

Geological heritage sites assessment in the northern flank of the Calbuco volcano (Southern Andes, Chile)

***Florencia D. Sánchez¹, Jorge E. Romero², Paulo Pereira¹, Manuel E. Schilling³**

¹ *Institute of Earth Sciences, Pole of the University of Minho, 4710-057 Braga, Portugal.*

florenciasanro@gmail.com, paolo@det.uminho.pt

² *Instituto de Ciencias de la Ingeniería, Universidad de O'Higgins, Avda. Libertador Bernardo O'Higgins 611, Rancagua, Chile.*

jorge.romero@uoh.cl

³ *Instituto de Ciencias de la Tierra, Facultad de Ciencias, Universidad Austral de Chile, Campus Isla Teja, Valdivia 5090000, región de Los Ríos, Chile.*

manuel.schilling@uach.cl

* *Corresponding author: florenciasanro@gmail.com*

ABSTRACT. Calbuco volcano (41.3° S, Southern Andes) ranks second in the Chilean volcanic risk ranking. The products of Calbuco's last eruption (April 22-23, 2015) severely affected the surroundings of the volcano, particularly the Ensenada village (~1,500 inhab.), evidencing a growing need for effective volcanic risk management and mitigation. The geological study of volcanic deposits and landforms is a key step in reconstructing past volcanic eruptions and for the evaluation of volcanic hazards and associated risks. Additionally, well-preserved and easily accessible volcanic deposits can be considered as geological heritage sites (geosites) that could be used to educate communities and visitors about geological hazards and volcanic risk through different outreach, educational, and touristic activities. In the northern flank of Calbuco, a series of protected public and private areas (Llanquihue National Reserve, Valle Los Ulmos Park, and Volcanes Park) foster the conservation of natural heritage and facilitate the accessibility to volcanic deposits. Our contribution therefore assesses the geological heritage potential of the northern flank of the Calbuco volcano through literature review, geological mapping, and stratigraphic and petrographic studies of recent eruptive deposits. The identified geosites were scored and ranked through a quantitative procedure. The top three-ranked geosites hold high scientific value and good accessibility conditions. These sites may sustain a geoconservation strategy based on scientific, educational, and touristic activities, contributing thus to volcanic risk reduction in the area.

Keywords: Calbuco volcano, Volcanic hazards, Volcanic risk reduction, Geological heritage, Southern Andes of Chile.

RESUMEN. Evaluación de sitios de patrimonio geológico en el flanco norte del volcán Calbuco (Andes del Sur, Chile). El volcán Calbuco (41,3° S, Andes del Sur) se encuentra segundo en el *ranking* de riesgo volcánico de Chile. Los productos de su última erupción (22-23 de abril del año 2015) afectaron severamente los alrededores del volcán, particularmente el pueblo de Ensenada (~1.500 habitantes), lo cual evidencia la creciente necesidad de una efectiva gestión y mitigación del riesgo volcánico. El estudio geológico de los depósitos y morfologías volcánicas es clave para reconstruir erupciones pasadas y así evaluar el peligro geológico y sus riesgos asociados. Adicionalmente, depósitos volcánicos bien preservados y con buena accesibilidad son considerados como sitios de patrimonio geológico (geositos) que pueden ser usados para educar a la comunidad y a los visitantes sobre peligros geológicos a través de diferentes actividades de difusión, educativas y turísticas. En el flanco norte del volcán Calbuco existen varias áreas protegidas, tanto públicas (Reserva Nacional Llanquihue) como privadas (Parque Valle Los Ulmos y Parque Los Volcanes), en las cuales se promueve la conservación del patrimonio natural. La presente contribución, por ende, consiste en evaluar el potencial del patrimonio geológico en el flanco norte del volcán Calbuco a través de una exhaustiva revisión bibliográfica, mapeo geológico y estudios estratigráficos y petrográficos de depósitos eruptivos recientes. Los geositos identificados fueron evaluados y clasificados con una metodología cuantitativa. Los tres mejores geositos identificados poseen atributos científicos elevados y buenas condiciones de accesibilidad. Estos sitios pueden sustentar una estrategia de geoconservación basada en actividades científicas, educativas y turísticas, lo que contribuiría a la reducción del riesgo volcánico en la región.

Palabras clave: Volcán Calbuco, Peligros volcánicos, Reducción del riesgo volcánico, Patrimonio geológico, Andes del Sur de Chile.

1. Introduction

Volcanic eruptions are one of the most powerful manifestations of the Earth's internal energy. As demonstrated during the May 18, 1980, eruption of Mount St. Helens (Washington, USA), it can take minutes for a volcano to transform vast areas of its surroundings, with consequences lasting from decades to several thousand years (e.g., Driedger *et al.*, 2020). The explosive Hunga Tonga-Hunga Ha'apai eruption that occurred on January 15, 2022, in the Kingdom of Tonga, southern Pacific, evidenced how oceanic and atmospheric perturbations triggered by large-magnitude volcanic eruptions can have impacts on a trans-oceanic or even global scale (Amores *et al.*, 2022; Yuen *et al.*, 2022; Le Mével *et al.*, 2023; Purkis *et al.*, 2023). Moreover, the September-December 2021 eruption of the Cumbre Vieja volcano (Canary Islands, Spain) highlights the devastating character that even smaller-scale eruptions may have in highly populated and exposed areas nearby the volcano (e.g., Houghton *et al.*, 2021; Carracedo *et al.*, 2022; Romero *et al.*, 2022). In this way, the geological study of volcanic deposits, landforms, and structures is fundamental to the understanding of the formation and evolution of volcanoes, including the magnitude and recurrence of their eruptions, and therefore of the associated potential hazards. Also, geological studies based on mapping, sedimentology, and petrology, allow the identification, characterization, and assessment of geological heritage sites (geosites). Some of these sites are related to recent eruptions (e.g., Dóniz-Páez *et al.*, 2024), and the study of their deposits may help to better understand the volcano's most recent eruptive history, encouraging their preservation and providing an efficient means for the education of local communities and visitors about volcanic processes and their impacts. This is of particular interest for at-risk communities around active and hazardous volcanoes.

Geodiversity is the natural variety of geological features, including their relationships, interpretations, properties, and systems (Gray, 2004). On the other hand, geological heritage (geoheritage) corresponds to the set of geodiversity sites and elements (minerals, fossils, rocks, etc.) that are recognized for their scientific, cultural, and educative value (Carcavilla *et al.*, 2008). Within these elements, geosites are defined as places that show *in situ* one or many characteristics, considered important in the geological history of a

region (Ferreira, 2017). Mondéjar and del Ramo Jiménez (2004) argue that the study of geodiversity and geoheritage lies within a complex context because of the origin of the concept itself and the close relation with other disciplines, where the interest, in many cases, surpasses the geoscientific aspects. Geoheritage also represents an important didactic resource and has relevant cultural connotations. Geoconservation is thus developed by the need to protect and promote geoheritage (Gray, 2008).

Like many of the recent eruptions that dramatically impacted their surroundings, on April 22, 2015, Calbuco volcano (41.3° S, Southern Andes of Chile) sourced a moderate VEI 4 eruption with important social and environmental effects, the latter on a global scale (Manville *et al.*, 2018; Pardini *et al.*, 2018; Zhu *et al.*, 2018; Hayes *et al.*, 2019; Sangeetha *et al.*, 2018). Calbuco is an ice-clad, 2,015 m high andesitic stratovolcano, currently ranked second in the Chilean volcanic risk ranking (Sernageomin, 2023)¹. During historical eruptions (>1750 CE), Calbuco has generated tephra fallout, pyroclastic density currents (PDCs), lava flows, and lahars. These products have been radially emitted from the summit down the river valleys (Sellés and Moreno, 2011), being the volcano's north-northeast flank the most severely affected (Romero *et al.*, 2021).

In this contribution, we present the first inventory of geological heritage sites of Calbuco volcano. Our research comprises the geological characterization of 25 potential geosites, which were assessed using qualitative and quantitative procedures. Based on the quantitative methodology, three of them are described in detail. These sites were selected due to either their high scientific value or their high score in touristic and educational use. Inhabited historically active volcanoes such as Calbuco represent challenging areas for volcanic risk management. Possible measures contributing to volcanic risk mitigation include the education of the population about volcanic processes and their potential impacts. The selected geosites can also be used as an effective tool to promote research divulgation and touristic activities in cooperation with local authorities and neighboring communities.

2. Geological background

Between 33 and 46° S, the Southern Volcanic Zone (SVZ) of the Andes results from the oblique subduction of the Nazca Plate beneath the South American Plate

¹ Sernageomin. 2023. Ranking de riesgo específico de volcanes activos en Chile (available at <https://rnvv.sernageomin.cl/que-es-ranking-de-riesgo/>)

at a rate of ~7-9 cm/year (DeMets *et al.*, 2010). This zone includes at least, 60 historically and potentially active volcanoes in Chile and Argentina, as well as three silicic caldera systems and numerous minor eruptive centers (Stern, 2004). The central segment of the SVZ (CSVZ; 38-41.5° S) is characterized by the subduction of <18 Ma old oceanic lithosphere, and a narrow (~80 km wide) arc located in the boundary of the Central Valley and the western edge of the Main Andean Cordillera (Stern, 2004). Most of the CSVZ volcanoes display a compositional range between dominantly basaltic andesites and dacites (e.g., Vander Auwera *et al.*, 2019). In this region, the volcanism is structurally controlled by the Liquiñe-Ofqui Fault Zone (LOFZ) (Fig. 1), a ~1,200 km long intra-arc feature represented as dextral transpressional ~N-S ductile-to-brittle shear zones (López-Escobar *et al.*, 1995; Cembrano and Lara, 2009).

Calbuco volcano lies over Miocene plutonic rocks of the North Patagonian Batholith and early Pleistocene volcanic and volcanoclastic rocks of the Hueñuhueñu strata (Munizaga *et al.*, 1988; López-Escobar *et al.*, 1992; Sellés and Moreno, 2011). Calbuco is at least ~100 kyr old, and its geological history has been grouped into four stages (Mixon *et al.*, 2021). During the second stage, it experienced two lateral collapse events at ~17.5 and 9 ka, which affected the west and north of the current

vent (Clavero *et al.*, 2008; Sellés and Moreno, 2011; Zellmer *et al.*, 2014; Mixon *et al.*, 2021). Mixon *et al.* (2021) indicate that during the Holocene Calbuco has erupted remarkably homogeneous basaltic andesite to andesite products (54-58 wt% SiO₂) at eruption rates varying from 3.4 to 4.8 km³/kyr, higher than other CSVZ arc volcanoes. Similarly, Vander Auwera *et al.* (2021), through high-resolution geochemistry, show that no secular compositional change has occurred at Calbuco throughout its history, indicating a steady magmatic system beneath the volcano. Hence, Calbuco is one of the most productive volcanoes in the CSVZ and thus an active source of both landscape and environmental transformations.

Calbuco's historical eruptive record extends back to ca. 230 years (~1790 CE), being summarized in detail by several authors (e.g., Petit-Breuilh and Moreno, 1997; Moreno, 1999; Petit-Breuilh, 1999; Sellés and Moreno, 2011). At least two types of eruptions have been described: moderate, mostly sub-Plinian events with repose intervals of 60±10 years; and smaller-scale eruptions (mostly Vulcanian, phreatic, phreatomagmatic, and dome-building effusive events) which seem to occur with a mean frequency of ~20 years (Romero *et al.*, 2021). A map of the most relevant volcanic deposits in Calbuco's northeastern flank is shown in figure 2.

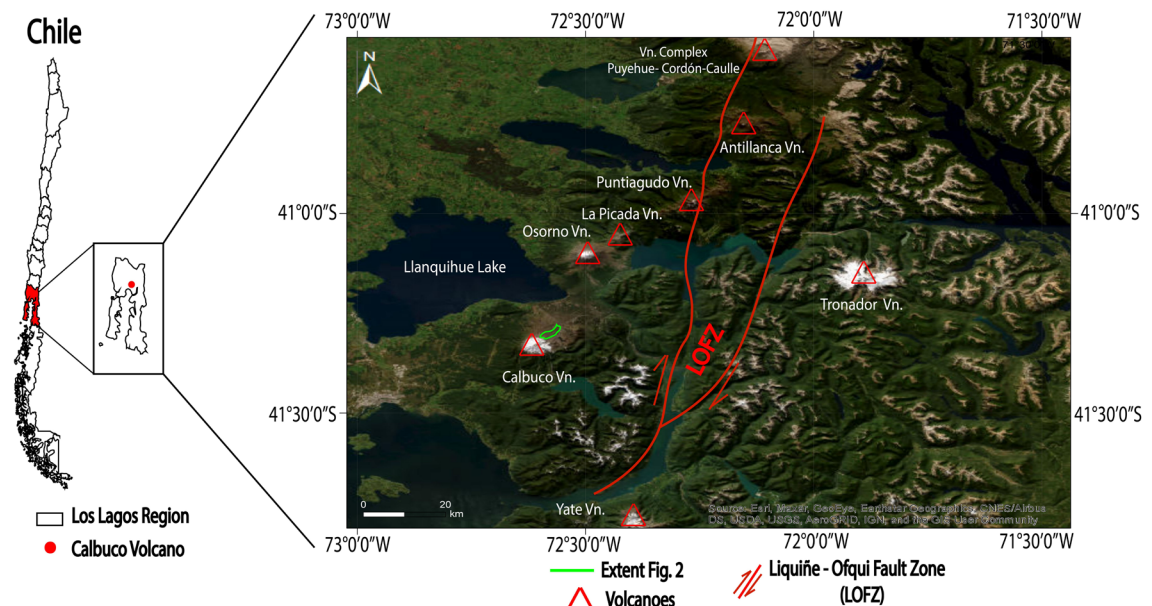


FIG. 1. Study area depicting the main volcanoes and lakes, and the main trace of the LOFZ (Liquiñe-Ofqui Fault Zone). Figure extracted from Cembrano and Lara (2009) and Orozco (2009).

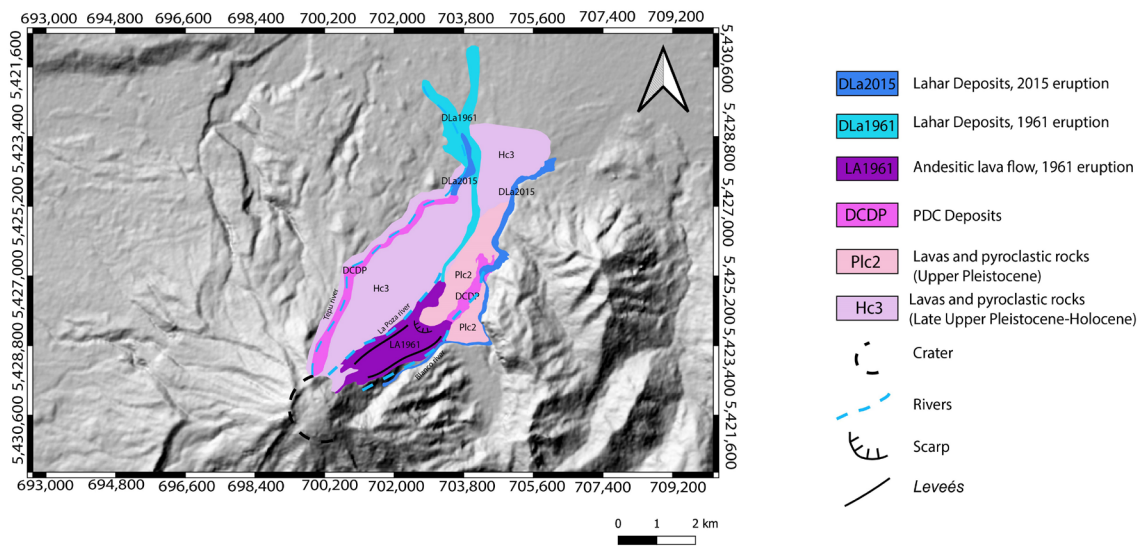


FIG. 2. Geological map of the northern flank of the Calbuco volcano modified from Sellés and Moreno (2011), Mella *et al.* (2015) and Romero *et al.* (2021).

In 1792, the eruptive activity of Calbuco was accompanied by perceptible earthquakes (Petit-Breuilh and Moreno, 1997). In 1893-95 the volcano erupted again, with eruption columns that rose to a maximum height of ~12 km, accompanied by PDC generation and dome extrusion (Petit-Breuilh and Moreno, 1997; Sellés and Moreno, 2011). The 1893-95 eruption produced $0.54 \pm 0.13 \text{ km}^3$ of basaltic andesite tephra (53-54 wt% SiO_2) and reached a magnitude and intensity of 4.8 and 10.5, respectively, thus being the volcano's largest historical eruption (Romero *et al.*, 2021). In 1917, a new eruption produced ash plumes dispersed to the east, together with lava flows and lahars in the volcano's northeastern flank (Sellés and Moreno, 2011; Romero *et al.*, 2021). Another explosive eruption in January 1929 produced a series of PDCs, affecting most of the volcano's northeast flank by overbanking (Stone, 1930; Petit-Breuilh and Moreno, 1997; Sellés and Moreno, 2011; Romero *et al.*, 2021).

Most recently, between January and March 1961, renewed activity produced PDCs and triggered lahars down the volcano's north-northeastern and southeastern flanks, as well as two lava flows down the Tepu (La Poza) and Amarillo rivers (Klohn, 1963; Moreno *et al.*, 2006; Sellés and Moreno, 2011; Romero *et al.*, 2021). The paroxysmal stage consisted of a sub-Plinian eruptive column ~12 km high and

a $0.1 \pm 0.01 \text{ km}^3$ basaltic andesite (55-56 wt% SiO_2) fallout deposit dispersed east-northeast (Klohn, 1963; Daga *et al.*, 2014; Romero *et al.*, 2021). The 1961 eruption achieved a magnitude of 4.08 and an intensity of 9.74 (Romero *et al.*, 2021). A short-lived ash emission event, probably phreatic in origin, was observed in August 1972 (Sellés and Moreno, 2011).

Finally, the latest eruption occurred on April 22, 2015, preceded by an apparent short period of unrest, consisting of ~140 volcano-tectonic events, roughly 3 hours before the eruption (Valderrama *et al.*, 2016). The eruption had three explosive pulses, two of them sub-Plinian with eruptive columns up to 23 km high with a noticeable dispersion towards the northeast (Bertin *et al.*, 2015; Castruccio *et al.*, 2016; Romero *et al.*, 2021). During this eruption, PDCs, tephra fallout, and lahars were generated, all of which damaged public and private infrastructure (Mella *et al.*, 2015; Castruccio *et al.*, 2016; Romero *et al.*, 2023). The distribution of these products was constrained within the volcanic hazard areas identified by Moreno (1999) (Romero *et al.*, 2016). The revised volume for the 2015 tephra deposit is $0.3 \pm 0.16 \text{ km}^3$ (magnitude to 4.47 and intensity to 10.18); its composition was basaltic andesite (55-56 wt% SiO_2) with an andesite-to-dacite glass geochemistry (61-65 wt% SiO_2) (Romero *et al.*, 2021).

The eruptive history of Calbuco implies a continuous transformation of the landscape through the rapid deposition of volcanic and volcanoclastic materials, especially on its north-northeastern flank. Additionally, the 2015 eruption showed striking aspects of a sudden initiation and short-lived precursors, thus revealing enhanced hazards. The triggering of this eruption has been explained by either a continuing crystallization inducing second boiling and an over-pressurization of the system (Arzilli *et al.*, 2019), or localized heating of the sub-volcanic reservoir caused by an injection of hot magma (Morgado *et al.*, 2019).

3. Conservation of natural heritage and protected areas

In the northern flank of Calbuco there is one public (Llanquihue National Reserve) and two private (Valle Los Ulmos Park and Volcanes Park) protected areas (Fig. 3). The Valle Los Ulmos Park started in 1954 as an agricultural property, which in 2014, changed to a private park with the mission to preserve the volcanic ecosystem. The project integrates a community of 45 shareholders that value and encourage conservation through the purchase of stocks that give the rights

and obligations for the protection of the volcanic ecosystem. The project design includes landscape restoration, the protection of 65 hectares of forest, and the possibility for the community to use the park areas for sustainable development, education, science, tourism, and human-nature coexistence. The Volcanes Park is a private project that seeks to preserve the ecosystem through the conservation and regeneration of the native forest. The park is currently inhabited and includes numerous houses. The park stands out by its large variety of native flora and fauna. Finally, the Llanquihue National Reserve is a public protected area created in 1912 with a surface of 33,972 hectares that is administrated by the National Forestry Corporation (Conaf). The objectives related to the management of natural resources of this reserve that are relevant for this study are (Conaf, 2014)²:

- To create and develop lines of action for scientific investigation.
- To protect ecosystems and living species of flora and fauna.
- To identify and manage lines of action for the protection of water resources.

The three protected areas listed above have different missions but do share a common objective: the conservation of nature and its use for local development.

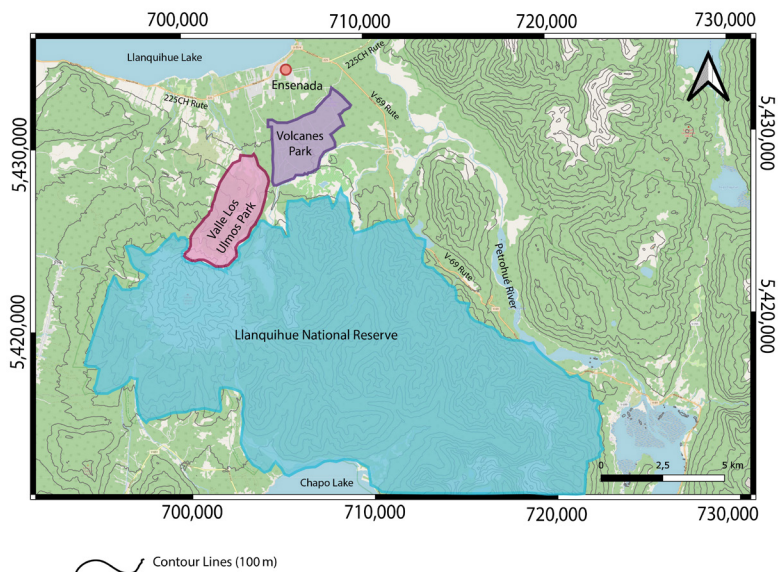


FIG. 3. Northern flank of Calbuco volcano. Private protected areas: Valle Los Ulmos Park (red) and Volcanes Park (purple). Public protected area: Llanquihue National Reserve (blue).

² Conaf. 2014. Plan de Manejo Reserva Nacional Llanquihue. Corporación Nacional Forestal: 166 p.

4. Methodology

This research started with a literature review of geological heritage assessment methods, volcanic processes and hazards, and the Calbuco volcano eruptions record. The quantitative assessment procedure was based on Brilha (2016), which consisted of scoring each geosite using a 0-4 scale. Each criterion was supported by a set of parameters (Table A1 in the Appendix) from the absence of the attribute (0 points) to the excellence (4 points) regarding a specific criterion. A specific weight was considered for each criterion in accordance with its relative importance for the geological heritage value proposed by Brilha (2016). The sum of the scores results in the total score of each geosite, which can be also interpreted for each value or use.

A fieldwork was conducted on the northern flank of Calbuco to identify and characterize potential geosites. A simplified form based on Martínez (2010), Pantoja (2017), and Urrutia (2018) was used to characterize the geosites in the field. Diverse volcanic deposits were identified, including lahars, PDCs, lava flows, and tephra falls. We measured thicknesses, made schematic drawings accompanied by detailed photography, and elaborated stratigraphic sections of

the deposits. Samples were collected for granulometric analyses and thin sections. Viewpoints were described differently, focusing on their observational properties and potential use for tourism.

A thematic geological map at 1:85,000 scale of the northern flank of Calbuco was made (Fig. 2) based on field information and previous works of Sellés and Moreno (2011), Mella *et al.* (2015) and Romero *et al.* (2021). Due to the low accessibility to some geosites, photointerpretation using satellite imagery (Google Earth®) was performed to complete the map, considering the morphology, colors, and spatial continuity of the known deposits.

Based on a selected list of criteria that consider four categories: scientific value, degradation risk, didactic use, and touristic use (Fig. 4), we ranked the potential geosites through the quantification methodology proposed by Brilha (2016). To avoid losing relevant information, we quantified the values of each category instead of only considering the total score of each geosite.

The selection of the three top geosites was based on the following two conditions:

- Highest scientific value: sites with the potential to be used in scientific research, given its novelty and unique occurrence in the study area.

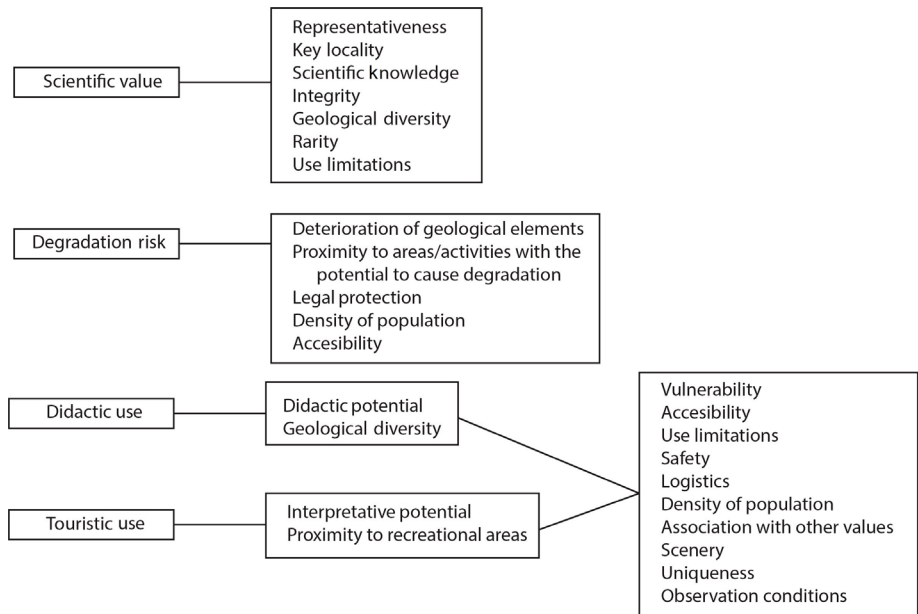


FIG. 4. Criteria used in the quantitative assessment of potential geosites of the northern flank of the Calbuco volcano, separated in four values/uses: scientific, degradational risk, didactic use, and touristic use. Source: Brilha (2016).

- Highest didactic and touristic uses: sites with the capacity to be used for didactic and touristic purposes. These sites are relevant for scientific divulgation, educational (increasing knowledge in the communities), and touristic (major economic benefits for the communities) purposes.

Due to the purpose of the investigation, the degradation risk was not taken into account in the selection of the top three geosites. We chose geosites that can contribute to the understanding of geological/volcanological processes (education) and that can promote local economies through tourism and science.

5. Results

5.1. Identification and assessment of potential geological heritage sites

Twenty-five potential geosites were identified in the northern flank of Calbuco, most of them located within the Valle Los Ulmos Park (Fig. 5; Table A2 in the Appendix). Results for the scientific, didactic, and touristic uses of all geosites are listed in tables 1, 2, and 3, respectively (all the scores, including those for the degradation risk, are available in Table A3 in the Appendix). It is important to clarify that at the time of writing neither of these

25 geosites is used by schools, universities, or tour operators.

In table 1 (scientific use) the highest score was 350, corresponding to geosite Los Volcanes Viewpoint (VC19-10). There are other geosites with scores close to that of geosite VC19-10, such as Blanco river volcanic deposits (VC19-23) with 340 or Lava front at La Poza (VC19-04) with 330.

In table 2 (didactic use) the highest score obtained is 365, corresponding to geosite Los Volcanes Viewpoint (VC19-10). This geosite has the highest potential in terms of education, so it can be used to increase knowledge in the communities. Since VC19-10 was already selected in the scientific use procedure, we added the second highest score (325), which corresponded to geosite Lava front at Blanco River (VC19-22).

In table 3 (touristic use) the highest scores were 320 and 310, corresponding to geosites Hueñu-Hueñu Viewpoint (VC19-24) and Los Volcanes Viewpoint (VC19-10), respectively. These sites show a high touristic potential, which is important for the development of local economies.

Based on the information provided above, three geosites were selected for a more detailed description (see following subsection): Los Volcanes Viewpoint (VC19-10), Lava front at Blanco River (VC19-22), and Hueñu-Hueñu Viewpoint (VC19-24).

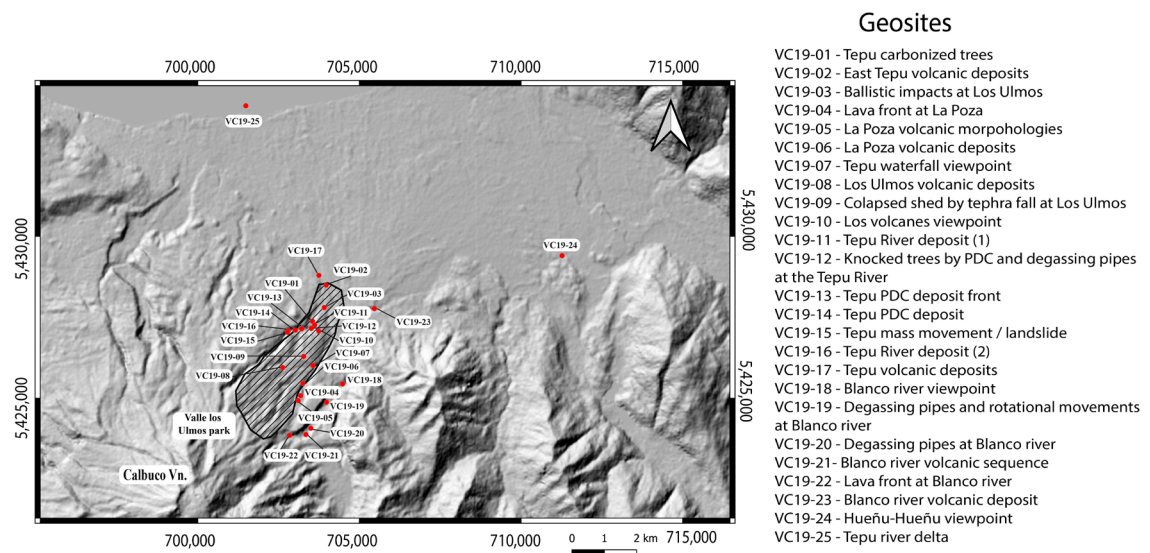


FIG. 5. Map showing the location of the 25 geosites identified in the present study (red dots). The striped, black area is the Valle Los Ulmos Park, where most of the geosites were accessed through.

TABLE 1. SCIENTIFIC VALUE OF EACH OF THE 25 GEOSITES.

Uses/Values	Criteria	Weight	VC19-01	VC19-02	VC19-03	VC19-04	VC19-05	VC19-06	VC19-07	VC19-08	VC19-09	VC19-10	VC19-11	VC19-12	VC19-13	VC19-14	VC19-15	VC19-16	VC19-17	VC19-18	VC19-19	VC19-20	VC19-21	VC19-22	VC19-23	VC19-24	VC19-25
Scientific value	Representativeness	30	1	4	4	4	4	2	2	4	4	4	1	2	2	2	2	2	4	4	4	1	2	4	4	4	1
	Key locality	20	1	1	0	4	4	1	0	4	0	4	1	1	0	1	1	2	4	4	1	1	2	4	4	1	1
	Scientific knowledge	5	0	0	0	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4	0	0
	Integrity	15	1	2	4	4	4	1	4	4	2	4	0	2	2	2	2	1	4	1	1	1	4	4	2	4	4
	Geological diversity	5	1	1	0	4	4	1	0	4	0	4	1	1	0	1	1	2	4	4	1	1	2	4	4	1	1
	Rarity	15	2	2	1	2	2	1	1	2	1	2	0	1	1	1	2	2	2	2	4	1	2	2	4	4	4
	Use limitations	10	1	1	1	0	0	0	1	1	1	4	1	0	0	0	0	0	1	0	0	0	1	0	1	1	4
TOTAL			110	215	205	330	320	115	145	320	175	350	65	130	105	130	145	155	320	265	220	85	210	315	340	275	215

Highest-score site: VC19-10 (Los Volcanes viewpoint).

TABLE 2. DIDACTIC USE OF EACH OF THE 25 GEOSITES.

Uses/ Values	Criteria	Weight	VC19-01	VC19-02	VC19-03	VC19-04	VC19-05	VC19-06	VC19-07	VC19-08	VC19-09	VC19-10	VC19-11	VC19-12	VC19-13	VC19-14	VC19-15	VC19-16	VC19-17	VC19-18	VC19-19	VC19-20	VC19-21	VC19-22	VC19-23	VC19-24	VC19-25
Didactic use	Vulnerability	10	0	2	4	0	0	0	0	4	4	4	0	1	0	0	0	0	4	4	1	1	1	1	4	4	4
	Accessibility	10	1	2	4	4	4	1	4	4	2	4	0	2	2	2	2	1	4	1	1	1	4	4	2	4	4
	Use limitations	5	0	4	2	0	0	0	0	2	2	2	0	0	0	0	0	0	4	4	2	1	1	1	0	4	0
	Safety	5	0	4	2	0	0	0	0	2	2	2	0	0	0	0	0	0	4	4	2	1	1	1	0	4	0
	Logistics	5	1	4	4	1	0	1	0	4	4	4	2	2	2	2	2	2	4	4	4	4	4	4	4	4	2
	Density of population	10	1	4	2	1	0	1	0	4	4	4	2	2	2	4	2	2	4	4	4	4	4	4	4	4	2
	Association with other values	15	1	0	1	2	1	1	1	0	2	4	1	1	1	2	2	4	2	1	1	1	0	4	1	1	0
	Scenery	10	2	2	1	2	2	1	1	2	1	2	0	1	1	1	2	4	2	2	4	1	2	2	4	4	4
	Uniqueness	5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Observation conditions	5	4	4	4	4	4	4	4	4	4	4	2	4	4	4	2	2	4	4	4	4	4	4	4	4	4
	Didactic potential	20	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	1	4	4	4	1	4	4	4	4
	Geological diversity	10	2	2	1	2	2	1	1	2	1	2	0	1	1	1	2	2	2	2	4	1	2	2	4	4	4
TOTAL			185	285	280	230	200	165	180	305	295	365	140	200	190	225	215	255	295	310	300	230	205	325	320	380	295

Highest-score sites: VC19-10 (Los Volcanes viewpoint) and VC19-22 (Lava front at Blanco river).

TABLE 3. TOURISTIC USE OF EACH OF THE 25 GEOSITES.

Uses/ Values	Criteria	Weight	VC19-01	VC19-02	VC19-03	VC19-04	VC19-05	VC19-06	VC19-07	VC19-08	VC19-09	VC19-10	VC19-11	VC19-12	VC19-13	VC19-14	VC19-15	VC19-16	VC19-17	VC19-18	VC19-19	VC19-20	VC19-21	VC19-22	VC19-23	VC19-24	VC19-25
Touristic use	Vulnerability	10	0	2	4	0	0	0	0	4	4	4	0	1	0	0	0	0	4	4	1	1	1	1	4	4	4
	Accessibility	10	1	2	4	4	4	1	4	4	2	4	0	2	2	2	2	1	4	1	1	1	4	4	2	4	4
	Use limitations	5	0	4	2	0	0	0	0	2	2	2	0	0	0	0	0	0	4	4	2	1	1	1	0	4	0
	Safety	5	0	4	2	0	0	0	0	2	2	2	0	0	0	0	0	0	4	4	2	1	1	1	0	4	0
	Logistics	5	1	4	4	1	0	1	0	4	4	4	2	2	2	2	2	2	4	4	4	4	4	4	4	4	2
	Density of population	10	1	4	2	1	0	1	0	4	4	4	2	2	2	4	2	2	4	4	4	4	4	4	4	4	2
	Association with other values	15	1	0	1	2	1	1	1	0	2	4	1	1	1	2	2	4	2	1	1	1	0	4	1	1	0
	Scenery	10	2	2	1	2	2	1	1	2	1	2	0	1	1	1	2	4	2	2	4	1	2	2	4	4	4
	Uniqueness	5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Observation conditions	5	4	4	4	4	4	4	4	4	4	4	2	4	4	4	2	2	4	4	4	4	4	4	4	4	4
	Interpretative potential	10	4	4	2	4	4	4	4	4	4	4	1	4	4	4	4	2	1	4	4	4	1	4	4	4	4
	Proximity to recreational areas	5	2	2	2	0	1	2	2	2	1	1	2	0	0	2	2	1	1	1	2	0	0	0	0	4	4
TOTAL			135	235	220	170	145	125	140	255	250	310	80	150	140	185	165	180	270	255	230	180	175	265	240	320	235

Highest-score sites: VC19-10 (Los Volcanes viewpoint) and VC19-24 (Hueñu-Hueñu viewpoint).

5.2. Characterization of selected geosites

5.2.1. VC19-10: Los Volcanoes Viewpoint

This geosite is located at the Valle Los Ulmos Park (703741 E; 5427081 N), and allows the observation of four volcanoes of the region (Calbuco, Osorno, La Picada, and Puntiatgudo) (Fig. 6; see Fig. 1 for a location map). From this site, it is possible to interpret the structural control of these volcanic centers due to the LOFZ, where ~N-S alignments prevail. Contrary to other sites, this viewpoint offers the visitor large-scale geodiversity elements. In addition, it has the potential to provide comprehensive explanations about long-term (*i.e.*, thousands of years) landscape evolution and geological processes. Thus, this geosite can be part of geotourism and educational initiatives. The accessibility criterion was positively assessed, as the geosite can be accessed either by vehicle or foot from the entrance of the Valle Los Ulmos Park. Since the site is a

viewpoint, a set of initiatives and tools regarding the interpretation of geoheritage, volcanic processes, and volcanic hazards could be implemented (*e.g.*, infographic panels). Moreover, the implementation of geotouristic routes within the park could include this geosite as a starting point.

5.2.2. VC19-22: Lava front at Blanco River

This geosite is located next to the Blanco River (702,838 E; 5,423,863 N), and shows the ~30 m-thick blocky lava flow front emplaced during the eruption of 1961 (Fig. 7A). The lava is an andesite with pyroxene, plagioclase, and amphibole crystals showing diverse textures, where pyroxenes and plagioclases form cumulates (Fig. 7B). Unlike the 1961 lava front at La Poza River (site VC19-04), the one at the Blanco River is less prominent and does not show its base, only the central, massive part of the lava is visible. The surface of the lava is mostly covered by tephra of the 2015 eruption, smoothing its blocky surface.

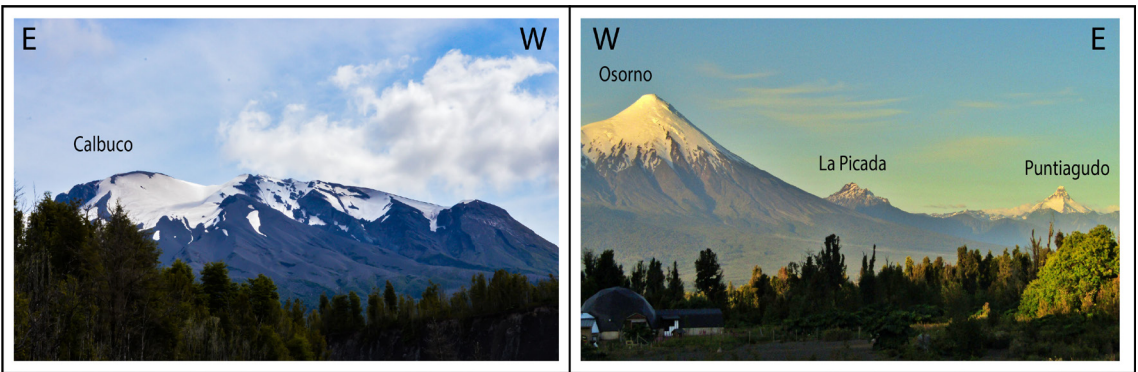


FIG. 6. Calbuco, Osorno, La Picada, and Puntiatgudo volcanoes, as observed from geosite VC19-10.

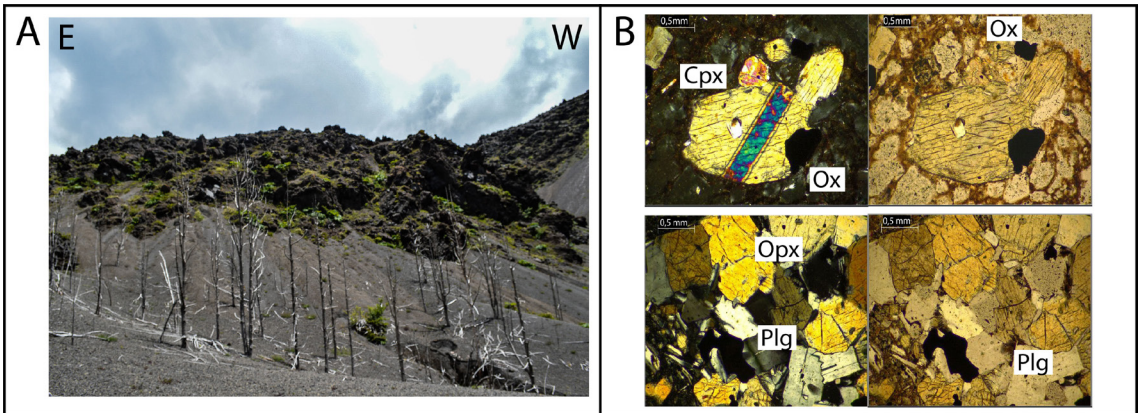


FIG. 7. **A.** The 1961 lava front along the Blanco River corresponds to the geosite VC19-22. The gray material that covers the surface is tephra fall from the 2015 Calbuco eruption, which caused the death of small trees. **B.** Thin section images of the 1961 pyroxene andesites showing sieve and porphyritic textures. Left image: crossed polars; right image: plane-polarized light. **Cpx:** Clinopyroxene, **Ox:** Oxides, **Opx:** Ortopyroxene, **Plg:** Plagioclase.

The 1961 lava flow stopped at ~1.6 km from the volcano in the La Poza River valley (VC19-04), and at ~0.6 km in the Blanco River valley (VC19-22). The accessibility criterion was also positively assessed, because the site can be reached by car, and then a walk of less than 1 km. Along this path, it is possible to visit other geosites assessed in this work, such as the Degassing Pipes and rotational movements at Blanco River (VC19-19), the Degassing pipes at Blanco River (VC19-20), and the Volcanic sequence of the Blanco River (VC19-21).

5.2.3. VC19-24: Hueñu-Hueñu Viewpoint

This geosite, located at the confluence of the Hueñu-Hueñu and Blanco rivers (711,267 E; 5,429,409 N), is very favorable in terms of accessibility. Around the site there is a bridge with a sidewalk, visited frequently due to its panoramic view (Fig. 8A). Laharic deposits up the Blanco River are of volcanological and geomorphological interest, and can be used to explain depositional and erosive processes in active fluvial systems influenced by volcanic processes as well as their interaction

with the forest (Romero *et al.*, 2023) (Fig. 8B). The Hueñu-Hueñu (Fig. 8C) and Blanco (Fig. 8B) rivers are born on the northeastern flank of Calbuco and both are anastomosed. The Blanco River has a wider flood plain, and the deposition of volcanic material has generated sand and gravel bars (Carrizo, 2019) (Fig. 8B). During the 1893-95 eruption, lahars descended through the Blanco and Hueñu-Hueñu rivers, being described as “a wall with a black superior part and a reddish inferior part, covering big part of the oriental horizon.” (Petit-Breuilh and Moreno, 1997). This observation probably refers to hot lahars.

6. Discussion

6.1. Methodology and limitations

In this study, we followed the proposal of Brilha (2016) to incorporate a quantitative methodology to inventory and assess geosites. This methodology provides a quantitative assessment of each geosite respect to a particular value or use. This is relevant

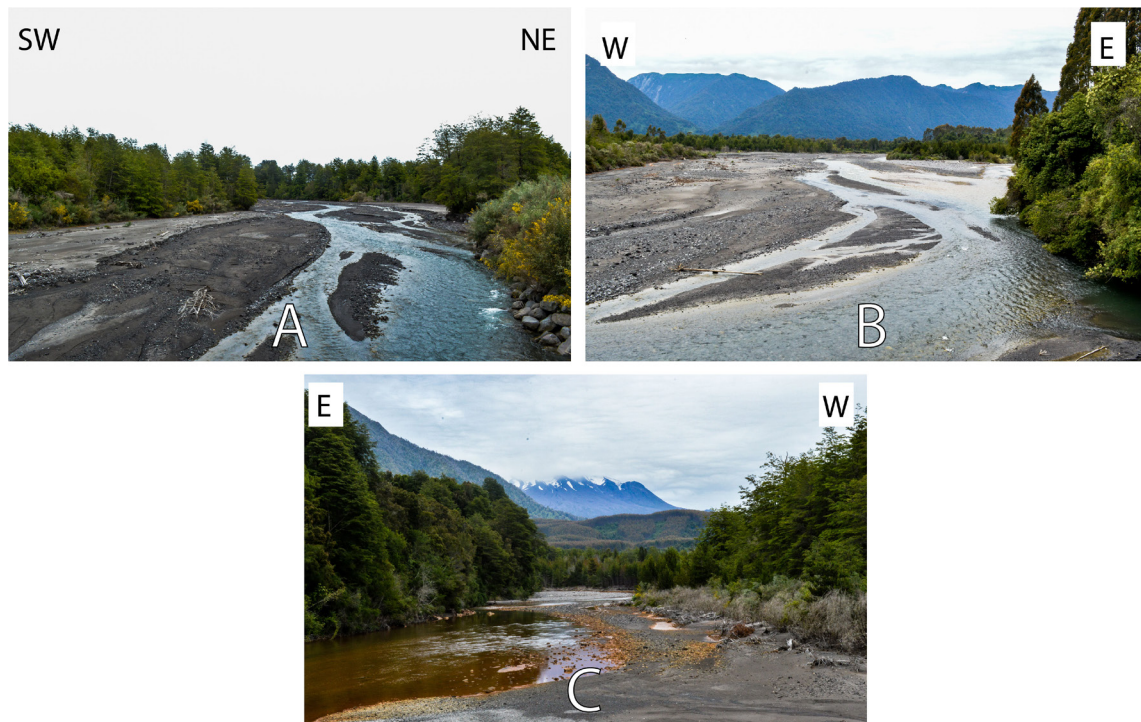


FIG. 8. **A.** The confluence of Hueñu-Hueñu and Blanco Rivers. **B.** Erosion and depositional zones in the Blanco River. **C.** Hueñu-Hueñu River view.

as in case a single score is calculated for each geosite, we are not able to identify the usefulness of each geosite in geoheritage or geoconservation strategies. Another important aspect of the Brilha (2016) methodology lies in the global use it brings, different from other methodologies, for example, Serrano and González-Trueba (2005) or Santos *et al.* (2020), that can mostly be used for landforms or rural landscapes. Brilha (2016) provides a useful methodology that can be used from landforms to deposits or even to more specific geological elements.

The methodology used in this study has some subjectivity when it comes to quantifying the geosite values and criteria, as the scores are assigned by the person or group in charge of the evaluation. By introducing a personal bias in the assessment, the results are influenced by subjective opinions and appreciations, even within the strict framework of the same evaluation criteria valid for all sites. This drawback could be overcome with additional assessments conducted by other experts, using the same methodology.

6.2. Geoconservation and geoeeducation initiatives

After selecting 25 potential geosites, they were scored accordingly. The top-three ranked geosites with the highest scientific, didactic, or touristic values were described in detail. These geosites are representative of the different processes of Calbuco volcano. Also, they hold high potential not only for scientific and educative purposes, but also for conservation and tourism. The latter is relevant as, by conserving geosites, their value can be preserved for future generations (Gray, 2008; Henriques *et al.*, 2011; Hose and Vasiljevic, 2012). Geoconservation initiatives should be framed within the scope of conservation strategies of the protected areas. Likewise, valorization initiatives are needed, aiming to promote conservation and local socioeconomic development through geotourism and educational tools.

Azman *et al.* (2010), Henriques *et al.* (2011), and Sánchez (2011) state the importance of using geoheritage in the education of local communities, especially those that are more exposed to volcanic processes. Calbuco volcano represents a serious geological hazard to the population of Ensenada. A recent study conducted by Alegría

and Vergara-Pinto (2024) shows that people living in Ensenada are eager to participate in future emergency management planning and adopt preventive attitudes at local, household, and individual levels. The implementation of tailored educative and touristic initiatives can be improved with interactive information about volcanic processes and hazards. The sustainable use of the selected geosites for education about Earth and environmental sciences can therefore contribute to volcanic risk reduction in the region.

7. Conclusions

The geological heritage sites studied in this contribution can be used to explain active geological processes in the Calbuco volcano area. The geosites contain diverse volcanic deposits, landforms, and lithologies that can be used for educational purposes.

The inventory of 25 geosites allows not only the compilation of information under the same criteria, but represents a systematic way to provide comparisons and the selection of the most relevant sites. This methodological approach can be implemented in future studies in other similar volcanic regions. Regarding the Calbuco volcano area, the addition of further geosites to the inventory provided here is encouraged for a more detailed characterization and the gradual inclusion of geoconservation and geotourism initiatives.

The systematic assessment of geosites to increase scientific knowledge and awareness of volcanic processes and hazards can benefit the local population through social and economic development. Geotourism activities in a specific area can be an incentive for local economic development and a way to educate the population about geodiversity, geoheritage, and geological hazard topics. Geoconservation and geotourism strategies will require the participation of local entities, such as local government, universities, local associations, and research and nature conservation institutions.

Acknowledgements

The authors are grateful to R. Rivera, P. Martínez, and one anonymous reviewer for their critical reviews that contributed to improve this manuscript. The editorial handling of D. Bertin, together with constructive ideas and suggestions, is also acknowledged.

References

- Alegria, C.; Vergara-Pinto, F. 2024. Living in-between: Implications of local risk perceptions for the management of future eruptions at the Calbuco and Osorno volcanoes (Ensenada, Chile). *Andean Geology* 51 (1): 63-85. doi: <http://dx.doi.org/10.5027/andgeoV51n1-3668>
- Amores, A.; Monserrat, S.; Marcos, M.; Argüeso, D.; Villalonga, J.; Jordà, G.; Gomis, D. 2022. Numerical simulation of atmospheric Lamb waves generated by the 2022 Hunga-Tonga volcanic eruption. *Geophysical Research Letters*: e2022GL098240. doi: <https://doi.org/10.1029/2022GL098240>
- Arzilli, F.; Morgavi, D.; Petrelli, M.; Polacci, M.; Burton, M.; Di Genova, D.; Spina, L.; La Spina, G.; Hartley, M.; Romero, J.E.; Fellowes, J.; Díaz-Alvarado, J.; Perugini, D. 2019. The unexpected explosive sub-Plinian eruption of Calbuco volcano (22-23 April 2015; southern Chile): Triggering mechanism implications. *Journal of Volcanology and Geothermal Research* 378: 35-50. doi: <https://doi.org/10.1016/j.jvolgeores.2019.04.006>
- Azman, N.; Halim, S.A.; Liu, O.P.; Saidin, S.; Komoo, I. 2010. Public education in heritage conservation for geopark community. *Procedia-Social and Behavioral Sciences* 7: 504-511.
- Bertin, D.; Amigo, Á.; Mella, M.; Astudillo, V.; Bertin, L.; Bucchi, F. 2015. Erupción del volcán Calbuco 2015: Estratigrafía eruptiva y volumen involucrado. *In* Congreso Geológico Chileno, No. 14, Actas: 132-135. La Serena.
- Brilha, J. 2016. Inventory and Quantitative Assessment of Geosites and Geodiversity Sites: A Review. *Geoheritage* 8: 119-134.
- Carcavilla, L.; Durán, J.J.; López-Martínez, J. 2008. Geodiversidad: concepto y relación con el patrimonio geológico. *Geo-Temas* 10: 1299-1303.
- Carracedo, J.C.; Troll, V.R.; Day, J.M.; Junca, M.A.; Soler, V.; Deegan, F.; Pérez-Torrado, F.; Gisber, G.; Gazel, E.; Rodríguez-González A.; Albert, H. 2022. The 2021 eruption of the Cumbre Vieja Volcanic Ridge on La Palma, Canary Islands. *Geology Today*, 38: 94-107.
- Carrizo, V.Z. 2019. Evolución geomorfológica del río Blanco Este después de erupciones del Volcán Calbuco (sur Chile). Tesis de Magister (Inédito), Universidad Austral de Chile: 75 p.
- Castruccio, A.; Clavero, J.; Segura, A.; Samaniego, P.; Roche, O.; Le Pennec, J.L.; Droguett, B. 2016. Eruptive parameters and dynamics of the April 2015 sub-Plinian eruptions of Calbuco volcano (southern Chile). *Bulletin of Volcanology* 78 (9): 62. doi: <https://doi.org/10.1007/s00445-016-1058-8>
- Clavero, J.; Godoy, E.; Arancibia, G.; Rojas, R.; Moreno, H. 2008. Multiple Holocene sector collapses at Calbuco volcano, Southern Andes. *In* International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI), General Assembly: p. 41 Reykjavik.
- Cembrano, J.; Lara, L. 2009. The link between volcanism and tectonics in the southern volcanic zone of the Chilean Andes: a review. *Tectonophysics* 471 (1-2): 96-113.
- Daga, R.; Guevara, S.R.; Poire, D.G.; Arribére, M. 2014. Characterization of tephra dispersed by the recent eruptions of volcanoes Calbuco (1961), Chaitén (2008) and Cordón Caulle Complex (1960 and 2011), in Northern Patagonia. *Journal of South American Earth Sciences* 49: 1-14.
- DeMets, C.; Gordon, R.G.; Argus, D.F. 2010. Geologically current plate motions. *Geophysical Journal International* 181 (1): 1-80. doi: <https://doi.org/10.1111/j.1365-246X.2009.04491.x>
- Dóniz-Páez, J.; Becerra-Ramírez, R.; Németh, K.; Gosálvez, R.U.; Lahoz, E.E. 2024. Geomorfositos de interés geoturístico del volcán monogenético Tajogaite, erupción de 2021 (La Palma, Islas Canarias, España). *Geofísica Internacional* 63 (1): 731-748. doi: <https://doi.org/10.22201/igef.2954436xe.2024.63.1.1731>
- Driedger, C.L.; Major, J.J.; Pallister, J.S.; Clynnne, M.A.; Moran, S.C.; Westby, E.G.; Ewert, J.W. 2020. Ten ways Mount St. Helens changed our world-The enduring legacy of the 1980 eruption. *United States Geological Survey Fact Sheet* 2020-3031: 6 p. doi: <https://doi.org/10.3133/fs20203031>
- Ferreira, I. 2017. Caracterización de geositos para la protección y conservación del patrimonio geológico del municipio Baracoa. Memoria de Título (Inédito), Facultad de Geología y Minas, Departamento de Geología, Instituto Superior Minero Metalúrgico de Moa. doi: <https://doi.org/10.13140/RG.2.2.31798.11844>
- Gray, M. 2004. *Geodiversity: Valuing and conserving abiotic nature*. John Wiley and Sons, Ltd.: 450 p. Chichester.
- Gray, M. 2008. *Geodiversity: A new paradigm for valuing and conserving geoheritage*. *Geoscience Canada* 35: 51-59.
- Hayes, J.L.; Calderón, R.; Deligne, N.I.; Jenkins, S.F.; Leonard, G.S.; McSporran, A.M.; Williams, G.T.; Wilson, T.M. 2019. Timber-framed building damage from tephra fall and lahar: 2015 Calbuco eruption, Chile. *Journal of Volcanology and Geothermal Research* 374: 142-159.
- Henriques, M.; Pena dos Reis, R.; Brilha, J.; Mota, T. 2011. Geoconservation as an emerging geoscience. *Geoheritage* 3: 117-128.

- Hose, T.; Vasiljevic, A. 2012. Defining the nature and purpose of modern geotourism with particular reference to the United Kingdom and south-east Europe. *Geoheritage* 4: 25-43.
- Houghton, B.F.; Cockshell, W.A.; Gregg, C.E.; Walker, B.H.; Kim, K.; Tisdale, C.M.; Yamashita, E. 2021. Land, lava, and disaster create a social dilemma after the 2018 eruption of Kīlauea volcano. *Nature Communications* 12 (1): 1-4.
- Klohn, E. 1963. The February 1961 eruption of Calbuco volcano. *Bulletin of the Seismological Society of America* 53: 1435-1436.
- Le Mével, H.; Miller, C.A.; Ribó, M.; Cronin, S.; Kula, T. 2023. The magmatic system under Hunga volcano before and after the 15 January 2022 eruption. *Science Advances* 9 (50): eadh3156. doi: <https://doi.org/10.1126/sciadv.adh3156>
- López-Escobar, L.; Parada, M.A.; Moreno, H.; Frey, F.A.; Hickey-Vargas, R.L. 1992. A contribution to the petrogenesis of Osorno and Calbuco volcanoes, Southern Andes (41°00'-41°30' S): comparative study. *Revista Geológica de Chile* 19 (2): 211-226.
- López-Escobar, L.; Parada, M.A.; Hickey-Vargas, R.; Frey, F.A.; Kempton, P.D.; Moreno, H. 1995. Calbuco Volcano and minor eruptive centers distributed along the Liquiñe-Ofqui Fault Zone, Chile (41-42 S): contrasting origin of andesitic and basaltic magma in the Southern Volcanic Zone of the Andes. *Contributions to Mineralogy and Petrology* 119 (4): 345-361.
- Manville, V.; Neuberg, J.; Jones, R.; Calder, E.; Mudd, S. 2018. Morpho-sedimentary responses to explosive volcanism: aftermath of the 22-23 April 2015 Calbuco eruption, southern Chile. *EGU General Assembly. Geophysical Research Abstracts* 20: EGU2018-8643.
- Martínez, P. 2010. Identificación, Caracterización y Cuantificación de Geositos, para la Creación del I Geoparque en Chile, en Torno al Parque Nacional Conguillío. *Memoria de Título (Inédito)*, Universidad de Chile, Departamento de Geología: 172 p.
- Mella, M.; Moreno, H.; Vergés, A.; Quiroz, D.; Bertin, L.; Basualto, D.; Bertin, D.; Garrido, N. 2015. Productos volcánicos, impactos y respuesta a la emergencia del ciclo eruptivo abril-mayo (2015) del Volcán Calbuco. *In Congreso Geológico Chileno*, No. 14, Actas: 98-101. La Serena.
- Mixon, E.E.; Singer, B.S.; Jicha, B.R.; Ramírez, A. 2021. Calbuco, a monotonous andesitic high-flux volcano in the Southern Andes, Chile. *Journal of Volcanology and Geothermal Research* 416: 107279. doi: <https://doi.org/10.1016/j.jvolgeores.2021.107279>
- Mondéjar, F.G.; del Ramo Jiménez, A. 2004. Patrimonio geológico y geodiversidad de la Molata de Charán (Moratalla, Murcia). *Geo-Temas* 6 (4): 103-106.
- Moreno, H. 1999. Mapa de peligros del volcán Calbuco, Región de Los Lagos. Servicio Nacional de Geología y Minería, Documentos de Trabajo 12, 1 mapa escala 1:75:000. Santiago.
- Moreno, H.; Naranjo, J.A.; Clavero, J. 2006. Generación de lahares calientes en el volcán Calbuco, Andes del sur de Chile (41,3° S). *In Congreso Geológico Chileno*, No. 9, Actas: 512-513. Antofagasta.
- Morgado, E.; Morgan, D.J.; Harvey, J.; Parada, M.A.; Castruccio, A.; Brahm, R.; Gutiérrez, F.; Georgiev, B.; Hammond, S.J. 2019. Localised heating and intensive magmatic conditions prior to the 22-23 April 2015 Calbuco volcano eruption (Southern Chile). *Bulletin of Volcanology* 81 (24): 1-21. doi: <https://doi.org/10.1007/s00445-019-1280-2>
- Munizaga, F.; Hervé, F.; Drake, R.; Pankhurst, R.J.; Brook, M.; Snelling, N. 1988. Geochronology of the Lake Region of south-central Chile (39-42° S): Preliminary results. *Journal of South American Earth Sciences* 1 (3): 309-316.
- Orozco, O.G. 2009. Sistema de Centros Eruptivos de Flanco de la Erupción de 1835 AD, Volcán Osorno (SCEFVO-1835): Significado Tectónico. *Memoria de Título (Inédito)*, Universidad de Chile, Departamento de Geología: 69 p.
- Pantoja, I.A. 2017. Geopatrimonio de la península La Carmela, región de Aysén, Chile. *Memoria de Título (Inédito)*, Universidad de Andrés Bello, Departamento de Geología: 125 p. Santiago.
- Pardini, F.; Burton, M.; Arzilli, F.; La Spina, G.; Polacci, M. 2018. SO₂ emissions, plume heights and magmatic processes inferred from satellite data: The 2015 Calbuco eruptions. *Journal of Volcanology and Geothermal Research* 361: 12-24.
- Petit-Breuilh, M.E. 1999. Cronología eruptiva histórica de los volcanes Osorno y Calbuco, Andes del Sur (41°-41°30'S). *Servicio Nacional de Geología y Minería, Boletín* 53: 46 p. Santiago.
- Petit-Breuilh, M.E.; Moreno, H. 1997. La erupción de 1893-1895 del volcán Calbuco (41.3°S) y sus efectos ambientales. *In Congreso Geológico Chileno*, No. 8, Actas: 780-784. Antofagasta.
- Purkis, S.J.; Ward, S.N.; Fitzpatrick, N.M.; Garvin, J.B.; Slayback, D.; Cronin, S.J.; Palaseanu-Lovejoy, M.; Dempsey, A. 2023. The 2022 Hunga-Tonga megatsunami: Near-field simulation of a once-in-a-century event. *Science Advances* 9 (15): eadf5493. doi: <https://doi.org/10.1126/sciadv.adf5493>

- Romero, J.E.; Morgavi, D.; Arzilli, F.; Daga, R.; Caselli, A.; Reckziegel, F.; Viramonte, J.; Díaz-Alvarado, J.; Polacci, M.; Burton, M.; Perugini, D. 2016. Eruption dynamics of the 22-23 April 2015 Calbuco Volcano (southern Chile): Analyses of tephra fall deposits. *Journal of Volcanology and Geothermal Research* 317: 15-29. doi: <https://doi.org/10.1016/j.jvolgeores.2016.02.027>
- Romero, J.E.; Alloway, B.V.; Gutiérrez, R.; Bertin, D.; Castruccio, A.; Villarosa, G.; Schipper, I.; Guevara, A.; Bustillos, J.; Pisello, A.; Daga, R.; Montiel, M.; Gleeman, E.; González, M.; Morgavi, D.; Riveiro Guevara, S.; Mella, M. 2021. Centennial-scale eruptive diversity at Volcán Calbuco (41.3° S; Northwest Patagonia) deduced from historic tephra cover-bed and dendrochronologic archives. *Journal of Volcanology and Geothermal Research* 417: 107281. doi: <https://doi.org/10.1016/j.jvolgeores.2021.107281>
- Romero, J.E.; Burton, M.; Cáceres, F.; Taddeucci, J.; Civico, R.; Ricci, T.; Pankhurst, M.J.; Hernández, P.A.; Bonadonna, C.; Llewellyn, E.W.; Pistolesi, M.; Polacci, M.; Solana, C.; D'Auria, L.; Arzilli, F.; Andronico, D.; Rodríguez, F.; Asensio-Ramos, M.; Martín-Lorenzo, A.; Hayer, C.; Scarlato, P.; Pérez, N.M. 2022. The initial phase of the 2021 Cumbre Vieja ridge eruption (Canary Islands): Products and dynamics controlling edifice growth and collapse. *Journal of Volcanology and Geothermal Research* 431: 107642. doi: <https://doi.org/10.1016/j.jvolgeores.2022.107642>
- Romero, J.; Swanson, F.; Jones, J.; Morgavi, D.; Giordano, G.; Trolese, M.; Aguilera, F.; Izquierdo, T.; Perugini, D. 2023. The April 2015 Calbuco eruption pyroclastic density currents: deposition, impacts on woody vegetation, and cooling on the northern flank of the cone. *Andean Geology* 50 (3): 319-345. doi: <https://dx.doi.org/10.5027/andgeoV50n3-3650>
- Sánchez, J.L. 2011. Geoconservación y Geoparques en el contexto global: Una visión holística para América Latina y El Caribe. *In* Congreso Nacional de Geoturismo, No. 2, Vol. 203 (5). Fundación Geoparques de Venezuela: 12 p. San Felipe.
- Sangeetha, S.K.; Sivakumar, V.; Gebreslasie, M. 2018. Long-range transport of SO₂ over South Africa: A case study of the Calbuco volcanic eruption in April 2015. *Atmospheric Environment* 185: 78-90. doi: <https://doi.org/10.1016/j.atmosenv.2018.04.056>
- Santos, D.S.; Mansur, K.L.; Seoane, J.C.; Mucivuna, V.C.; Reynard, E. 2020. Methodological proposal for the inventory and assessment of geomorphosites: an integrated approach focused on territorial management and geoconservation. *Environmental Management* 66: 476-497.
- Sellés, D.; Moreno, H. 2011. Geología del volcán Calbuco, Región de Los Lagos. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 130: 38 p., 1 mapa escala 1:50.000. Santiago.
- Serrano, E.; González-Trueba, J.J. 2005. Assessment of geomorphosites in natural protected areas: the Picos de Europa National Park (Spain). *Géomorphologie: Relief, Processus, Environment* 11 (3): 197-208.
- Stern, C.R. 2004. Active Andean volcanism: its geologic and tectonic setting. *Revista Geológica de Chile* 31 (2): 161-206.
- Stone, J. 1930. Two active volcanoes of Chile. *The Volcano Letter* 284. Hawaiian Volcano Observatory: 284 p. Hawaii.
- Urrutia, P. 2018. Identificación, caracterización y cuantificación del patrimonio geológico de la zona Sur de la Reserva de la Biósfera corredor biológico Nevados de Chillán, Laguna del Laja, Región del BioBío, Chile. Memoria de Título (Inédito), Universidad de Concepción, Departamento de Geología: 225 p. Concepción. *In* Cities on volcanoes Congress 9. Puerto Varas.
- Vander Auwera, J.; Namur, O.; Dutrieux, A.; Wilkinson, C.M.; Ganerød, M.; Coumont, V.; Bolle, O. 2019. Mantle melting and magmatic processes under La Picada stratovolcano (CSVZ, Chile). *Journal of Petrology* 60 (5): 907-944.
- Vander Auwera, J.; Montalbano, S.; Namur, O.; Bechon, T.; Schiano, P.; Devidal, J.L.; Bolle, O. 2021. The petrology of a hazardous volcano: Calbuco (Central Southern Volcanic Zone, Chile). *Contributions to Mineralogy and Petrology* 176 (6): 1-34.
- Yuen, D.A.; Scruggs, M.A.; Spera, F.J.; Zheng, Y.; Hu, H.; McNutt, S.R.; Thompson, G.; Mandli, K.; Keller, B.L.; Shawn Wei, S.; Peng, Z.; Zhou, Z.; Mulargia, F.; Tanioka, Y. 2022. Under the Surface: Pressure-Induced Planetary-Scale Waves, Volcanic Lightning, and Gaseous Clouds Caused by the Submarine Eruption of Hunga Tonga-Hunga Ha'apai Volcano Provide an Excellent Research Opportunity. *Earthquake Research Advances* 2 (3). doi: <https://doi.org/10.1016/j.eqrea.2022.100134>
- Zellmer, G.F.; Freymuth, H.; Cembrano, J.M.; Clavero, J.E.; Veloso, E.A.; Sielfeld, G.G. 2014. Altered mineral uptake into fresh arc magmas: insights from U-Th isotopes of samples from Andean volcanoes under differential crustal stress regimes. *Geological Society, London, Special Publications* 385 (1): 185-208.

- Zhu, Y.; Toon, O.B.; Kinnison, D.; Harvey, V.L.; Mills, M.J.; Bardeen, C.G.; Pitts, B.; Begue, N.; Renard, J-B.; Berthet, G.; Jégou, F. 2018. Stratospheric aerosols, polar stratospheric clouds, and polar ozone depletion after the Mount Calbuco eruption in 2015. *Journal of Geophysical Research: Atmospheres* 123 (21): 12-308.

Manuscript received: February 09, 2023; revised/accepted: April 29, 2024; available online: April 29, 2024.

Appendix

TABLE A1. DETAIL OF EACH CRITERION WITH ITS RESPECTIVE PARAMETER AND SCORES ASSIGNED. EXTRACTED FROM BRILHA (2016).

Use/Value	Criterion	Parameter	Score
Scientific value	Representativeness	The geosite is the best example in the study area to illustrate elements or processes, related with the geological framework under consideration.	4
		The geosite is a good example in the study area to illustrate elements or processes, related with the geological framework under consideration.	2
		The geosite reasonably illustrates elements or processes in the study area, related with the geological framework under consideration.	1
	Key locality	The geosite recognized as a GSSP or ASSP by the IUGs or is an IMA reference site.	4
		The geosite is used by international science, directly related with the geological framework under consideration.	2
		The geosite is used by national science, directly related with the geological framework under consideration.	1
	Scientific knowledge	There are papers in international scientific journals about this geosite, directly related with the geological framework under consideration.	4
		There are papers in national scientific journals about this geosite, directly related with the geological framework under consideration.	2
		There are abstracts presented in international scientific events about this geosite, directly related with the geological framework under consideration.	1
	Integrity	The main geological elements (related with the geological framework under consideration, when applicable) are very well preserved.	4
		Geosite not so well preserved, but the main geological elements (related with the geological framework under consideration, when applicable) are still preserved.	2
		Geosite with preservation problems and the main geological elements (related with the geological framework under consideration, when applicable) are quite altered or modified.	1
	Geological diversity	Geosite with more than three types of distinct geological features with scientific relevance.	4
		Geosite with three types of distinct geological features with scientific relevance.	2
		Geosite with two types of distinct geological features with scientific relevance.	1
	Rarity	The geosite is the only occurrence of this type in the study area (representing the geological framework under consideration, when applicable).	4
		In the study area, there are two or three examples of similar geosites (representing the geological framework under consideration, when applicable).	2
		In the study area, there are four or more examples of similar geosites (representing the geological framework under consideration, when applicable).	1
	Use limitations	The geosite has no limitations (e.g., legal permissions, physical barriers) for sampling or fieldwork.	4
		It is possible to collect samples and do fieldwork after overcoming the limitations.	2
		Sampling and fieldwork are very hard to be accomplished due to limitations difficult to overcome (e.g., legal permissions, physical barriers).	1

Table A1 continued.

Use/Value	Criterion	Parameter	Score
Didactic and touristic uses	Vulnerability	The geological elements of the geosite present no possible deterioration by anthropic activity.	4
		There is a possibility of deterioration of secondary geological elements by anthropic activity.	3
		There is a possibility of deterioration of main geological elements by anthropic activity.	2
		There is a possibility of deterioration of all geological elements by anthropic activity.	1
	Accessibility	Site located less than 100 m from a paved road with bus parking .	4
		Site located less than 500 m from a paved road.	3
		Site accessible by bus through gravel road.	2
		Site with no direct access by road but located less than 1 km from a road accessible by bus.	1
	Use limitations	The site has no limitations to be used by students and tourists.	4
		The site can be used by students and tourists but only occasionally.	3
		The site can be used by students and tourists but only after overcoming limitations (e.g., legal permissions, physical barriers).	2
		The use by students and tourists is very hard to be accomplished due to limitations difficult to overcome (e.g., legal permissions, physical barriers).	1
	Safety	Site with safety facilities (e.g., fences, stairs, handrails), mobile phone coverage, and located less than 5 km from emergency services.	4
		Site with safety facilities (e.g., fences, stairs, handrails), mobile phone coverage, and located less than 25 km from emergency services.	3
		Site with no safety facilities but with mobile coverage and located less than 50 km from emergency services.	2
		Site with no safety facilities, no mobile coverage, and located more than 50 km from emergency services.	1
	Logistics	Lodging and restaurants for groups of 50 people less than 15 km away from the site.	4
		Lodging and restaurants for groups of 50 people less than 50 km away from the site.	3
		Lodging and restaurants for groups of 50 people less than 100 km away from the site.	2
		Lodging and restaurants for groups less than 25 people and less than 50 km away from site.	1
	Density of population	Site located in a municipality with more than 1000 inhabitants/km ² .	4
		Site located in a municipality with 250-1000 inhabitants/km ² .	3
		Site located in a municipality with 100-250 inhabitants/km ² .	2
		Site located in a municipality with less than 100 inhabitants/km ² .	1
	Association with other values	Occurrence of several ecological and cultural values less than 5 km away from the site.	4
		Occurrence of several ecological and cultural values less than 10 km away from the site.	3
		Occurrence of one ecological value and one cultural value less than 10 km away from the site.	2
		Occurrence of one ecological value or one cultural value less than 10 km away from the site.	1

Table A1 continued.

Use/Value	Criterion	Parameter	Score
Didactic and touristic uses	Scenery	Site currently used as a tourism destination in national campaigns.	4
		Site occasionally used as a tourism destination in national campaigns.	3
		Site currently used as a tourism destination in local campaigns.	2
		Site occasionally used as a tourism destination in local campaigns.	1
	Uniqueness	The site shows unique and uncommon features considering this and neighboring countries.	4
		The site shows unique and uncommon features in the country.	3
		The site shows common features in this region but they are uncommon in the other regions of the country.	2
		The site shows features rather common in the whole country.	1
	Observation conditions	All geological elements are observed in good conditions.	4
		There are some obstacles that make difficult the observation of some geological elements.	3
		There are some obstacles that make difficult the observation of the main geological elements.	2
		There are some obstacles that almost obstruct the observation of the main geological elements.	1
Didactic use	Didactic potential	The site presents geological elements that are taught in all teaching levels.	4
		The site presents geological elements that are taught in elementary levels.	3
		The site presents geological elements that are taught in secondary levels.	2
		The site presents geological elements that are taught in the university.	1
	Geological diversity	More than 3 types of geodiversity elements occur in the site (<i>e.g.</i> , mineralogical, paleontological, geomorphological).	4
		There are 3 types of geodiversity elements in the site.	3
		There are 2 types of geodiversity elements in the site.	2
		There is only 1 type of geodiversity element in the site.	1
Touristic use	Interpretative potential	The site presents geological elements in a very clear and expressive way to all types of public.	4
		The public needs to have some geological background to understand the geological elements of the site.	3
		The public needs to have a solid geological background to understand the geological elements of the site.	2
		The site presents geological elements only understandable to geological experts.	1
	Proximity to recreational areas	Site located less than 5 km from a recreational area or touristic attraction.	4
		Site located less than 10 km from a recreational area or touristic attraction.	3
		Site located less than 15 km from a recreational area or touristic attraction.	2
		Site located less than 20 km from a recreational area or touristic attraction.	1

Table A1 continued.

Use/Value	Criterion	Parameter	Score
Degradation risk	Deterioration of geological elements	Possibility of deterioration of all geological elements.	4
		Possibility of deterioration of the main geological elements.	3
		Possibility of deterioration of secondary geological elements.	2
		Minor possibility of deterioration of secondary geological elements.	1
	Proximity to areas/ activities with potential to cause degradation	Site located less than 50 m of a potential degrading area/activity.	4
		Site located less than 200 m of a potential degrading area/activity.	3
		Site located less than 500 m of a potential degrading area/activity.	2
		Site located less than 1 km of a potential degrading area/activity.	1
	Legal protection	Site located in an area with no legal protection and no control of access.	4
		Site located in an area with no legal protection but with a control of access.	3
		Site located in an area with legal protection but no control of access.	2
		Site located in an area with legal protection and control of access.	1
	Density of population	Site located in a municipality with more than 1000 inhabitants/km ² .	4
		Site located in a municipality with 250-1000 inhabitants/km ² .	3
		Site located in a municipality with 100-250 inhabitants/km ² .	2
		Site located in a municipality with less than 100 inhabitants/km ² .	1
	Accessibility	Site located less than 100 m from a paved road with bus parking.	4
		Site located less than 500 m from a paved road .	3
		Site accessible by bus through gravel road.	2
		Site with no direct access by road but located less than 1 km from a road accessible by bus.	1

TABLE A2. SUMMARIZED INFORMATION OF THE 25 POTENTIAL GEOSITES ON THE NORTHERN FLANK OF CALBUCO.

Code	UTM coordinates (WGS84/18S)		Geosite	Description
	E	N		
VC19-01	703,549	5,427,384	Tepu carbonized trees	Observation site, where due to a PDC several trees were knocked down and carbonized. The direction of the flow can be distinguished, as well as the cooling processes in the trees (in a radial manner).
VC19-02	703,975	5,428,503	East Tepu volcanic deposits	Located in the banks of the Tepu river, there are tephra fall and laharic deposits (the latter showing hyperconcentrated and debris flow rheologies).
VC19-03	703,910	5,427,808	Ballistic impacts at Los Ulmos	Within the Valle Los Ulmos Park, there are 2 sheds that were affected by ballistic impacts during the 2015 eruption.
VC19-04	703,179	5,425,084	Lava front at La Poza	Along the La Poza river, there is a lava front from the 1961 eruption. It has a height of ~50 m, an andesitic composition, and a predominant massive appearance.
VC19-05	703,104	5,424,933	La Poza volcanic morphologies	Viewpoint site over the geosite VC19-04. Diverse morphologies are visible (e.g., leveés, PDC fronts, lava blocks).
VC19-06	703,254	5,425,467	La Poza volcanic deposits	Volcanic deposits next to La Poza River that consist of 3 visible levels: PDC, tephra fall and laharic.
VC19-07	703,563	5,426,019	Tepu waterfall viewpoint	Waterfall visible from the path of geomorphological and observational value.
VC19-08	702,628	5,425,955	Los Ulmos volcanic deposits	Excavation site digged to study a deposit of 17 levels (PDC, tephra fall, lahar, and andosol). It has a high didactic and scientific value.
VC19-09	703,274	5,426,297	Collapsed shed by tephra fall at Los Ulmos	Towards the site VC19-08, there is a shed that collapsed by the weight of accumulated tephra during the 2015 eruption. By excavating near the fence, the amount of tephra accumulated is visible.
VC19-10	703,741	5,427,081	Los Volcanes viewpoint	Viewpoint site where 4 volcanoes are visible: Calbuco, Osorno, Puntagudo, and La Picada. It is very accessible (even by car) and has a high didactical value.
VC19-11	703,614	5,427,269	Tepu River deposit (1)	Through the Tepu River, PDCs eroded the riverbed and all of the vegetation in between. Here, the morphology, granulometry and behavior of different PDCs can be studied.
VC19-12	703,513	5,427,164	Knocked trees by PDC and degassing pipes at the Tepu river	Site where there are abundant trees that were knocked down due to a PDC. Site also important to study several degassing pipes sourced from the same PDCs.
VC19-13	703,217	5,427,151	Tepu PDC deposit front	PDC front in the Tepu river that shows how the flow decreased in energy until it finally stopped. The morphology of the flow is different in the front (blocks), where lobes are also distinguished.
VC19-14	703,016	5,427,108	Tepu PDC deposit	A 10 m-high PDC deposit. It mainly shows levels of pyroclastic deposits, but also pre-eruptive (with organic matter) and laharic levels.
VC19-15	702,800	5,427,094	Tepu mass movement / landslide	Site that should be observed from the distance, because the hillside was already affected by a mass movement. It is possible to see two laharic pulses, distinguished due to their different grain sizes and structures.
VC19-16	702,772	5,427,043	Tepu River deposit (2)	Eroded PDC deposit with a sharp appearance towards the top, located in the middle of the riverbed. Towards the west, there is an outcrop where columnar joints are visible, with basal laminar appearance.
VC19-17	703,745	5,428,801	Tepu volcanic deposits	Deposit 5 m-high where the levels have no lateral continuity. It presents an eroded base level.

Table A2 continued.

Code	UTM coordinates (WGS84/18S)		Geosite	Description
	E	N		
VC19-18	704,479	5,425,451	Blanco river viewpoint	Viewpoint site in the Blanco river, where the main element is the evolution of the riverbed. Several PDC and laharc pulses are recognized, showing how the area has been affected repeatedly by diverse volcanic processes.
VC19-19	703,982	5,424,883	Degassing pipes and rotational movements at Blanco river	Rotational movements are present in the river banks, where degassing pipes weakened the ground, leading to the creation of these “spoon-like” morphologies.
VC19-20	703,498	5,424,080	Degassing pipes at Blanco river	Abundant degassing pipes that are recognized as white circles in the ground. Pipes caused by a PDC.
VC19-21	703,345	5,423,888	Blanco river volcanic sequence	Deposit 50 m-high, where two lava flows and three tephra fall levels are distinguished. Different parts of the lava flow can be recognized due to their morphology (laminar, columnar joints, massive).
VC19-22	702,838	5,423,863	Lava front at Blanco river	Lava front of andesitic composition and massive appearance located in the Blanco river. Lava mainly covered by the 2015 tephra.
VC19-23	705,463;	5,427,773	Blanco river volcanic deposit	Deposit 15 m-high that shows levels of diverse origin (PDC, lahar, andosol, and tephra fall). The deposit shows different volcanic processes that occurred and interacted within the same context.
VC19-24	711,267	5,429,409	Hueñu-ueñu viewpoint	Confluence of the Tepu and Hueñu-Hueñu rivers, where the depositional and eroded zones are visible. Important to visualize the interaction between these rivers and volcanic material from Calbuco volcano.
VC19-25	701,488	5,434,037	Tepu river delta	Delta located at the end of the Tepu river, in the Llanquihue lake. Polymictic deposit with sub-rounded clasts.

TABLE A3. QUANTIFICATION PROCEDURE FOR THE SELECTION OF THE TOP-THREE GEOSITES TO BE CHARACTERIZED IN DETAIL.

Uses/Values	Criteria	Weight	VC19-01	VC19-02	VC19-03	VC19-04	VC19-05	VC19-06	VC19-07	VC19-08	VC19-09	VC19-10	VC19-11	VC19-12	VC19-13	VC19-14	VC19-15	VC19-16	VC19-17	VC19-18	VC19-19	VC19-20	VC19-21	VC19-22	VC19-23	VC19-24	VC19-25
Scientific value	Representativeness	30	1	2	2	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	1	2	2	2	4	2
	Key locality	20	1	1	0	4	4	1	0	4	0	4	1	1	0	1	1	2	4	4	1	1	2	4	4	1	1
	Scientific knowledge	5	0	0	0	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4	0	0
	Integrity	15	1	2	4	4	4	1	4	4	2	4	0	2	2	2	2	1	4	1	1	1	4	4	2	4	4
	Geological diversity	5	1	1	0	4	4	1	0	4	0	4	1	1	0	1	1	2	4	4	1	1	2	4	4	1	1
	Rarity	15	2	2	1	2	2	1	1	2	1	2	0	1	1	1	2	2	2	2	4	1	2	2	4	4	4
	Use limitations	10	1	1	1	0	0	0	1	1	1	4	1	0	0	0	0	0	1	0	0	0	1	0	1	1	4
Degradation risk	Deterioration of geological elements	35	4	1	1	4	4	4	4	1	1	4	4	4	4	4	4	4	1	0	1	1	4	4	0	0	0
	Proximity to areas/ activities with the potential to cause degradation	20	2	2	2	0	1	2	2	2	1	1	2	0	0	2	2	1	1	1	2	0	0	0	0	4	4
	Legal protection	20	4	4	4	4	4	4	4	4	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Density of population	10	1	4	2	1	0	1	0	4	4	4	2	2	2	4	2	2	4	4	4	4	4	4	4	4	2
	Accessibility	10	1	2	4	4	4	1	4	4	2	4	0	2	2	2	2	1	4	1	1	1	4	4	2	4	4
Didactic and Touristic uses	Vulnerability	10	0	2	4	0	0	0	0	4	4	4	0	1	0	0	0	0	4	4	1	1	1	1	4	4	4
	Accessibility	10	1	2	4	4	4	1	4	4	2	4	0	2	2	2	2	1	4	1	1	1	4	4	2	4	4
	Use limitations	5	0	4	2	0	0	0	0	2	2	2	0	0	0	0	0	0	4	4	2	1	1	1	0	4	0
	Safety	5	0	4	2	0	0	0	0	2	2	2	0	0	0	0	0	0	4	4	2	1	1	1	0	4	0
	Logistics	5	1	4	4	1	0	1	0	4	4	4	2	2	2	2	2	2	4	4	4	4	4	4	4	4	2
	Density of population	10	1	4	2	1	0	1	0	4	4	4	2	2	2	4	2	2	4	4	4	4	4	4	4	4	2
	Association with other values	15	1	0	1	2	1	1	1	0	2	4	1	1	1	2	2	4	2	1	1	1	0	4	1	1	0
	Scenery	10	2	2	1	2	2	1	1	2	1	2	0	1	1	1	2	4	2	2	4	1	2	2	4	4	4
	Uniqueness	5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Observation conditions	5	4	4	4	4	4	4	4	4	4	4	2	4	4	4	2	2	4	4	4	4	4	4	4	4	4
Didactic use	Didactic potential	20	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	1	4	4	4	1	4	4	4	4
	Geological diversity	10	2	2	1	2	2	1	1	2	1	2	0	1	1	1	2	2	2	2	4	1	2	2	4	4	4
Touristic use	Interpretative potential	10	4	4	2	4	4	4	4	4	4	4	1	4	4	4	4	2	1	4	4	4	1	4	4	4	4
	Proximity to recreational areas	5	2	2	2	0	1	2	2	2	1	1	2	0	0	2	2	1	1	1	2	0	0	0	0	4	4