ORIGINAL ARTICLE

Geo-Circuit for Interpretation of the Geological Evolution in the Nevados de Chillán Volcanic Complex, Chile

Rayén Rivera Vidal[1] · Andrés Tassara[1]

Abstract

Geological heritage is an important part of our natural heritage, and it can be disseminated and preserved through geotourism and geoconservation initiatives. Geotourism involves fostering the conservation of geological heritage through appropriate sustainability measures, promoting a solid conservation of geology through interpretation and education, and finally, generating satisfaction among tourists and visitors. This study focuses on the geoheritage of the Las Trancas Valley, an area characterized by its enormous natural beauty and significant tourism activity, located on the western slope of Nevados de Chillán Volcanic Complex, one of the most hazardous volcanoes in Chile. Using a methodology consisting of quantitative assessment of geological heritage, 16 sites of geological interest (or geosites) were identified, which reflect a history of ~ 22 million years, from Miocene volcanism to the formation of currently active volcanic craters. Besides promoting the education of volcanic hazards in the area, this paper proposes a new category of geoheritage assessment, defined as a geo-circuit, in which geosites are organized in a manner consistent with the chronology of the events that gave rise to the current landscape. This proposal establishes a methodological tool that is potentially useful for geotourism and geo-education purposes.

Keywords Geotourism · Geosites · Geo-circuit · Chile · Geo-evolution

Introduction

Chile, a country with a territory recognized by its natural beauty and landscape diversity, is located along the convergent plate margin between the oceanic Nazca plate and the South America continental plate and hosts one of the most active volcanic chains in the world. These features, along with more than 4300 km of continental coastline and a great variety of climates, result in a vast diversity of geological and geomorphological landscapes, forms, and structures (Benado et al. 2019). This rich geodiversity should have a place within geoconservation projects, and it could be more and better exploited through the development of geotourism initiatives that also promote geo-education, which ultimately points toward geoconservation, as we humans only take care of the things we know.

Among its varied definitions, geotourism is considered a form of tourism that takes place in natural areas, focused specifically on understanding geology and landscapes, and aimed at promoting the conservation of geodiversity and geosites, through reflection and learning (Newsome & Dowling 2010). This type of special-purpose tourism can provide a vital tool for local development and identity, as it is often in rural areas that geological heritage is found. It is also directed at raising awareness and educating visitors on the importance of considering the way in which society relates to the natural environment and the communities that inhabit it. In addition, it is a tool to explain the relationship between geology, geomorphology, and society and has been defined as "a tourism that sustains and improves the identity of a territory, considering its geology, environment, culture, aesthetic values, and heritage and represents an alternative in the search for the wellbeing of its residents" (Urrutia 2018).

Geosites, can be defined as sites that present one or more elements of geodiversity, are well delimited geographically, and present unique value from a scientific, educational, cultural, tourism, or other perspective.

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Geo-routes are usually defined as interpretation systems designed for the visitor to follow a previously defined path that includes two or more geosites and is intended to provide a good scientific knowledge of a specific area. In some cases, the concept of geo-circuits has been used as a synonymous for geotrail or georoute (Salhi et al. 2020; Gravis et al. 2020; Santos et al. 2016). In this paper, the proposed geo-circuit is not a single path, but a series of georoutes and geosites arranged in an order consistent with geologic history of the study area.

In 2021, the Chilean Geology and Mining Survey (Servicio Nacional de Geologia y Mineria, SERNAGEOMIN) developed a National Inventory of Geosites, understood as a basic tool for the future elaboration, in conjunction with academia and civil society, of a national geoconservation strategy. Currently (March 2023), the inventory includes more than 500 geosites located within the 18 regions of the country (https://portalgeominbeta.serna geomin.cl/).

Mourgues et al. (2012) proposed a list of 22 geological frameworks for the Chilean territory, representative of all the fundamental elements of Chile's geological history. In the study area, 5 of the 22 geological frameworks can be found, namely Quaternary volcanism, mega structures and neotectonics of Chile, geoforms and glacial deposits of central and southern Chile, Cenozoic batholiths and the large porphyry copper and gold deposits of Chile, and Cenozoic continental deposits.

In Chile, there are currently 7 projects for the creation of geoparks that follow UNESCO guidelines: Atacama (Atacama Region), Petorca Valley and Puchuncavi (both in the Valparaíso Region), Cajón del Maipo (Metropolitan Region), Pillan Mapu (Maule Region), Minero Litoral del Bio-Bío (Bio-Bío Region), and Kütralkura (Araucanía Region), the latter being the only Chilean geopark officially recognized by UNESCO, gaining this recognition in 2019.

The present study aims to contribute with the presentation of a method for the dissemination of geological heritage through the creation of an interpretative geological circuit at the foothills of Nevados de Chillan Volcanic Complex (NCVC) in south-central Chile (Fig. 1). This entire circuit can be traversed in 7 days, after which the visitor will have a complete understanding of the geological history of the area. After reviewing the geographical context along with the geological and geomorphological setting of the study area, and a hazard assessment, we present the quantitative methodology used to characterize a number of geosites and create a ranking of them in terms of their value for different potential uses. Particularly, we then show how these geosites can be integrated and chronologically organized in a geo-circuit that facilitates the interpretation of the last 22 million years of geological evolution exposed in the area. The entire evolution of the landscape is summarized in 12 diagrammatic blocks (Fig. 6).

The proposed circuit is thus a novel interpretive tool designed for geotourism and educational purposes that maximizes the dissemination, preservation, and potential touristic utilization of the underlying geological information.

Additionally, this work attempts to promote the awareness raising of volcanic hazards in the area around the NCVC.

Geographical, Geological, and Geomorphological Setting

An important sector of the Biobío and Ñuble Regions along the south-central Chilean Andes is considered a protected area by UNESCO, who declared it in 2011 as the Biological Corridor Nevados de Chillán—Laguna del Laja Biosphere Reserve (hereafter NCLLBR, Fig. 1). Along with promoting the conservation of species diversity, this category of protected area bolsters the development of ecotourism (tourism that promotes the appreciation and conservation of flora and fauna) and promotes greater participation by local communities in administration, management, training, and supervision activities related to conservation of natural biodiversity and economic development. Two protected wildlife areas can be found in the vicinity of the NCVC (Fig. 2): Los Huemules de Niblinto National Reserve located north of the volcanic area, and Ñuble National Reserve, to the south. However, none of the geosites assesed in this work are located in a protected area; therefore, there is plenty of work yet to be done on geoconservation in the region.

Located within the NCLLBR is the Nevados de Chillán Volcanic Complex (NCVC), on the western slope of which is Las Trancas Valley. This zone is characterized by its unique natural beauty and significant tourism activity, and it has been extensively studied because of its intense volcanic activity during at least the last century. In fact, the NCVC is ranked fourth by SERNAGEOMIN in terms of hazards and exposure (www.sernageomin.cl) and also scored high in other hazards classification schemes (e.g., Lara et al. 2021).

A total number of 64 geosites have been recognized within the NCLLBR, 13 of which were addressed by Donoso (2017), 20 by Rivera (2014), and 31 by Urrutia (2018), representing the various geological contexts observed inside the reserve.
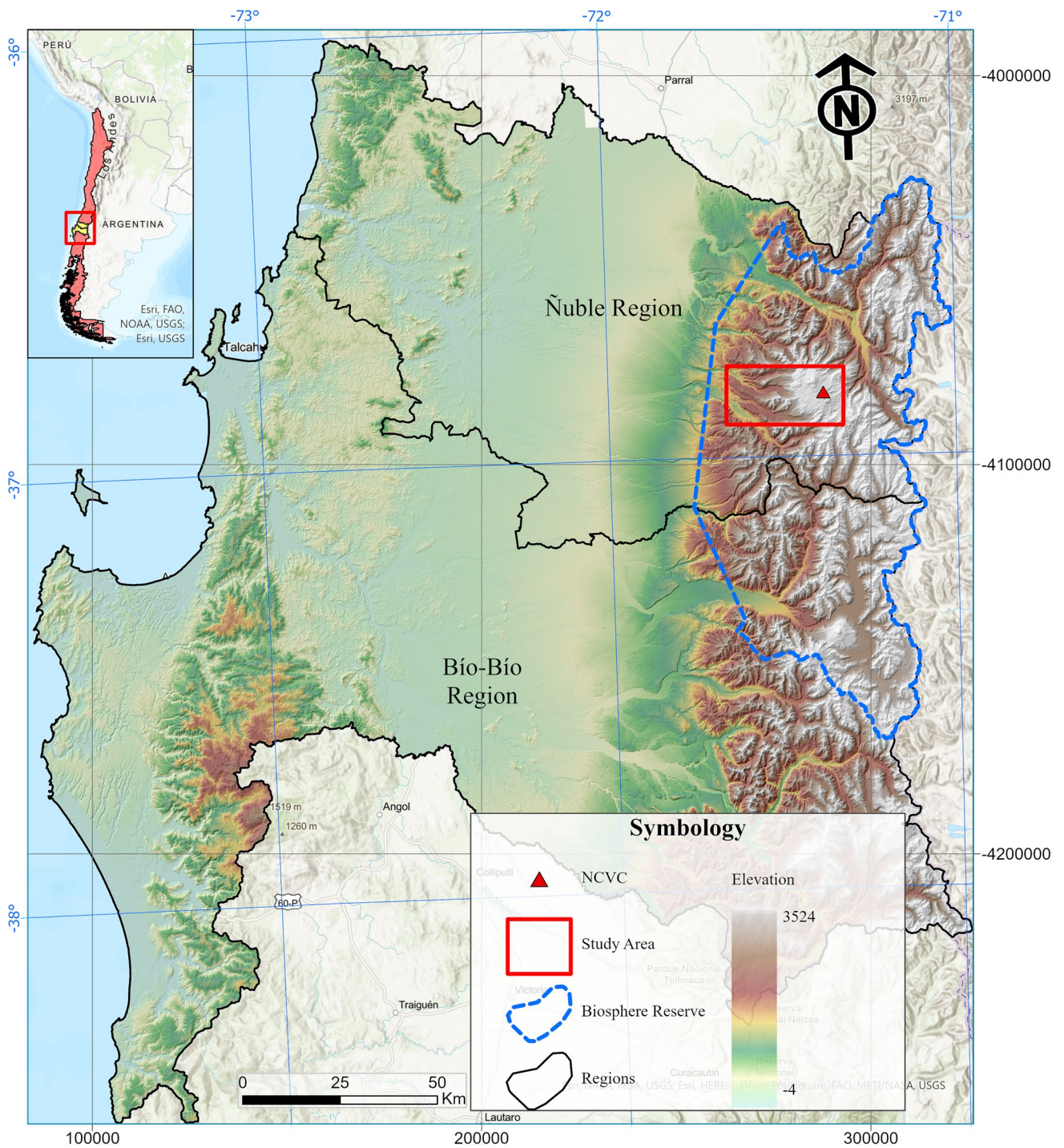
Fig. 1 Location of the study area, NCVN and the NCLLBR

Geology

The area of the NCVC records a geological history of ~ 22 million years, from Miocene volcanism (Cura-Mallín Formation) to the formation of the Nicanor crater in January 2016 (Benet et al. 2021; Cardona et al. 2021), after which

NCVC has been uninterruptedly active and continues in an eruptive process at the time of writing (March 2023).

The 1:50.000-scale geological map created by Naranjo et al. (2008) provides the basic information for this work. The map shows the distribution of the two large groups of geological units that will be described below: first, the
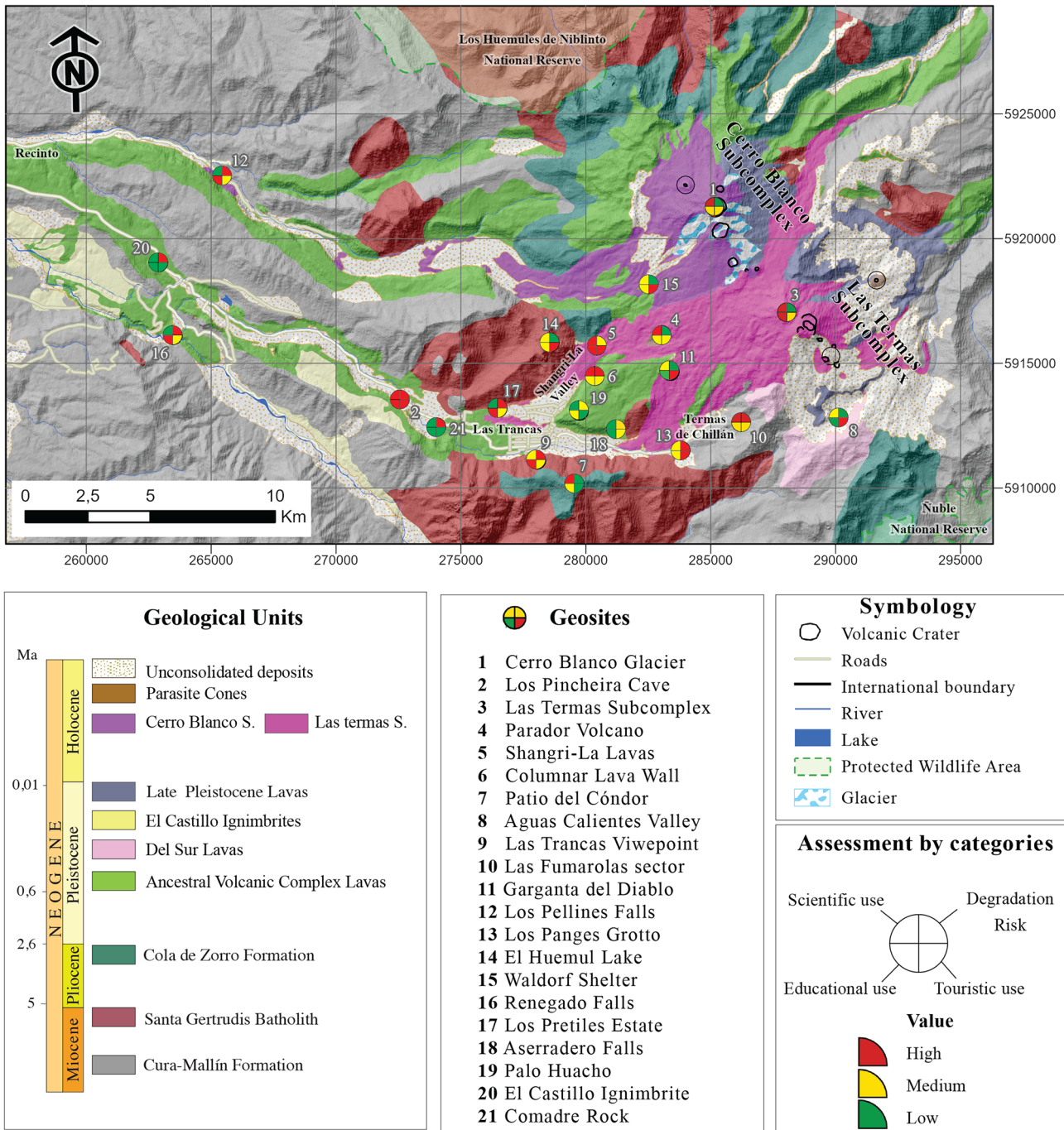
Fig. 2 Simplified geological map of Nevados de Chillán Volcanic Complex (NCVC), modified from Naranjo et al. (2008). Numbered circles divided in colored quadrants are geosites (see legend below the map and explanations in the main text)

bedrock basement of NCVC, and second, the units that make of the volcanic complex itself.

The rocks that compose the basement of the area where the NCVC has formed are volcanic, volcanoclastic, sedimentary, and plutonic rocks with an age range of ~22 to 1.8 million years. The oldest unit is the Cura-Mallín Formation (Early Miocene – Late Miocene, Pedroza et al. 2017), made up of a sub-horizontal succession of pyroclastic and clastic sedimentary rocks, and subordinate lava flows. These rocks were intruded by the Santa Gertrudis-Bullileo Batholith at 17.2–5.8 Ma (Muñoz and Niemeyer 1984). The lavas and pyroclastic rocks of the Cola de Zorro Formation, formed at 1.8 ± 0.3 Ma (Dixon et al. 1999), are then arranged horizontally and discordantly over the previous units. Above this

bedrock, a deep glacial landscape has been carved, above which the NCVC has evolved. Basement remnants are found in the mountain ridges that have been eroded by glaciers and rivers, forming the valleys that border the volcanic complex.

Considering morphostructural, stratigraphic, geochronological, geochemical, and lithological parameters, Naranjo et al. (2008) recognize 5 units that account for the development of the ancestral volcanic complex, prior to the independent activity of later subcomplexes. These units form extensive lavas and ignimbrite deposits, accumulated after their channeling along the deep glacial valleys. With various degrees of development, most of the ancestral lavas display notable columnar jointing structures due to cooling upon contact with ice, as they were mostly emplaced during Pleistocene glaciations. These characteristics stand out in the oldest lavas of the NCVC: Los Pincheira lavas. However, the last unit of the ancestral complex, Lanalhue lavas, is defined as a group of lavas of various compositions and a wide range of ages, spanning glacial and interglacial periods.

Based on morphostructural observations of the lavas identified in the field, Rivera (2014) proposed the definition of a new unit: Renegado lavas (Fig. 6g), formed in a period after the emplacement of the Lanalhue lavas (~ 51 to 97 ka) and before the massive retreat of ice from the Last Glacial Maximum, which in this zone occurred ~ 33–14 ka (Lowell et al. 1995). Unlike the other units of the ancestral complex, the Renegado lavas do not present obvious signs of glacial erosion and are arranged in a hilly morphology in the Las Trancas Valley.

In its current state of postglacial development, the NCVC is made up of two structures that have been defined as the Cerro Blanco subcomplex to the northwest and the Las Termas subcomplex to the southeast, separated by a notable pass. Each of these structures comprises volcanoes composed of several summits and emission centers, approximately aligned in a N35°W direction (Fig. 2; Fig. 4). The Cerro Blanco subcomplex includes Santa Gertrudis, Gato, Cerro Blanco (the highest summit at 3,212 m.a.s.l.), Calfú, Pichicalfú, and Baños volcanoes. Meanwhile, the Las Termas subcomplex is composed of the following eruptive center: Democrático, Viejo, Chillán, Pata de Perro, Nuevo (1906–1948), Arrau (1973–1986), Chudcún (2003), San Sebastián (2008), and Nicanor (2016) (Moussallam et al. 2018; Benet et al. 2021; Cardona et al. 2021).

Due to its geochemical affinity with Chillán Volcano, Shangri-La Volcano, located in the pass zone, is assigned to this subcomplex (Dixon et al. 1999). Beyond the Cerro Blanco and Las Termas structures, two parasitic cones can be observed: Las Lagunillas and Parador, located 4 km east and west of the main alignment, respectively.

Geomorphology

In Fig. 3, six geomorphological units can be observed: (1) mountain ridges of fluvial and glacial erosion, which make up the highest non-volcanic summits and include volcanic and plutonic rocks from the bedrock; (2) valleys of fluvial and glacial origin, mainly in an east–west orientation, filled with fluvial sediment and Holocene lavas; (3) terraces formed by Pleistocene lavas (Los Pincheira lavas) attached to the slopes of the main valleys; (4) Upper Pleistocene Volcanic platform, formed by Lanalhue lavas; this triangular-shaped platform is delimited on its edges by steep escarpments that form the slopes of the Shangri-la and Alto Renegado valleys (both of glacial origin); (5) current volcanic complex and accumulation reliefs of glacial origin; 13 stratovolcanoes and 2 parasitic cones are located in this sector, as well as Pleistocene moraines; and (6) reliefs associated with mass movement processes such as landslides, debris cones, avalanche corridors, and debris flows.

Volcanic Processes and Volcanic Hazards

Nevados de Chillan Volcanic Complex is one of the most hazardous volcanoes in Chile due to the proximity of the touristic towns of Las Trancas and Termas de Chillán — approximately 10 and 5 km away from the active crater, respectively — with permanent populations of 1600 rising to 30,000 during the high season (Moussallam et al. 2018).

While Holocene activity is represented by widespread pyroclastic flow and tephra fall deposits around the volcano, lahars associated with snow melt are considered to be the greatest potential hazard. The latest hazard map (Fig. 4) shows high lahar threats extending up to 40 km away from the complex (Orozco et al. 2016).

The historical activity shows eruptive records from 1646 to 2008, being the most prominent eruptions those occurred in 1906 (creation of 'Nuevo' volcano), 1973 (formation of Arrau crater), 2003 (Chudcún crater; Naranjo and Lara 2004), and 2008 (with the formation of Sebastian lava flow). Its permanent instrumental surveillance started in 2012, with few seismic stations, then in 2015, this network was complemented by tiltmeters, GNSS, DOAS, fixed and thermal cameras, and acoustic stations (Cardona et al. 2021). The most recent eruption cycle started in January 2016 with the formation of the Nicanor crater (Astort 2022; Moussallam et al. 2018; Oyarzún et al. 2022; Benet et al. 2021, Cardona et al. 2021) and continues until the time of writing (March 2023).

For the spatial assessment of volcanic hazards made by Orozco et al. (2016), processes related to the emission of lavas, lava-domes, debris flows, pyroclastic flows, ballistic projectiles, and accumulation of falling pyroclasts were considered and analyzed, which, restricted by the topography of the area, made it possible to delineate the different
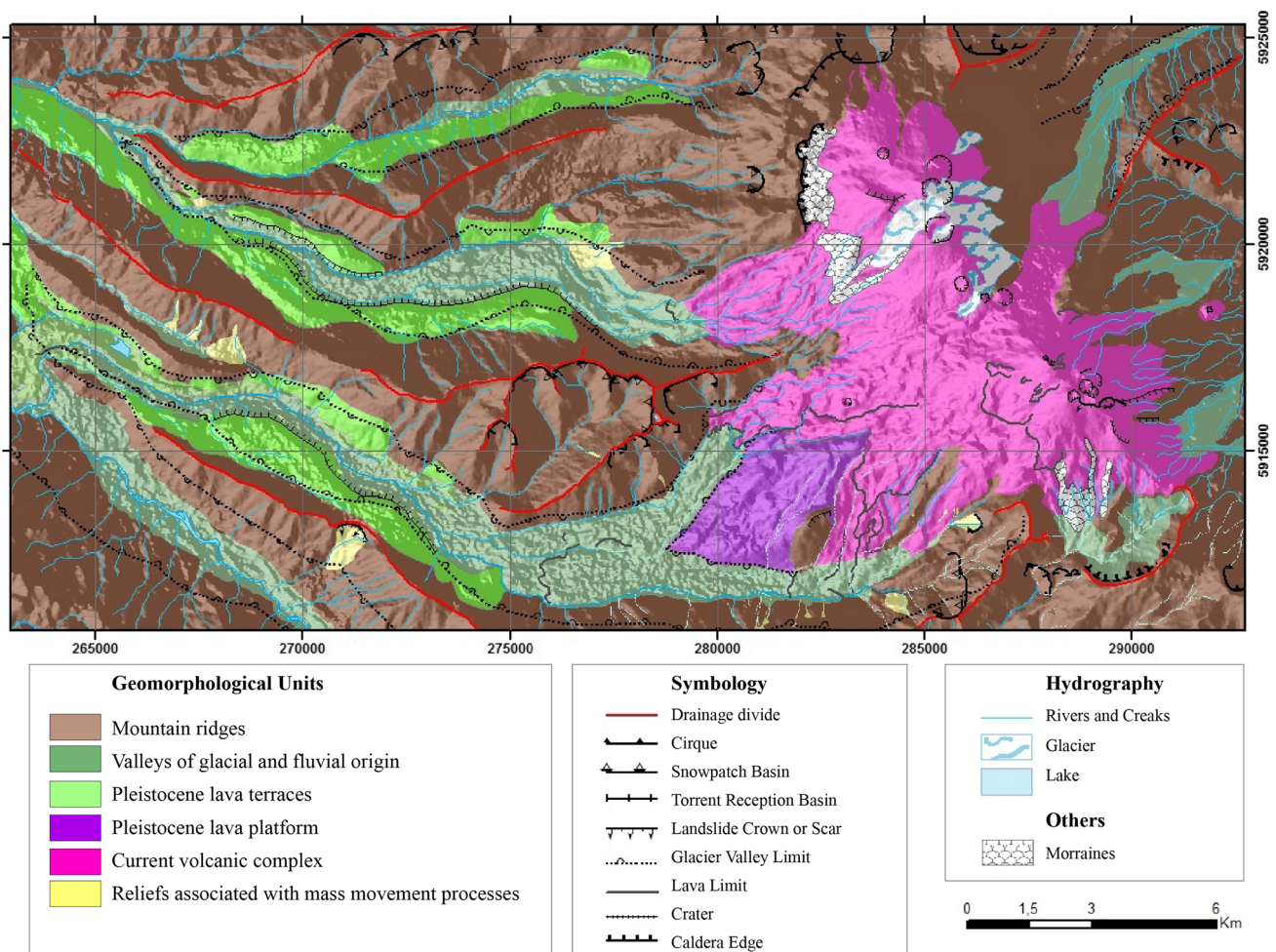
Fig. 3 Geomorphological map of the study area

volcanic hazard zones. The ejection of ballistic pyroclasts and the accumulation of tephra have been treated independently from the integrated zonation, being represented in an overlapping layer, due to the fact that topography has a very low influence on their deposition in the air transport phenomena. The zoning of the integrated hazards and those associated with ballistic trajectory projectiles, together with lines indicating the annual probability of accumulation of pyroclastic fallout material, are represented on a map at a scale of 1:75.000 (Fig. 4).

Geoheritage Quantification and Geosites Charcaterization

First, a characterization of the physical environment was carried out, which consisted of (1) recognition of the geomorphology through analysis of aerial photographs (1:30.000 scale) and satellite images, (2) study of the geology, based on the geological map of Naranjo et al. (2008) and Dixon

et al. (1999), and (3) field recognition and verification of the geological and geomorphological information. With this base information, the recognition of the possible sites of geological interest was carried out, considering on the one hand sites currently promoted as tourist attractions and on the other ensuring the integration of the most important geological and geomorphological characteristics for understanding the formation of the relief.

For the geoheritage assessment, a methodology based on that proposed by Partarrieu (2013) for the creation of a geosite inventory for Lonquimay Commune, within the framework of the Kütralkura Geopark project, was used. This methodology was chosen because it fits the objectives and scale of this study. It consists of applying a qualitative-quantitative assessment to a set of sites that are potentially suitable for classification as sites of geological interest according to one of the three defined use categories (scientific, educational, and touristic); it also evaluates the "degradation risk" of the potential geosites. To compare the characteristics of each site, the following parameters are analyzed: rarity (or uniqueness),
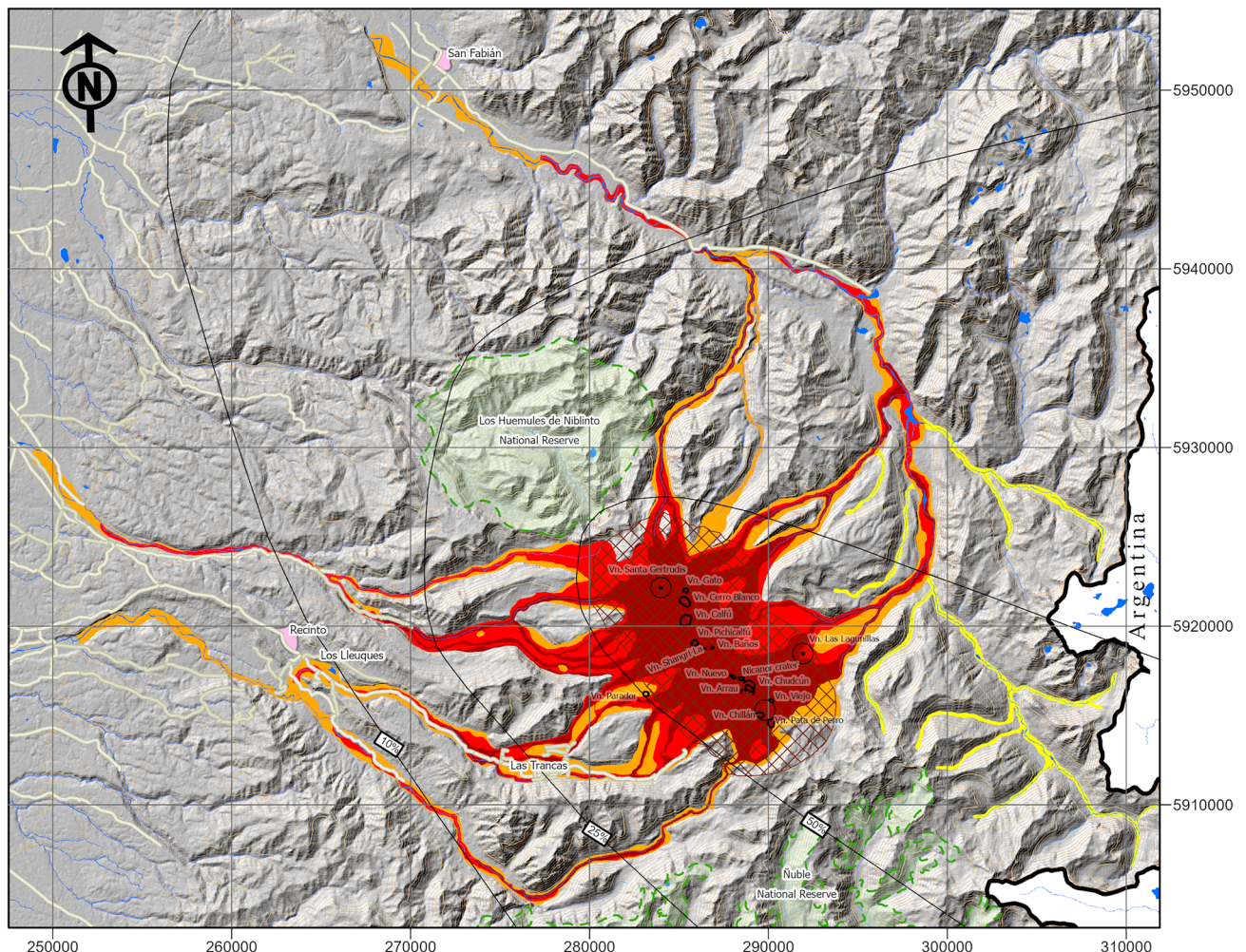
Legend

Very High Hazard. Area likely to be affected by falling ballistic pyroclasts (>6.4 cm in diameter) within a radius of approximately 4 km around the main emission centers.

Very High Hazard. Area susceptible to be affected by eruptions of similar magnitude to those that occurred in the historical period. Includes the occurrence of lava and pyroclastic flows with a reach of less than 4 km, in addition to the presence of low volume laharic flows (up to 1 million m3), with a reach of less than 25 km in the channels coming from the main volcanic edifices.

High Hazard. Area susceptible to be affected by eruptions of similar magnitude to the largest recorded in the last 3 ka. Includes the occurrence of lava and pyroclastic flows with reaches of less than 8 km, and laharic flows of moderate volume (up to 5 million m3), with distances of up to 35 km along the channels coming from the main volcanic edifices.

Moderate Hazard: Area susceptible to be affected by eruptions of similar magnitude to the largest recorded in the last 12 thousand years. Includes the occurrence of lava and pyroclastic flows with a reach of up to 12 km and high volume laharic flows (up to 20 million m3), which could reach up to 45 km away through the main channels.

Low Hazard. Area susceptible to be affected by the occurrence of secondary lahars, triggered by heavy rains that remobilize pyroclasts accumulated in the headwaters of the valleys of the eastern sector of the volcanic complex, in the most likely region of atmospheric dispersion after eruptions associated with eruptive columns over 10 km in height.

Porcentaje probability of accumulation of at least 10 cm of tephra, given a major plinian eruption scenario (IEV:6).

Symbology

- ⬡ Volcanic crater
- Road
- Internacional boundary
- River
- Lake
- Protected Wildlife Area
- Urban Area

0   2,5   5   10   Km

Fig. 4 Hazard map, from Orozco et al. (2016)

representativeness in the commune of one or more geological frameworks, degree of scientific knowledge, recognition as "type locality" or "volcanic emission center," diversity of geological elements, state of conservation, observation conditions, educational use, possibility of collecting objects, road accessibility, seasonal accessibility, degree of difficulty of access, proximity to population centers and services, intrinsic fragility, association with cultural and/or natural elements, visual quality, current use, current or potential threats, vulnerability to natural processes, and current legal situation. For each parameter, there is a series of predefined criteria with a corresponding quantitative value between 0 and 1. The details of the methodology for the assessment of geosites and the results can be found in the supplementary material.

The values associated with each criterion vary by category. This is because the calculation of the "degradation risk" is influenced by some parameters that are shared with other categories but play a different role. Thus, for example, in places where "collection of samples is possible without damaging the geosite," associated with the parameter "possibility of collecting objects," the criterion will have a maximum value for educational purposes (value = 1), but it will have a minimum value when considering the "degradation risk" of the geosite (value = 0), as this factor elevates its vulnerability.

This methodology was used to assess the geoheritage value of 21 potential geosites. Then, the sites were organized in accordance with the values obtained in each category, tagging them with the labels "High," "Medium," and "Low." The thresholds that mark the limits between the different labels are defined according to Eq. 1:

$$U = X + (k * \sigma) \tag{1}$$

where "U" is the cut-off value, "X" the sample average of all sites, "σ" its standard deviation, and "k" a constant that in this case takes the value of 0.5. In other words, the results are separated depending on how far they deviate from the average. Thus, the difference between the "High-Medium" and "Medium–Low" limits is equal to the value of one standard deviation, for each use category and the sum of the three use categories. Only the sites with "Medium" or "High" values were included in the inventory when considering the sum of the three categories Table 1. Thus, the 16 highest ranked sites were incorporated into the geosite inventory. These results are graphically represented in Fig. 5.

Figure 2 also shows the results of the assessment for each site, in this case symbolized by traffic light colors: red, yellow, and green for "High," "Medium," and "Low" values, respectively, in a circle divided into quadrants, in which three quadrants are associated with each of the use categories (scientific, educational, and touristic) and the fourth with the degradation risk.

After the quantitative assessment, the selected geosites were ordered in a manner consistent with the geological and geomorphological evolution of the NCVC, considering the most noteworthy geological and geomorphological information at each site (Fig. 6).

Integrating Geosites in Geo-Circuit for the Interpretation of the Geological Evolution

Figure 6 summarizes the evolution of the NCVC in 12 block diagrams. This summary is the result of a compilation and integration of the existing geological information (in particular the publications of Naranjo et al. 2008 and Dixon et al. 1999), complemented by geological and geomorphological mapping. The first block diagram (Fig. 6a) represents the geology of the Mid-Late Miocene, in which volcanic and volcano-sedimentary rocks of the Oligocene—Early Miocene Cura-Mallín Formation are intruded by the Santa Gertrudis Batholith. Outcrops of the oldest unit can be observed at the Las Fumarolas sector (S10, Fig. 7h), while the batholith is amply appreciated on the trails that lead to El Huemul Lake (S14). Following the formation of the batholith and exhumation via erosion of the rock massif, the volcanism that resulted in the rocks of the Cola de Zorro Formation took place (Upper Pliocene—Pleistocene, Fig. 5b), the best outcrops of which are located at the top of the Patio del Cóndor (S7). Then, over ~ 1 Ma, the extensive Pleistocene glaciers began to carve the walls of the valleys currently occupied by the rivers (Fig. 6c).

The first evidence of Quaternary volcanism in the area is recorded in the Los Pincheira lavas (S2, Figs. 6d and 7f), the morphological characteristics and fracturing types of which indicate subglacial volcanism occurring ~ 650 ka ago (Dixon et al. 1999), during a period of large glaciations worldwide. Subsequently, the Diguillín and Atacalco lavas were emplaced (Fig. 6e) at ~ 330–380 ka and ~ 160–100 ka, respectively (Naranjo et al. 2008). The distal portions of these lavas are found in the vicinity of Renegado Falls (S16), where the course of Renegado Creek shifts south to join the Diguillín River, forming a spectacular waterfall. Lanalhue lavas (S6, Fig. 6f), a diachronous unit of varied composition, formed ~ 90–60 ka, spanning a period that includes part of a global glaciation and interglacial period. Thus, in some areas, the Lanalhue unit is observed in the form of columnar lavas (Fig. 6b), a characteristic associated with subglacial emplacement (e.g., at sites such as the northern wall of the Palo Huacho plateau, on the route that leads to Parador Volcano), while in other areas, traits indicative of subaerial emplacement can be seen, such as Aserradero Falls (S18) or in the vicinity of Garganta del Diablo (S11). After the emplacement of the Lanalhue lavas and prior to the massive retreat of ice from the Last Glacial Maximum, the Renegado

Table 1 UTM coordinates of the geosites (Datum WGS 1984 UTM Zone 19S) and scores obtained for each geosite in the different categories

Code	Geosite	UTM coordinates		Use categories			Sum	Degradation
		East	South	Scientific	Educational	Touristic		risk
S1	Cerro Blanco Glacier	284912	5920715	100	71	71	**242**	15
S2	Los Pincheira Cave	272652	5913558	88	74	75	**237**	48
S3	Las Termas Subcomplex	287972	5917161	91	73	68	**232**	15
S4	Parador Volcano	283145	5916105	80	69	69	**218**	18
S5	Shangri-La Lavas	279882	5915664	70	78	76	**224**	30
S6	Columnar Lava Wall	283599	59111325	65	66	64	**195**	33
S7	Patio del Cóndor	279550	5910264	55	70	67	**192**	13
S8	Aguas Calientes	289260	5913440	58	60	74	**192**	15
S9	Las Trancas Viewpoint	277890	5911399	35	78	76	**189**	33
S10	Las Fumarolas Sector	286124	5912765	69	60	60	**189**	30
S11	Garganta del Diablo	283461	5915000	46	59	78	**183**	18
S12	Los Pellines Falls	266200	5922025	30	80	67	**177**	33
S13	Los Panges Grotto	283599	5911325	39	53	71	**163**	38
S14	El Huemul Lake	278520	5915772	35	56	78	**169**	18
S15	Waldorf Shelter	281929	59179805	36	51	76	**163**	15
S16	Renegado Falls	263415	5916091	25	79	57	**161**	38
S17	Los Pretiles Estate	276366	5913085	31	76	50	**157**	43
S18	Aserradero Falls	281196	5912381	26	49	69	**144**	28
S19	Palo Huacho	279885	5912950	26	55	50	**131**	30
S20	El Castillo Ignimbrite	262943	5918927	38	55	25	**118**	45
S21	Comadres Rocks	270837	5914969	11	36	24	**71**	45
	Average			**50**	**64**	**64**	178	29
	Standard deviation			**25**	**12**	**15**	41	11
	Thresholds	**Medium–high**		**63**	**70**	**72**	199	34
		Low–medium		**38**	**58**	**56**	158	23

Colors red, green and yellow depict "High," "Medium," and "Low" values, respectively, derived from the Sum of the 3 Use categories (Scientific + Educational + Touristic), for each geosite.
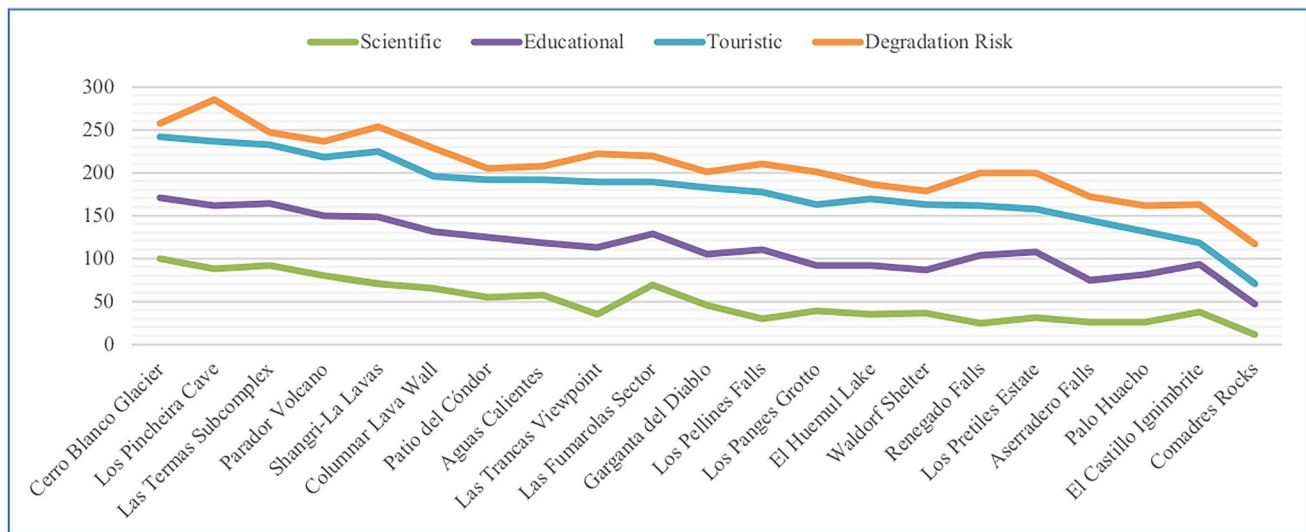
Fig. 5 Multivariate diagram with the values for each use category and degradation risk for each one of the assessed sites

Lavas originated (Fig. 6g), which comprise the foundation of almost the entire Las Trancas Valley.

The Las Termas subcomplex was formed ~ 40,000 ka, with the formation of the Southern lavas (Fig. 6h). These lavas outcrop on the southern edge of Aguas Calientes Valley (S8, Fig. 7d) and are distinguished by being exposed in an arched escarpment that faces the volcanoes. Some authors (such as Dixon et al. 1999) postulate that this escarpment represents the remnant of a caldera that collapsed during the event that formed the El Castillo Ignimbrites (Fig. 6i). These rocks, of pyroclastic origin, can be seen on one side of Route N-55 close to Recinto (S20).

Next, there is a series of Late Upper Pleistocene lavas (Fig. 6j), including the Aguas Calientes lavas in the Las Termas subcomplex and the Colcura Volcano (Fig. 7e) lavas in the Cerro Blanco subcomplex. The former can be seen in Aguas Calientes Valley and were formed at the beginning of the Last Glacial Maximum. The latter were formed as a result of the initial activity of the Cerro Blanco subcomplex and emanated from a volcano known locally as "the pyramid," which is a stratocone with lava (~ 14,000 years old) that flowed through the Chillán River Valley, reaching up to 22 km from their source. In these distal areas, one of the most beautiful waterfalls of the commune is found: Los Pellines Falls (S12, Fig. 7g). Currently, the volcanic edifice eroded by glacial action can be seen from the town of Las Trancas, as well as from Las Trancas viewpoint (S9, Fig. 7e) located in one of the hills that border the town.

The first Holocene lavas are that of Democrático Volcano (Fig. 6k), which flowed mainly to the northeast and

southwest, reaching a distance of up to 14 km. The farthest point from the source is in the Los Pretiles Estate (S17), a site at which frontal lobes outcrop from dacite lava with a vitreous exterior and crystalline interior, with fractures that indicate sudden cooling in peri-glacial conditions. These flows are not affected by glacial erosion; therefore, it is estimated that they formed shortly after the Last Glacial Maximum (~ 14,000 years ago). These rocks are covered by Shangri-La lavas (S5), formed 7.7 ± 1.4 ka ago (Mee 2004), and they have similar geochemical characteristics.

Two parasitic cones, located approximately 5 km east and west of the Las Termas subcomplex, were formed during the Holocene. To the east is Las Lagunillas Volcano, surrounded by Holocene tephra; to the west is Parador Volcano (known locally as "El Renegado," S4, Fig. 7c), which is located amid Shangri-la lavas; thus, it was formed less than 7.7 ± 1.4 ka ago.

Throughout the history of the NCVC there have been numerous events that formed pyroclastic flow deposits, one of the best examples of which is Los Panges Grotto (S13), covered by tephra dating 2.27 ± 7 ka (Dixon et al. 1999). The summit of the Cerro Blanco subcomplex (S1, Fig. 6l) is covered by the only remnant of the glacier that has carved the valleys that border the volcano system (Fig. 7c). The eruption of Santa Gertrudis Volcano (1861–1865) is the most recent activity recorded in this subcomplex.

As its name suggests, "Viejo Volcano" is the oldest of most intact volcanic edifices in the Las Termas subcomplex (Figs. 6l and 7e). Dating carried out by Dixon et al. (1999) indicates that activity in this cone began ~ 9.3 ka. Since
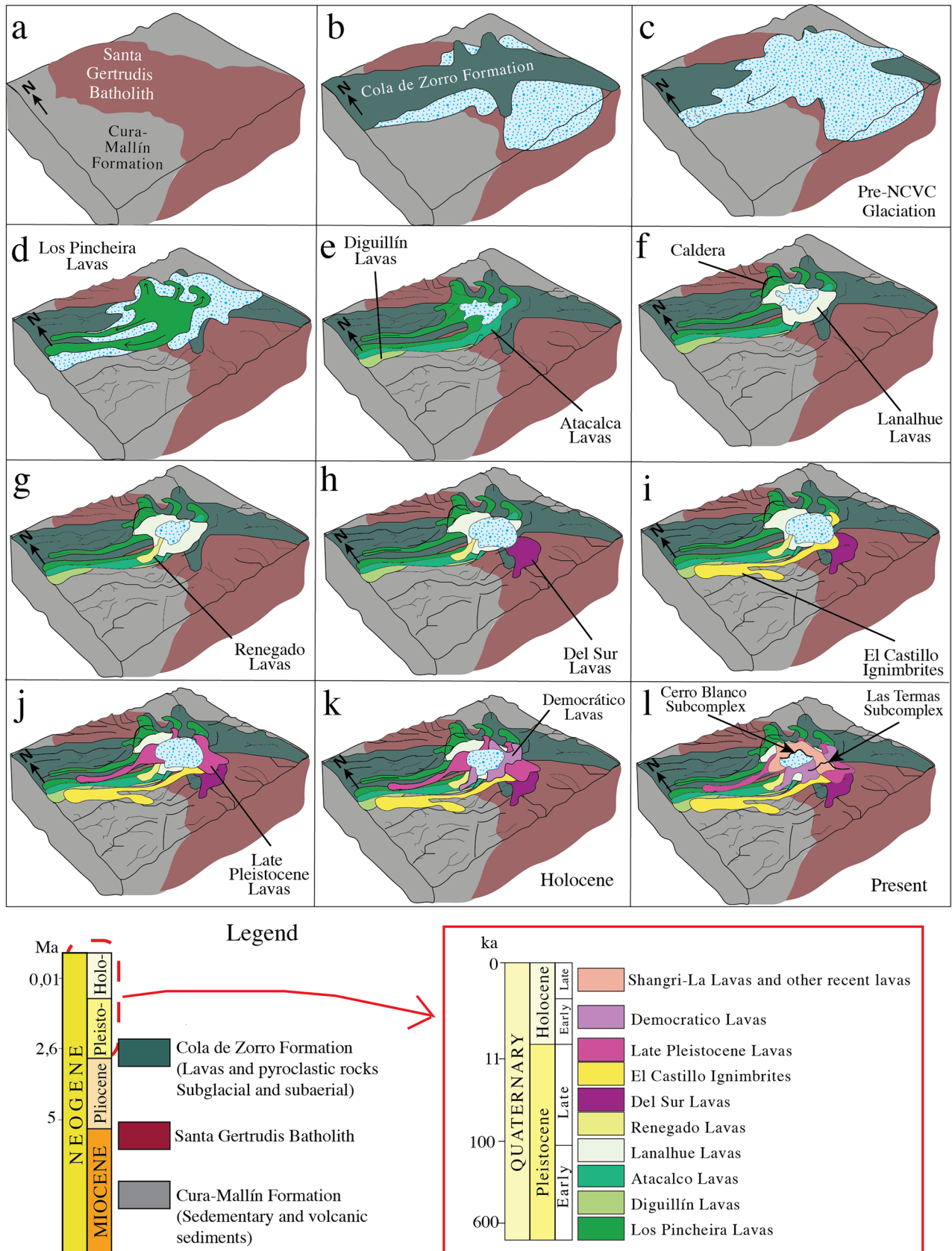
Fig. 6 Schematic representations of the main stages of the geological/geomorphological evolution of the study area

Fig. 7 El Huemul Lake. **b** Lanalhue Lavas. **c** Cerro Blanco Glacier and Parador Volcano. **d** Aguas Calientes. **e** View from Las Trancas Viewpoint. **f** Los Pincheiras Lavas. **g** Los Pellines Falls. **h** Las Fumarolas

then, it has spewed out an enormous quantity of pyroclastic fall deposits that accumulate east of the Las Termas subcomplex. The lava that makes up the cone of Viejo Volcano is interstratified, composed of andesite and dacite layers. On the route to the Las Termas subcomplex (S3), the different lavas and pyroclastic flows that make up the cone of Viejo Volcano can be seen, in addition to the products of Chillán, Nuevo (1906–1948), and Arrau (1973–1986) volcanoes, as well as the latter volcanic products formed in the twenty-first century, such as San Sebastián unit (2008), Nicanor crater and dome (2016) and even more recent small domes formed from 2018 to 2022. Due to the intense volcanic activity observed in this sector, we strongly recommend reviewing the volcanic alert information on the SERNAGEOMIN website before planning a visit to the Las Termas Subcomplex (www.sernageomin.cl/informacion-alertas-volcanicas).
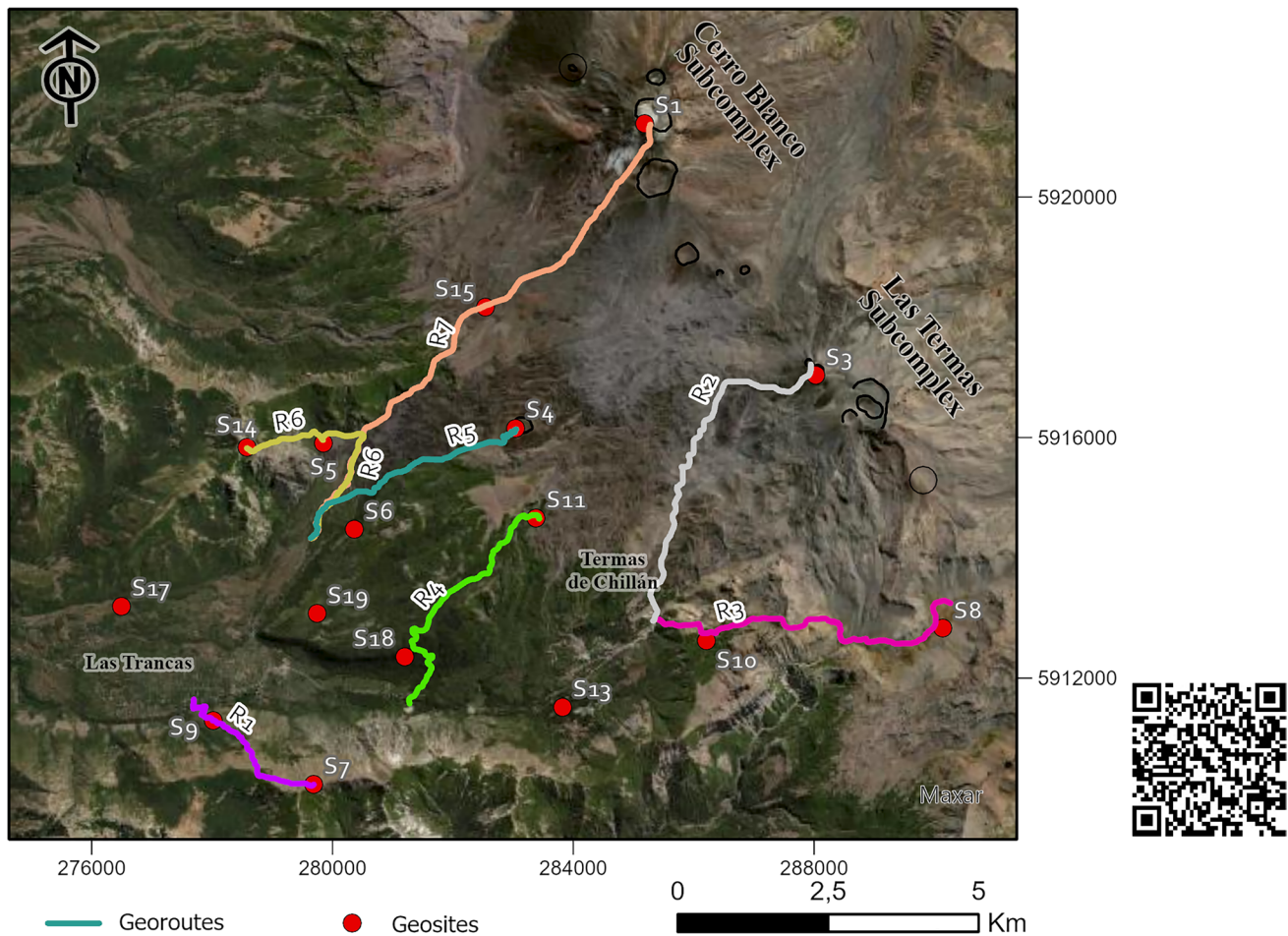
Suggested Georoutes

The entire geo-circuit can be visited in approximately 7 days. Some sites are easy to access; for example, Los Pincheira Cave (geosite 2) can be seen from the road and one can enter a cave that was formed by fluvial erosion of the lava base, which has turned it into a famous tourist attraction. Other sites are difficult to access; therefore, they could be traveled through georoutes, as one must walk four or more hours to reach them. In Table 2, there are 7 suggested georouts, with their length and estimated round-trip travel time, as well as the geosites that are found along the way and the geosite that is reached at the end of each route (Fig. 8).

This information can be explored in a Web Map,[1] developed using the software ArcGis Pro, where it can also be found a

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[1] https://dst-unab.maps.arcgis.com/apps/webappviewer/index.html?id=69f8e59ccc954ea49992e04cde8fbaa7

Table 2 Suggested georoutes

Code	Name	Length (km)	Difficulty	Time	Geosites
R1	Patio del Condor	3,4	Medium–high	7 h	S9 and S7
R2	Las Termas Subcomplex	6,5	Medium–high	1 day	S3
R3	Aguas Calientes—Fumarolas	6,5	Medium–high	1 day	S10 and S8
R4	Garganta del Diablo	5,2	Medium	6 h	S18 and S11
R5	Parador Vn	4,8	Medium	8 h	S6 and S4
R6	Huemul Lake via Shangri-La	4,4	Medium	6 h	S5 and S14
R7	Cerro Blanco Glacier	10,3	High	1 day	S5, S15, and S1

Fig. 8 Suggested georoutes and location of geosites, developed using World Imagery as base map in Arcgis Pro

description and a picture for each geosite. The QR code to visit the Web Map can be scanned from Fig. 7.

Concluding Remarks

The proposed interpretative geo-circuit accounts for ~22 Ma of history, in which volcanism and glaciations have played a fundamental role in the construction of the landscape. These and other aspects of geological/geomorphological evolution can be clearly and consistently recognized in the field through the series of expeditions previously described. None of the identified geosites is located within a protected area, which increases the importance of generating studies that reveal the value and fragility of these sites and the necessity to boost geoconservation strategies.

The knowledge provided through the descriptions of each geosite, along with the evolutionary history of the environment, generates a novel interpretation system that is potentially replicable in other territories. The main

contribution of this geo-circuit is to provide a good scientific understanding of the zone, which can be used for geotourism and geoeducation, based on high-level geological information in the Las Trancas Valley. For future works in the area, it is recommended that interpretative panels be installed, describing the part of the geological history that can be observed in each site, as well as geo-guides, magazines and videos that would help disclose this information for all inhabitants of and visitors of this mountain area.

Declarations

Conflict of Interest The authors declare no competing interests.

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