based monitoring; Monitoring Level 2 indicates that some ground-based monitoring systems are in place including ≤3 seismic stations; Monitoring Level 3 indicates the presence of a dedicated ground-based monitoring network, including ≥4 seismometers.

Galapagos Islands

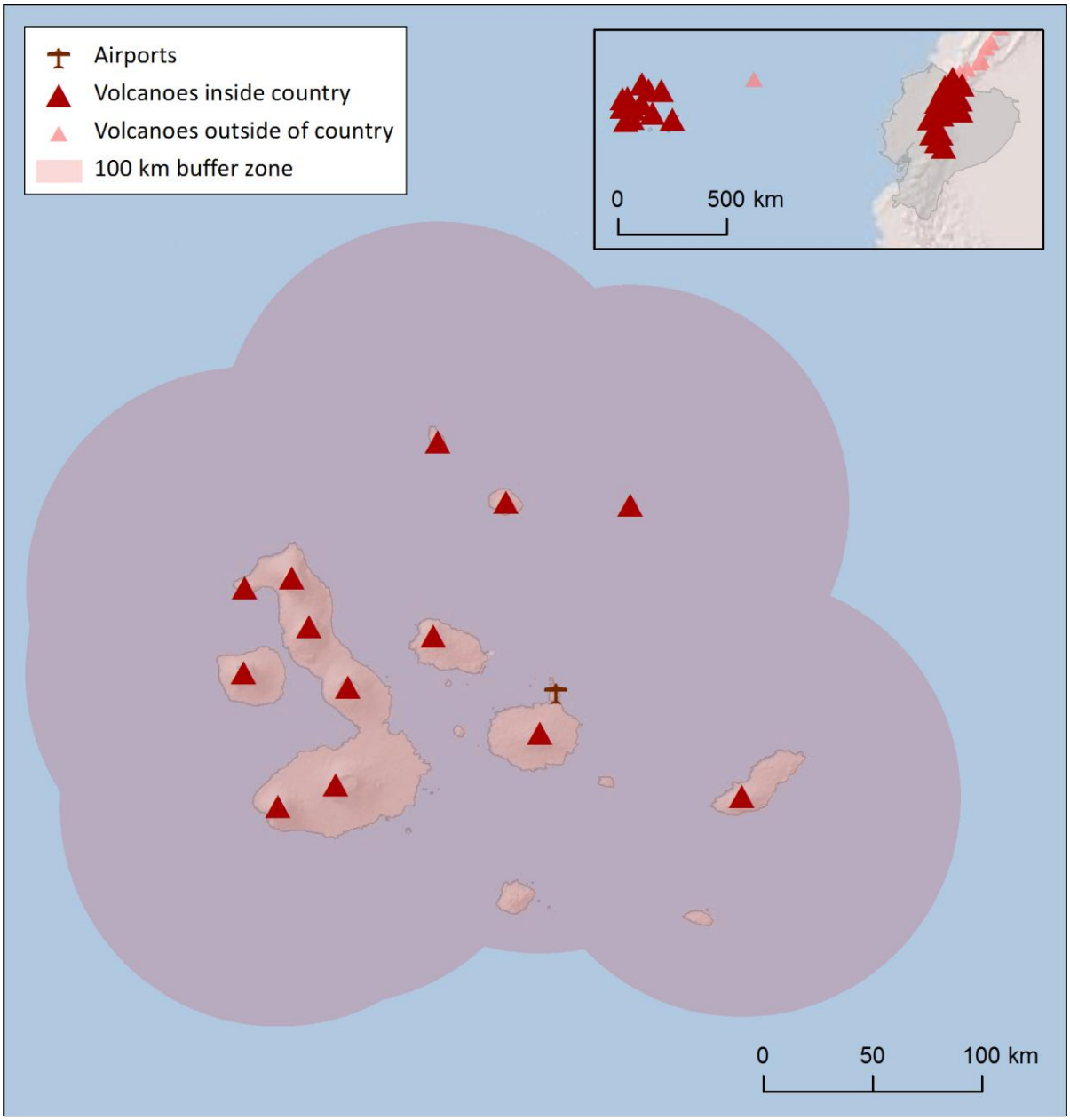

Figure 15.25 The volcanoes of the Galapagos Islands. Inset shows the location relative to mainland Ecuador.

Volcano Facts

Number of Holocene volcanoes	13
Number of Pleistocene volcanoes with M≥4 eruptions	1
Number of volcanoes generating pyroclastic flows	1
Number of volcanoes generating lahars	-
Number of volcanoes generating lava flows	9

Number of fatalities caused by volcanic eruptions	?1
Tectonic setting	13 Rift zone
Largest recorded Pleistocene eruption	The M5.2/VEI 5 Alcedo-A,B Tephra eruption of about 90,000 years ago.
Largest recorded Holocene eruption	The VEI 4 eruption of Fernandina in 1968.
Number of Holocene eruptions	82 confirmed eruptions
Recorded Holocene VEI range	0 – 4 and unknown
Number of historically active volcanoes	9
Number of historic eruptions	66

Number of volcanoes	Primary volcano type	Dominant rock type
13	Shield(s)	Basaltic (13)

Table 15.21 The number of volcanoes in Ecuador, their volcano type classification and dominant rock type according to VOTW4.0.

Population Exposure

Capital city	Puerto Baquerizo Moreno
Distance from capital city to nearest Holocene volcano	12.3 km
Total population (2010, www.inec.gob.ec/estadisticas/)	25,124
Percentage of people living within 100 km of a Holocene volcano	100%

Infrastructure Exposure

Number of airports within 100 km of a volcano	2
Number of ports within 100 km of a volcano	-
Total length of roads within 100 km of a volcano (km)	-
Total length of railroads within 100 km of a volcano (km)	0

In the Galapagos Islands, the 100 km radii extend to fully encompass the island group, exposing all infrastructure here.

Hazard, Uncertainty and Exposure Assessments

Of the thirteen volcanoes in the Galapagos Islands, just four have a sufficiently detailed eruption record to determine hazard levels through the calculation of the VHI. These are classified at Hazard Levels I and II.

Of the unclassified volcanoes, three have no confirmed Holocene eruptions on record. Six have a record of Holocene eruptions, including historical age events and post-1900 AD eruptions.

The size of the proximal populations at the volcanoes of the Galapagos is typically small, generating PEIs of 2 to 3. All classified volcanoes here are classed at Risk Level I.

CLASSIFIED	**Hazard III**							
	Hazard II		Fernandina					
	Hazard I		Wolf; Negra, Sierra; Azul, Cerro					
UNCLASSIFIED	**U – HHR**		Darwin; **Alcedo**; **Pinta; Marchena; Santiago**					
	U- HR		Ecuador					
	U-NHHR		Genovesa	Santa Cruz; San Cristóbal				
		PEI 1	**PEI 2**	**PEI 3**	**PEI 4**	**PEI 5**	**PEI 6**	**PEI 7**

*Table 15.22 Identity of the Galapagos Islands' volcanoes in each Hazard-PEI group. Those volcanoes with a sufficient record for determining a hazard score are deemed 'Classified' (top). Those without sufficient data are 'Unclassified' (bottom). The unclassified volcanoes are divided into groups: U-NHHR is Unclassified No Historic or Holocene Record: that is there are no confirmed eruptions recorded in the Holocene. U-HR is Unclassified with Holocene Record: that is there are confirmed eruptions recorded during the Holocene, but no historical (post-1500) events. U-HHR is Unclassified with Historic and Holocene record. The unclassified volcanoes in **bold** have experienced unrest or eruptions since 1900 AD, and those in red have records of at least one Holocene VEI ≥4 eruption.*

Volcano	Population Exposure Index	Risk Level
Azul, Cerro	2	I
Fernandina	2	I
Negra, Sierra	2	I
Wolf	2	I

Table 15.23 Classified volcanoes of the Galapagos Islands ordered by descending Population Exposure Index (PEI). Risk levels determined through the combination of the Hazard Level and PEI are given. Risk Level I – 4 volcanoes; Risk Level II –0 volcanoes; Risk Level III – 0 volcanoes.

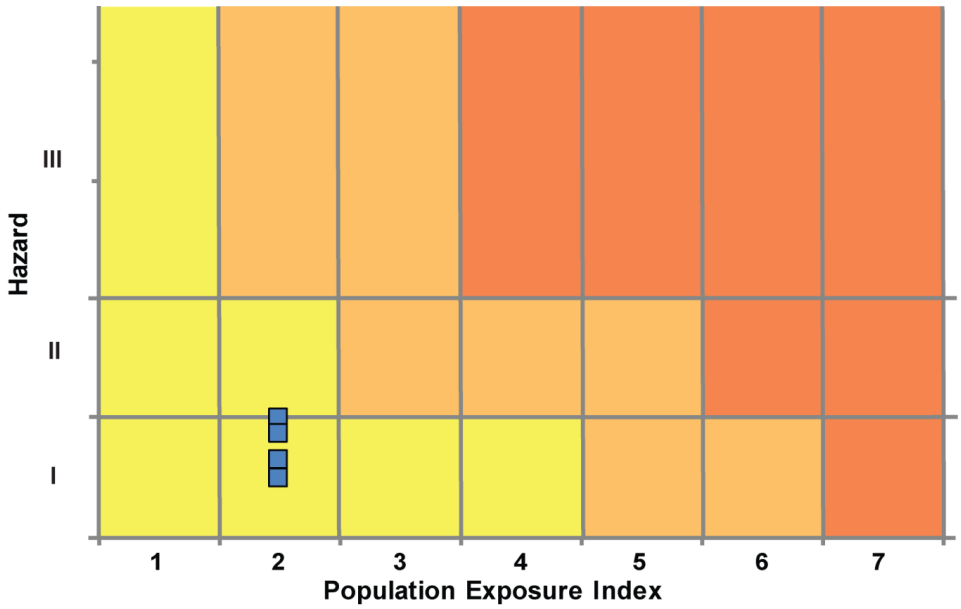

Figure 15.26 Distribution of the Galapagos Islands' classified volcanoes across Hazard and Population Exposure Index levels. The warming of the background colours illustrates increasing Risk levels from Risk Level I - III.

National Capacity for Coping with Volcanic Risk

Nine volcanoes in the Galapagos Islands have recorded historical activity. Monitoring is undertaken by the Instituto Geofisico EPN. Note that this institute also uses Monitoring Levels 1 - 3 to describe levels of monitoring at Ecuador's volcanoes, but these are different levels to those used here. A seismic monitoring network in the Galapagos Islands has been installed.

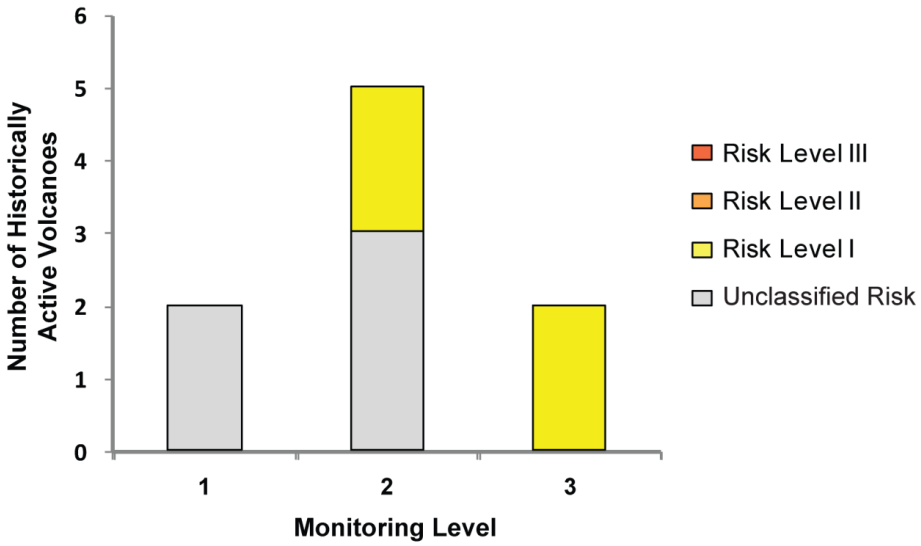

Figure 15.27 The monitoring and risk levels of the historically active volcanoes in the Galapagos Islands of Ecuador. Monitoring Level 1 indicates no known dedicated ground-based monitoring; Monitoring Level 2 indicates that some ground-based monitoring systems are in place including ≤3 seismic stations; Monitoring Level 3 indicates the presence of a dedicated ground-based monitoring network, including ≥4 seismometers.

Peru

Description

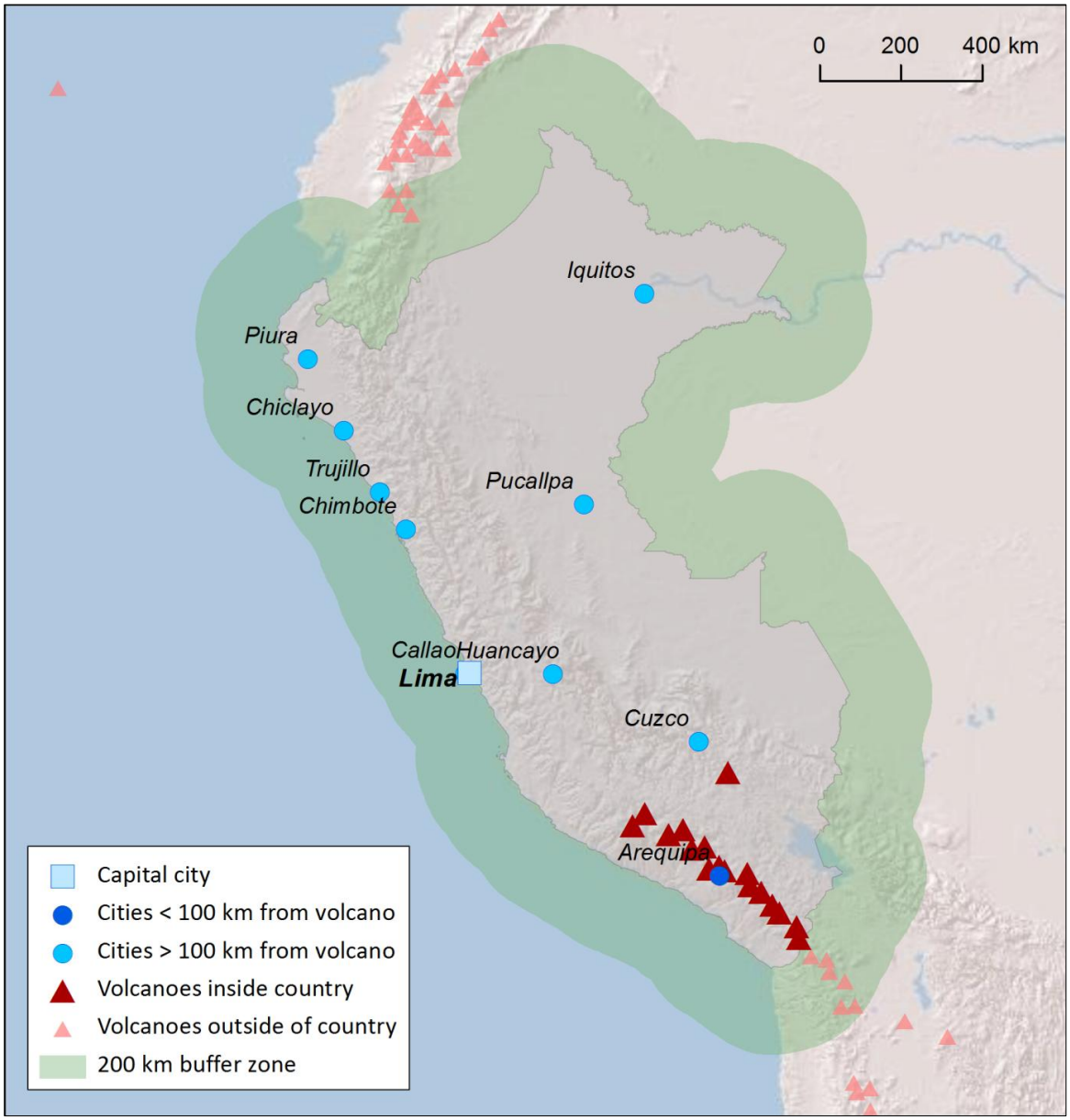

Figure 15.28 Location of Peru's volcanoes, the capital and largest cities. A zone extending 200 km beyond the country's borders shows other volcanoes whose eruptions may directly affect Peru.

Seventeen Holocene volcanoes are recorded in Peru. These volcanoes are located in the Andes in a chain through southern Peru to the border with Chile. Volcanism occurs here due to the subduction of the Nazca Plate beneath the South American Plate. Although subduction is also ongoing in northern Peru, the angle of the subducting slab has not led to recent volcanism. Although Peru's volcanoes are a variety of types, including cinder cones and lava domes, most are stratovolcanoes of dominantly andesitic composition.

Large explosive Pleistocene activity is recorded in Peru, and sixty eruptions of Holocene age are recorded here. Of these, thirty-six are of historical age. These historical eruptions occurred at six

volcanoes, and covered a range of sizes, from small events of VEI 1 to very large explosive VEI 6 eruptions. Three volcanoes have Holocene records of producing pyroclastic flows and four with lahars. The largest historical eruption was the 1600 AD eruption of Huaynaputina. This eruption produced voluminous tephra falls, pyroclastic flows and surges which travelled 13 km and lahars that reached the Pacific Ocean, 120 km away. The cities of Arequipa and Moquengua suffered significant damage, and about 1500 lives were lost.

Arequipa, one of the most populous cities in Peru, lies at about 75 km from Huaynaputina, and within 100 km of five other Holocene volcanoes, including the historically active Sabancaya, El Misti and Ubinas, the most frequently active volcano in Peru in historic times.

The Instituto Geofisico del Peru (IGP) and the Instituto Geológico Minero y Metalúrgico (INGEMMET) are responsible for scientific research and the monitoring of the volcanoes in Peru, and indeed actively monitor five historically active volcanoes and three further Holocene volcanoes through a variety of dedicated ground-based instrumentation, including seismic stations, geochemical and gas monitoring and various deformation monitoring. Monitoring is undertaken regularly, with an alarm system and automated seismic system. A regional seismic network is operational in Peru, which can register seismicity throughout the volcanic chain. Some resources and plans are available for monitoring to be extended to currently un-monitored volcanoes in developing situations. About a quarter of the observatory staff have experience of responding to an eruption.

In addition to ground-based monitoring, VDAP – the Volcano Disaster Assistance Program of the U.S. Geological Survey provides satellite information during eruptions, and InSAR and MODIS images are provided by Cornell University and Torino University.

The IGP provide scientific and technical advice to the Instituo Nacional de Defensa Civil (INDECI) in the event of unrest and eruption. The director of the Observatorio Vulcanologico de Sur (OVS), Orlando Macedo, represents the IGP on the regional committee for crises (the Comite de Operaciones de Emergencia Regional, COER). The regional aviation authority, Corporacion Peruana de Aviacion Comercial (CORPAC) reports to the regional VAAC.

The IGP extend a programme of hazard education to the public, and the IGP and INGEMMET websites are publically accessible, distributing information about Peru's volcanic activity. The IGP do not provide risk assessments but advise on management and mitigation of volcanic risk. An alert level system is in place, and the IGP, INGEMMET and IGUNSA recommend declaration of alerts to the COER authority.

Large and growing cities are located near active volcanoes in Peru, and with the expansion of the cities, the risk increases as larger populations live ever-closer to the volcanoes. Educational programs about volcanic risk and restriction of building in proximal areas would greatly improve the volcanic risk situation in Peru.

See also:

Instituto Geofisico del Peru: www.igp.gob.pe/portal/#

Instituto Geológico Minero y Metalúrgico (INGEMMET):
www.ingemmet.gob.pe/form/Inicio.aspx#

Observatorio Vulcanologico Del Sur: ovs.igp.gob.pe/monitoreo

Thouret, J-C., Finizola, A., Fornari, M., Legeley-Padovani, A., Suni, J. and Frechen, M. (2001) Geology of El Misti volcano near the city of Arequipa, Peru. *Geological Society of America Bulletin*, 113: 1593-1610.

Volcano Facts

Number of Holocene volcanoes	17, inclusive of one on the border with Chile
Number of Pleistocene volcanoes with M≥4 eruptions	4
Number of volcanoes generating pyroclastic flows	3
Number of volcanoes generating lahars	4
Number of volcanoes generating lava flows	3
Number of fatalities caused by volcanic eruptions	1,500?
Tectonic setting	Subduction zone
Largest recorded Pleistocene eruption	The M6.7 Sillar of Arequipa Ignimbrite eruption of Nevado Chachani at 2.42 Ma.
Largest recorded Holocene eruption	The 1600 AD eruption of Huaynaputina at M6.1.
Number of Holocene eruptions	60 confirmed eruptions. 14 uncertain eruptions.
Recorded Holocene VEI range	0 – 6 and unknown
Number of historically active volcanoes	6
Number of historic eruptions	36

Number of volcanoes	Primary volcano type	Dominant rock type
11	Large cone(s)	Andesitic (9), Dacitic (1), Trachytic / Andesitic (1)
2	Lava dome(s)	Dacitic (1), Rhyolitic (1)
4	Small cone(s)	Andesitic (3), Unknown (1)

Table 15.24 The number of volcanoes in Peru, their volcano type classification and dominant rock type according to VOTW4.0.

Socio-Economic Facts

Total population (2012)	30,041,000
Gross Domestic Product (GDP) per capita (2005 PPP $)	9,049
Gross National Income (GNI) per capita (2005 PPP $)	9,306
Human Development Index (HDI) (2012)	0.741 (High)

Population Exposure

Capital city	Lima
Distance from capital city to nearest Holocene volcano	533.1 km
Total population (2011)	29,248,943
Number (percentage) of people living within 10 km of a Holocene volcano	25,307 (<1%)
Number (percentage) of people living within 30 km of a Holocene volcano	1,143,689 (3.9%)
Number (percentage) of people living within 100 km of a Holocene volcano	2,836,138 (9.7%)

Ten largest cities, as measured by population and their population size:

Lima	7,737,002
Arequipa	841,130
Callao	813,264
Trujillo	747,450
Chiclayo	577,375
Iquitos	437,620
Huancayo	376,657
Piura	325,466
Chimbote	316,966
Cuzco	312,140

Infrastructure Exposure

Number of airports within 100 km of a volcano	3
Number of ports within 100 km of a volcano	1
Total length of roads within 100 km of a volcano (km)	1,410
Total length of railroads within 100 km of a volcano (km)	0

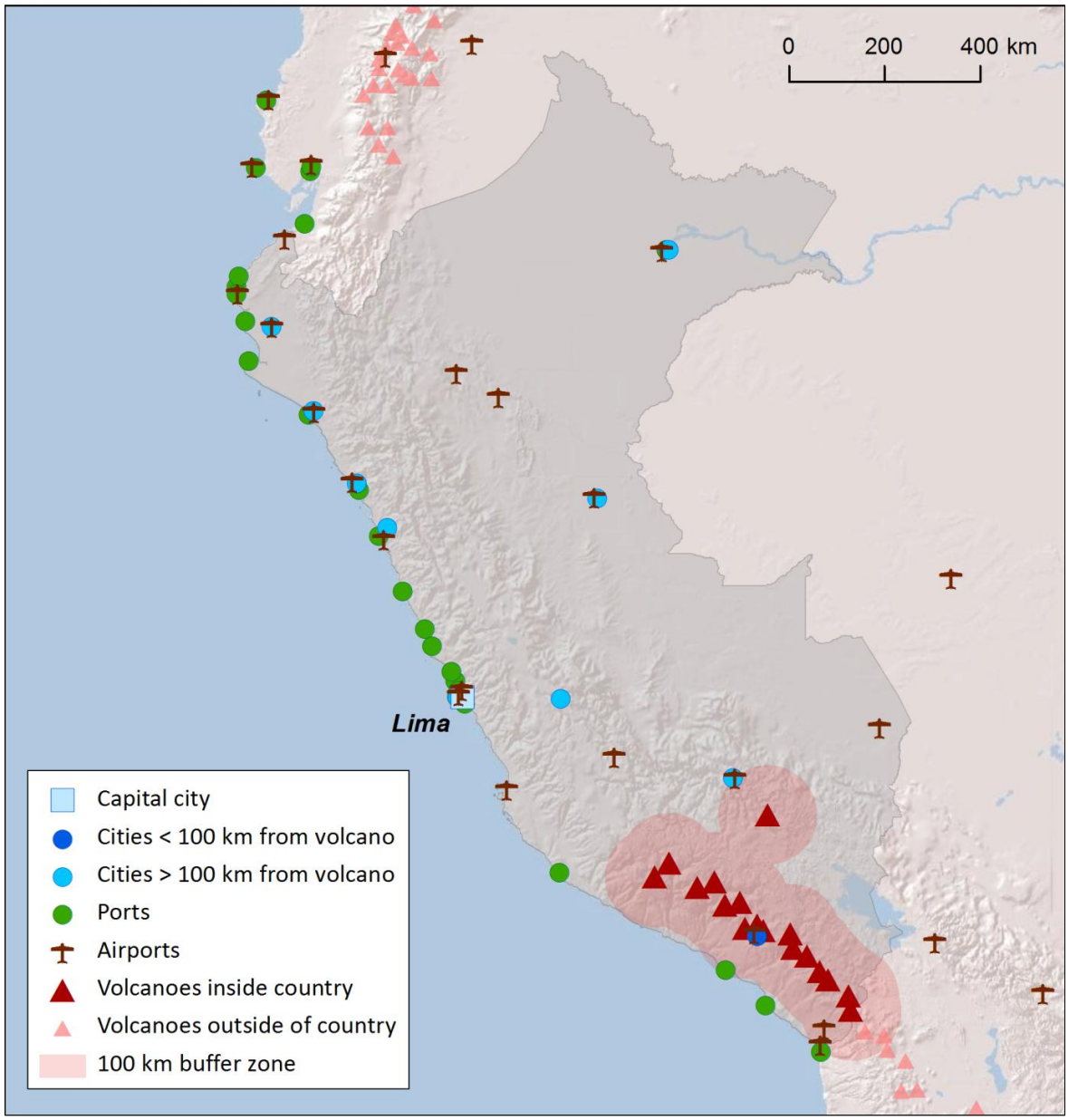

Figure 15.29 The location of Peru's volcanoes and the extent of the 100 km zone surrounding them. Ports, airports and the major cities are just some of the infrastructure that may be exposed to volcanic hazards.

The Peruvian volcanoes are located in the south of the country bordering Chile, through the Andean chain. The southernmost two volcanoes in Peru have 100 km radii that extend into Chile, exposing the infrastructure here, and similarly, several of the northernmost volcanoes in Chile have 100 km radii which extend into southern Peru. The capital, Lima, is distal to the volcanoes, being located over 500 km north. However, one of the largest cities in Peru, Arequipa, is located with 100 km of six Holocene volcanoes, including the historically active Sabancaya, El Misti, Ubinas and Huaynaputina volcanoes, and hence considerable infrastructure is exposed here, including an extensive road network.

Hazard, Uncertainty and Exposure Assessments

There are varying levels of information available in the eruption records of Peru's volcanoes. The record is sufficient at just four volcanoes to define the hazard through the calculation of the VHI. These are classified across Hazard Levels I and II.

Despite a Holocene record including a VEI 4 eruption, El Misti's eruption record is dominated by historical VEI 1 and 2 eruptions and older eruptions of an undetermined size. This mildly explosive historical activity controls the determination of the VHI giving El Misti a Hazard Level of I. However, Thouret et al. (2001) identified "tens of pyroclastic flows" over the last 50,000 years from this volcano, including pyroclastic flows which reached about 12 km - a distance at which the outskirts of the city of Arequipa now lies. Thouret et al. (2001) determine recurrence intervals for ash falls of about 500 to 1500 years, and for pumice falls of 2,000 to 4,000 years. El Misti is assigned a Risk Level of I due to the hazard level classification, however the potential for larger eruptions than seen historically must be recognised, along with the potential for extensive pyroclastic flows. Indeed, areas of Arequipa are designated as high risk by IGP (http://ovs.igp.gob.pe/) and INGEMMET (http://ovi.ingemmet.gob.pe/).

Of the unclassified volcanoes, eight have no confirmed Holocene age eruptions on record. Five have a Holocene record, including historical (post-1500 AD) age activity at Ticsani and Huaynaputina. Just the latter has a record of large explosive VEI ≥4 Holocene eruptions.

The PEI ranges from low to high in Peru, at PEI 2 to 4. Of the classified volcanoes, two are classed as Risk Level II and two at Risk Level I.

CLASSIFIED	**Hazard III**							
	Hazard II		Yucamane	Sabancaya; Ubinas				
	Hazard I				Misti, El			
UNCLASSIFIED	**U – HHR**		Ticsani	Huaynaputina				
	U- HR			Huambo	Quimsachata; Andahua-Orcopampa			
	U-NHHR		Auquihuato, Cerro; Sara Sara; Coropuna; Tutupaca; Casiri, Nevados; Tacora		Chachani, Nevado; Nicholson, Cerro			
		PEI 1	**PEI 2**	**PEI 3**	**PEI 4**	**PEI 5**	**PEI 6**	**PEI 7**

*Table 15.25 Identity of Peru's volcanoes in each Hazard-PEI group. Those volcanoes with a sufficient record for determining a hazard score are deemed 'Classified' (top). Those without sufficient data are 'Unclassified' (bottom). The unclassified volcanoes are divided into groups: U-NHHR is Unclassified No Historic or Holocene Record: that is there are no confirmed eruptions recorded in the Holocene. U-HR is Unclassified with Holocene Record: that is there are confirmed eruptions recorded during the Holocene, but no historical (post-1500) events. U-HHR is Unclassified with Historic and Holocene record. The unclassified volcanoes in **bold** have experienced unrest or eruptions since 1900 AD, and those in red have records of at least one Holocene VEI ≥4 eruption.*

Volcano	Population Exposure Index	Risk Level
Misti, El	4	I
Sabancaya	3	II
Ubinas	3	II
Yucamane	2	I

Table 15.26 Classified volcanoes of Peru ordered by descending Population Exposure Index (PEI). Risk levels determined through the combination of the Hazard Level and PEI are given. Risk Level I – 2 volcanoes; Risk Level II – 2 volcanoes; Risk Level III – 0 volcanoes.

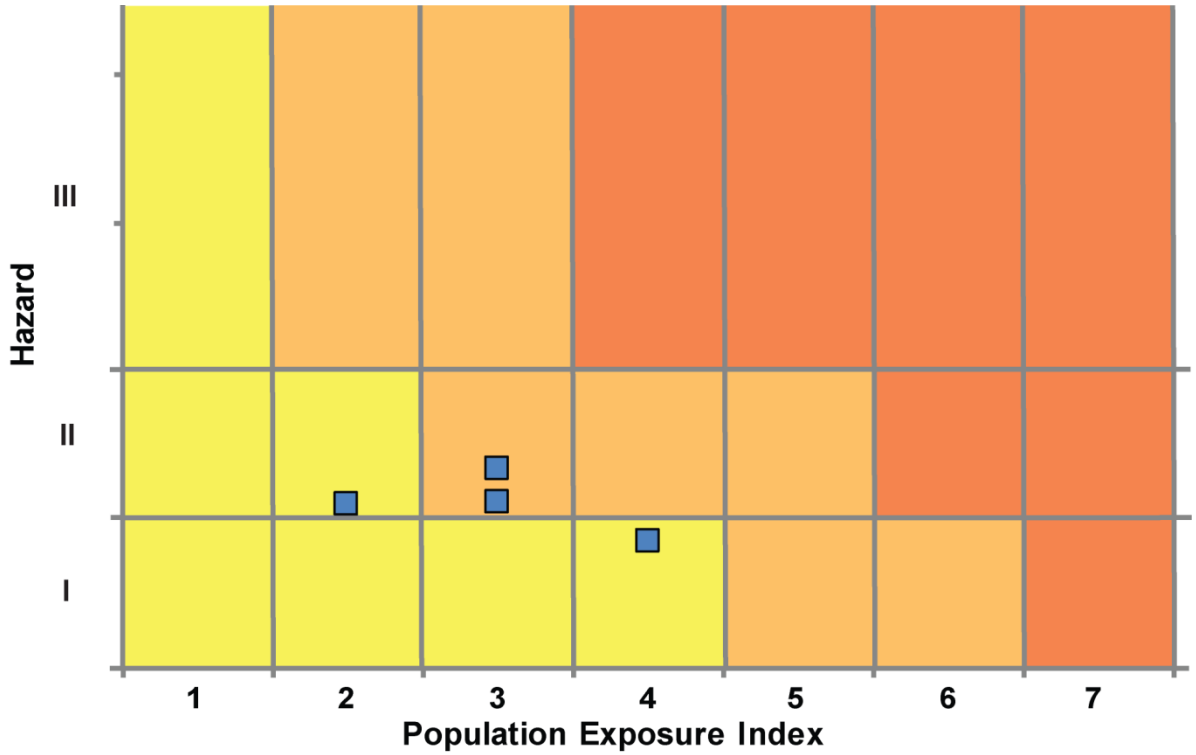

Figure 15.30 Distribution of Peru's classified volcanoes across Hazard and Population Exposure Index levels. The warming of the background colours illustrates increasing Risk levels from Risk Level I - III.

National Capacity for Coping with Volcanic Risk

Six volcanoes have records of historical activity in Peru. Of these, five have regular monitoring. Just Yucamane, a Risk Level I volcano, currently has no dedicated regular ground-based monitoring. The five others, including El Misti (Risk Level I), Sabancaya and Ubinas (Risk Level II) and Huaynaputina and Ticsani (Unclassified), are monitored by the Instituto Geofisico del Peru and the Instituto Geológico Minero y Metalúrgico (INGEMMET). These institutes also monitor Tutupaca, Coropuna

and Nevado Chachani. Seismic networks are used at Sabancaya and Huaynaputina. Seismic networks and additional deformation and gas monitoring is undertaken at Ticsani, El Misit and Ubinas.

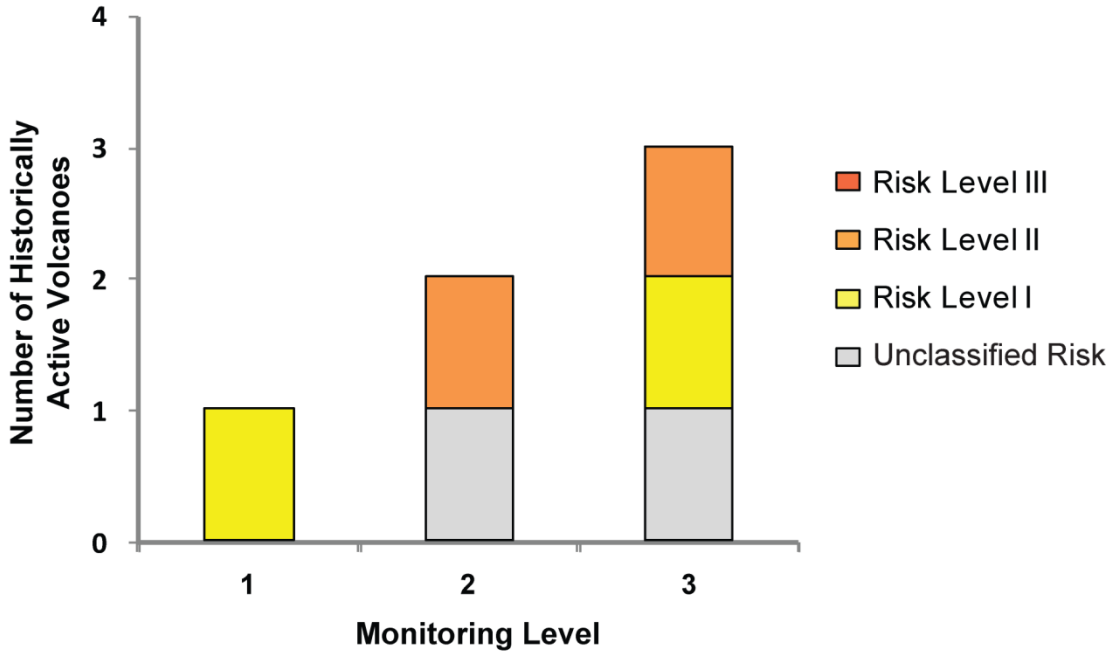

Figure 15.31 The monitoring and risk levels of the historically active volcanoes in Peru. Monitoring Level 1 indicates no known dedicated ground-based monitoring; Monitoring Level 2 indicates that some ground-based monitoring systems are in place including ≤3 seismic stations; Monitoring Level 3 indicates the presence of a dedicated ground-based monitoring network, including ≥4 seismometers.