Geotourism vol. 17, 3–4 (62–63) 2020 DOI: https://doi.org/10.7494/geotour.2020.3-4(62-63).47

Stratovolcanoes on the Chilean-Bolivian border as geoatraction

Stratowulkany na granicy chilijsko-boliwijskiej jako geoatrakcje

Paweł Panajew[1]*, Andrzej Gałaś[2]

[1] KGHM Polska Miedź SA, Polkowice-Sieroszowice Mine, Kaźmierzów 100, 59-101 Polkowice, Poland
[2] Division of Mineral Policy, Mineral and Energy Economy Research Institute, Polish Academy of Sciences, ul. Wybickiego 7A, 31-261 Krakow, Poland
pawel.panajew@kghm.com; agalas@min-pan.krakow.pl

* Corresponding Author

Article history:
Received: 28 April 2022
Accepted: 28 July 2022
Available online: January 2023

Abstract: *The cluster of stratovolcanoes located on the Chilean-Bolivian border, in the Western Cordillera, is composed of typical, for that part of the Central Volcanic Zone in the Andes, volcanic landforms. The highest volcano is the Nevado Sajama (6,542 m a.s.l.), apparently extinct. The other: Parinacota (6,336 m a.s.l.), Pomerape (6,222 m a.s.l.), Acotango (6,052 m a.s.l.) and Cerro Quisiquisini (5,542 m a.s.l.) were all active in both the Pleistocene and the Holocene. Recently, only the Guallatiri Volcano (6,071 m a.s.l.) is still active. The summits of these mountains are covered with permanent snow or ice caps. On the slopes, there are post-glacial valleys, rocks glaciers and debris avalanches. In the vicinity of volcanic cones, active fumaroles occur, along with hot springs, geysers and high-mountain peat bogs (bofedales), in addition to one of the highest in the world mountain lakes – the Lago Chungará (4,520 m a.s.l.). The unique landform is a huge debris avalanche and was formed during the eruption of the Parinacota Volcano. Small villages settled by Aymara Indians and their cultural monuments complete the extraordinary landscape of the Altiplano Plateau. The values of biotic nature are also unique and deserving of protection on both sides of the state border. Moreover, these sites have been registered into the UNESCO World Heritage List. Modest accommodation facilities located off the main roads satisfy the qualified tourists interested in volcanology. The authors describe the grueling trekking trails, the climbing routes leading to the summits of volcanoes and the other geoattractions, accessible for ordinary hikers.*

Keywords: *geosites, Central Volcanic Zone of Andes, lava, Nevado Sajama*

Treść: *Stratowulkany zgrupowane na chilijsko-boliwijskiej granicy, w Kordylierze Zachodniej, są klasycznymi formami dla tej części Centralnej Strefy Wulkanicznej w Andach. Najwyższy jest wygasły wulkan Nevado Sajama (6542 m n.p.m.). Wulkany Parinacota (6336 m n.p.m.), Pomerape (6222 m n.p.m.), Acotango (6052 m n.p.m.) i Cerro Quisiquisini (5542 m n.p.m.) były aktywne w plejstocenie i holocenie. Jedynie wulkan Guallatiri (6071 m n.p.m.) pozostaje nadal aktywny. Ich wierzchołki pokryte są wiecznym śniegiem lub czapą lodową. Na stokach wulkanów występują doliny polodowcowe, lawiny i lodowce gruzowe. W ich sąsiedztwie są aktywne fumarole, gejzery, gorące źródła, wysokogórskie torfowiska bofedales, a także jedno z najwyżej położonych jezior górskich na świecie – Lago Chungará (4520 m n.p.m.). Rzadko spotykaną formą jest wielkich rozmiarów lawina gruzowa, która powstała podczas erupcji wulkanu Parinacota. Małe osady Indian Aymara i zabytki ich kultury dopełniają niezwykłego charakteru krajobrazu pustkowi na Altiplano. Przyroda ożywiona po obu stronach granicy Boliwii z Chile jest na tyle wyjątkowa, że została wpisana na Listę Światowego Dziedzictwa UNESCO. Położenie na uboczu szlaków komunikacyjnych oraz skromna baza noclegowa gwarantują wykwalifikowanemu turyście zainteresowanemu wulkanologią wrażenie odkrywania nowych, dzikich szlaków. W pracy opisano zarówno trudno dostępne szlaki na szczyty wulkanów, jak i geoatrakcje spotykane na trasie górskiego trekkingu.*

Słowa kluczowe: *geostanowisko, Centralna Strefa Wulkaniczna Andów, lawa, Nevado Sajama*

Introduction

The study area is located in the Central Andes, in northern Chile and western Bolivia, in the Western Cordillera and in the Central Volcanic Zone (Fig. 1). On the Bolivian side, it belongs to the Sajama National Park (SNP), located in the Oruro Department of the Sajama Province. The relationship to other Bolivian national parks is given in the article by Paulo (2015). On the Chilean side, it is a part of the Lauca National Park. The ridges of the Cordillera rise up to elevations of 4,000–5,000 m a.s.l. They are topped by stratovolcanoes, rising over 6,000 m a.s.l.: Sajama (6,542 m a.s.l.), Parinacota (6,336 m a.s.l.), Pomerape (6,222 m a.s.l.), Guallatiri (6,071 m a.s.l.) and Acotango (6,052 m a.s.l.) (Tab. 1).

The area is dominated by a cold and dry climate with an average annual temperature of 3.4–4.7°C and precipitation of 300–400 mm/year. Vegetation shows clear zoning, related to the altitude and can be divided into several ecological zones, perfectly visible on the slopes of the Sajama Volcano, rising from 3,800 to 6,542 m a.s.l. (Beck *et al.*, 2010). The elevation range of 4,500–5,400 m is dominated by the semi-arid climate of the Andes. There are rocks and glacial crags covered with snow and poor, pioneering vegetation, dominated by mosses and lichens, and the long-lived *yareta* (*Azorella compacta*) bushes (Pugnaire *et al.*, 2020). The highest zone (from 5,500 or 5,800 to 6,542 m a.s.l.) is occupied by perpetual snow.

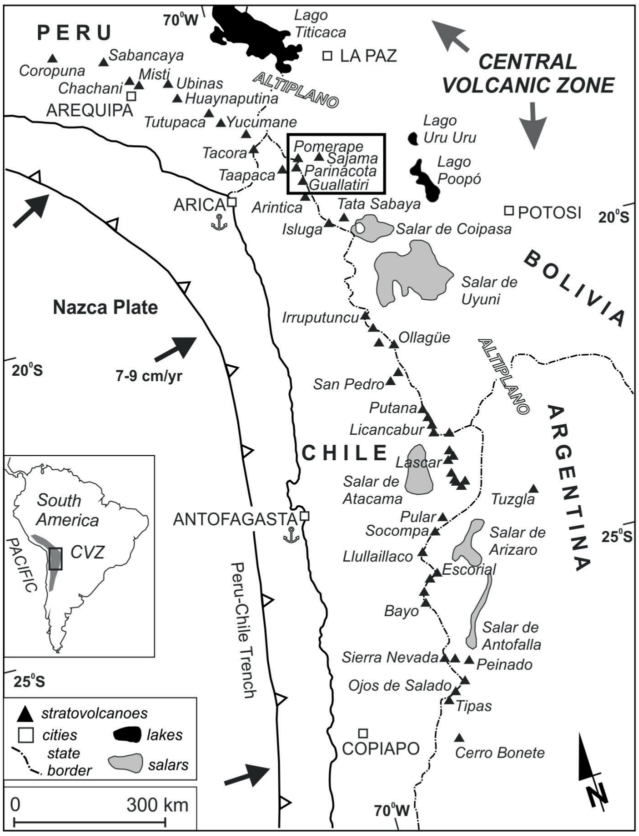

Fig. 1. Location map of the study area (black rectangle – Fig. 3) in the Central Volcanic Zone (CVZ) and covergence direction and rates (Fig. 2) (after Stern, 2004)

This part of the Central Andes presents unique scenic, geological, natural and cultural values (Tab. 2). On the Altiplano Plateau, the visitors can admire the ecosystems of the dry ecological zone named *puna*. The Altiplano is surmounted by composite volcanoes covered with snow or ice caps, five of them rising over 6,000 m a.s.l. This is a perfect example of a volcanic mountain landscape. The area is rich in endemic fauna and flora species, as well as numerous classic geodiversity objects: volcanoes, glaciers, lakes, geysers, hot springs, etc. At the foot of the Parinacota Volcano, one of the highest mountain lakes is located: Lago Chungara (4,520 m a.s.l.), inhabited by over 140 bird species (Rundel & Palma, 2000).

Table 1. Characterization of stratovolcanoes from the northern Chile

Name/coordinates	Elevation [m a.s.l.]	Last activity	Prognosis of activity
C. Parinacota (18°07′39″S, 69°07′50″W)	6,336	500–600 AD, fumaroles in 1989	PDC, tephra fallout, lahar
C. Pomerape (18°09′47″S, 69°08′32″W)	6,222	Pleistocene–Holocene	Plinian eruption
N. Sajama (18°06′29″S, 68°52′57″W)	6,542	Pleistocene–Holocene	Plinian eruption
C. Quisiquisini (18°14′19″S, 69°03′52″W)	5,542	Pleistocene–Holocene	Plinian eruption
C. Acotango (18°22′57″S, 69°02′47″W)	6,052	Upper Holocene	PDC, tephra fallout, lahar
V. Guallatiri (18°25′26″S, 69°05′24″W)	6,071	1985 and recent fumaroles	most active in the northern Chile

C – Cerro; N – Nevado; V – Volcano; PDC – pyroclastic density currents

Table 2. Selected geosites located in the vicinity of Pueblo Sajama (Fig. 3)

No.	Geosite names, elevations [m a.s.l.] and coordinates	Geosite type	Scientific value (*)	Educational value (*)	Accessibility (**)	Aesthetic value (***)
1.	Sajama (6,542) (18°06′30″S, 68°52′60″W)	volcanic and glacial	3	3	1	3
2.	Mirador Montecielo (4,550) (18°08′09″S, 68°57′14″W)	outlook, cultural site	2	2	3	3
3.	Pueblo Sajama (4,245): – 18°05′22″S, 68°58′38″W; – 18°08′S, 69°00′W; – 18°08′09″S, 68°58′33″W; – 18°08′10″S, 68°58′00″W	– hot springs; – peat bogs (*bofedales*); – historical monument (church); – geoglyph	2 3 2 3	2 3 2 3	3 3 3 3	2 3 2 3
4.	Geisers (4,400) (18°05′53″S, 69°01′45″W)	fumarole "jet-type"	2	2	3	2
5.	Pomerape (6,222) (18°07′34″S, 69°07′39″W)	volcanic and glacial	3	3	1	3
6.	Parinacota (6,336) (18°09′49″S, 69°08′33″W)	volcanic and glacial	3	3	1	3
7.	Debris avalanche (18°11′S, 69°12′W)	debris avalanche, volume: 6 km^3, length: 22 km	3	3	3	3
8.	Lago Chungará (4,520) (18°15′S, 69°09′W)	limnology, geomorphology	3	3	3	3
9.	Quisiquisini (QuisiQuisini) (5,542) (18°14′20″S, 69°03′52″W)	volcanic and glacial	3	3	2	2
10.	Acotango (6,052) (18°22′59″S, 69°02′52″W)	open amphitheater on the northern slope	3	3	1	2
11.	Guallatiri (6,071) (18°25′27″S, 69°05′25″W)	volcanic and glacial	3	3	1	2

* 1 – small, 2 – large, 3 – very large
** 1 – very difficult to access, 2 – difficult to access, 3 – easily accessible
*** 1 – not very attractive, 2 – moderately attractive, 3 – very attractive

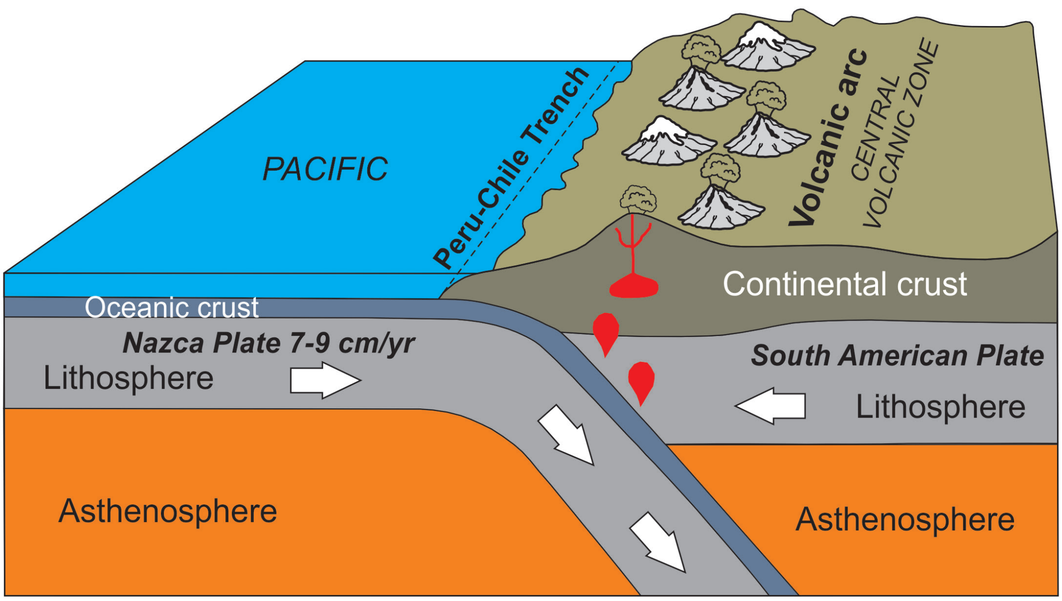

Fig. 2. Sketch of subduction zone in the Central Andes, southern Peru (USGS, modified)

To protect this unique corner of the Andes, national parks have been established on both sides of the Chilean-Bolivian border (Figs. 3, 4). On the Bolivian side, this is the Sajama National Park (SNP) covering an area of 1,002 km^2. It was established in 1939, in order to protect the high-mountain forest of *queñua* (*Polylepis tarapacana*) (Hoffmann, 2007). In 2003, the SNP was registered on the UNESCO World Heritage List. The Lauca National Park on the Chilean side, an area of 1,379 km^2, has been established in 1970. Since 1983, it has been recognized by the UNESCO as the International Biosphere Reserve (Rundel & Palma, 2000). Global warming observed in recent years poses a threat to the flora and fauna of these ecosystems, which are sensitive to microclimate changes.

Totally, 27 mammal's species have been identified up to now in the SNP (Beck *et al.*, 2010). The most common are: *vicuña* (*Vicugna vicugna*) (Wheeler & Laker, 2009), *guanaco* (*Lama guanicoe*), *huemul* deer (*Hippocamel usbisulcus*), Andean woolly *armadillo* (*Chaetophractus nationi*), Andean ocelot (*Felis jacobita*) and puma (*Felis concolor*) (Yensen *et al.*, 1994). The group of wild herbivores that feed on *bofedales* is represented by domesticated *llamas* (*Lama glama*) and *alpacas* (*Vicugna pacos*) (Kadwell *et al.*, 2001).

The Andean Indians, who have been living in such inhospitable Altiplano areas since the pre-Columbian epoch, worshiped the mountains as sacred sites named *huaco*. These were the abodes of gods and demons (Ryn, 1977). The mountains were worshiped, above all, for their control of both the weather and the water springs supplied by permanent snow fields and ice caps of high mountains (Reinhard, 1985). Access to water was a vital condition for survival on the dry Altiplano area, and it is still crucial to agriculture and livestock farming.

Thanks to the efforts of high-mountain archaeology, ceremonial constructions were discovered at the tops of stratovolcanoes, in which not only animals and plants and silver, gold and ceramic goods were sacrificed, but also humans, as for example at the Llullaillaco (6,739 m a.s.l.) (Reinhard, 1985), Ampato (6,288 m a.s.l.) (Reinhard & Ceruti, 2005) or Nevado Quehuar (6,130 m a.s.l.) (Reinhard, 1999; Reinhard & Ceruti, 2005). The motives for human sacrifices might have been plagues, famine, drought, earthquakes, deaths of important persons, as well as disturbing astronomical events (e.g. solar or lunar eclipses) (Ryn, 1977).

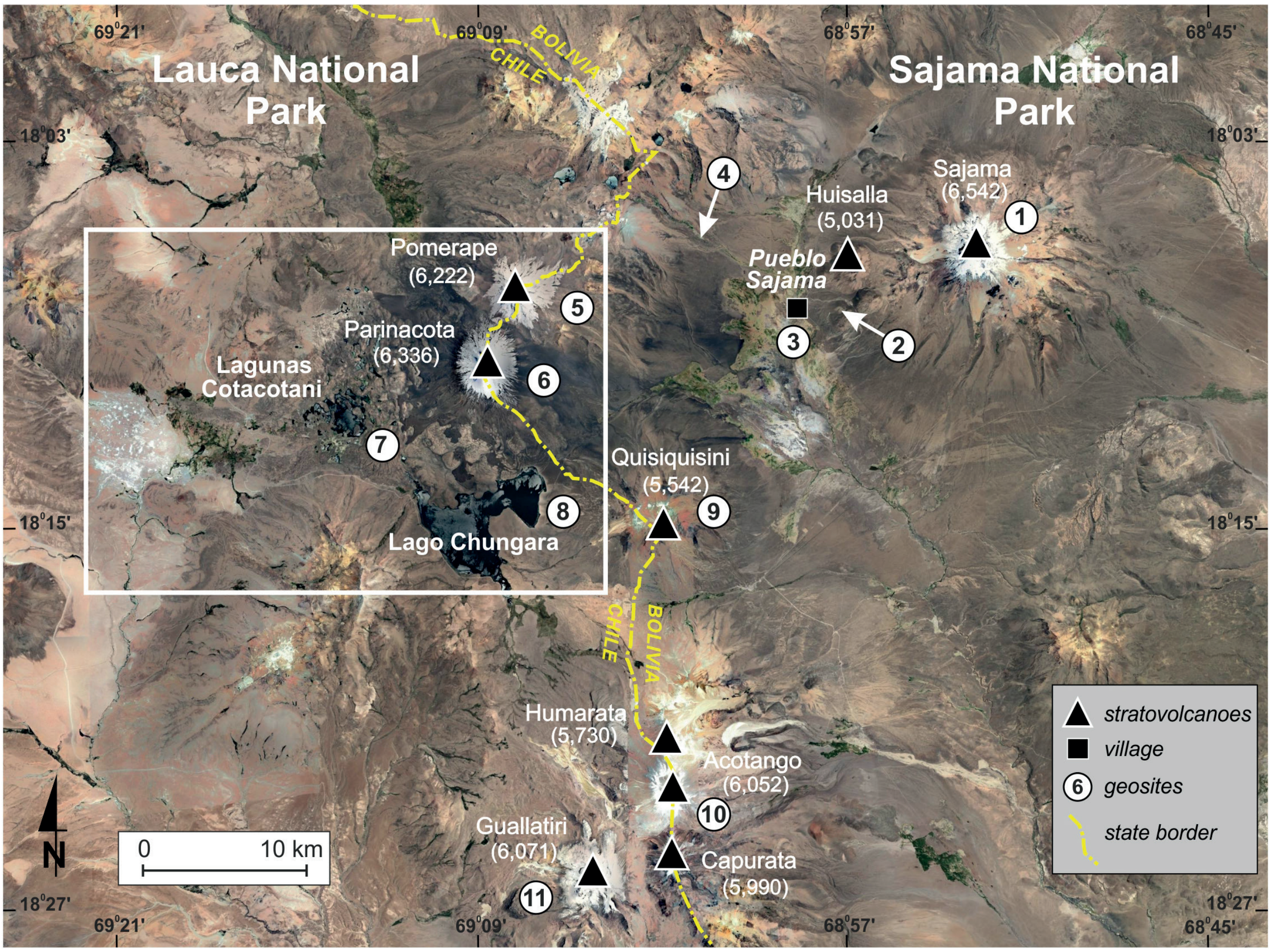

Fig. 3. Location map of described geosites; white rectangle indicates the area shown in Fig. 4 (terrain after Google Earth photo)

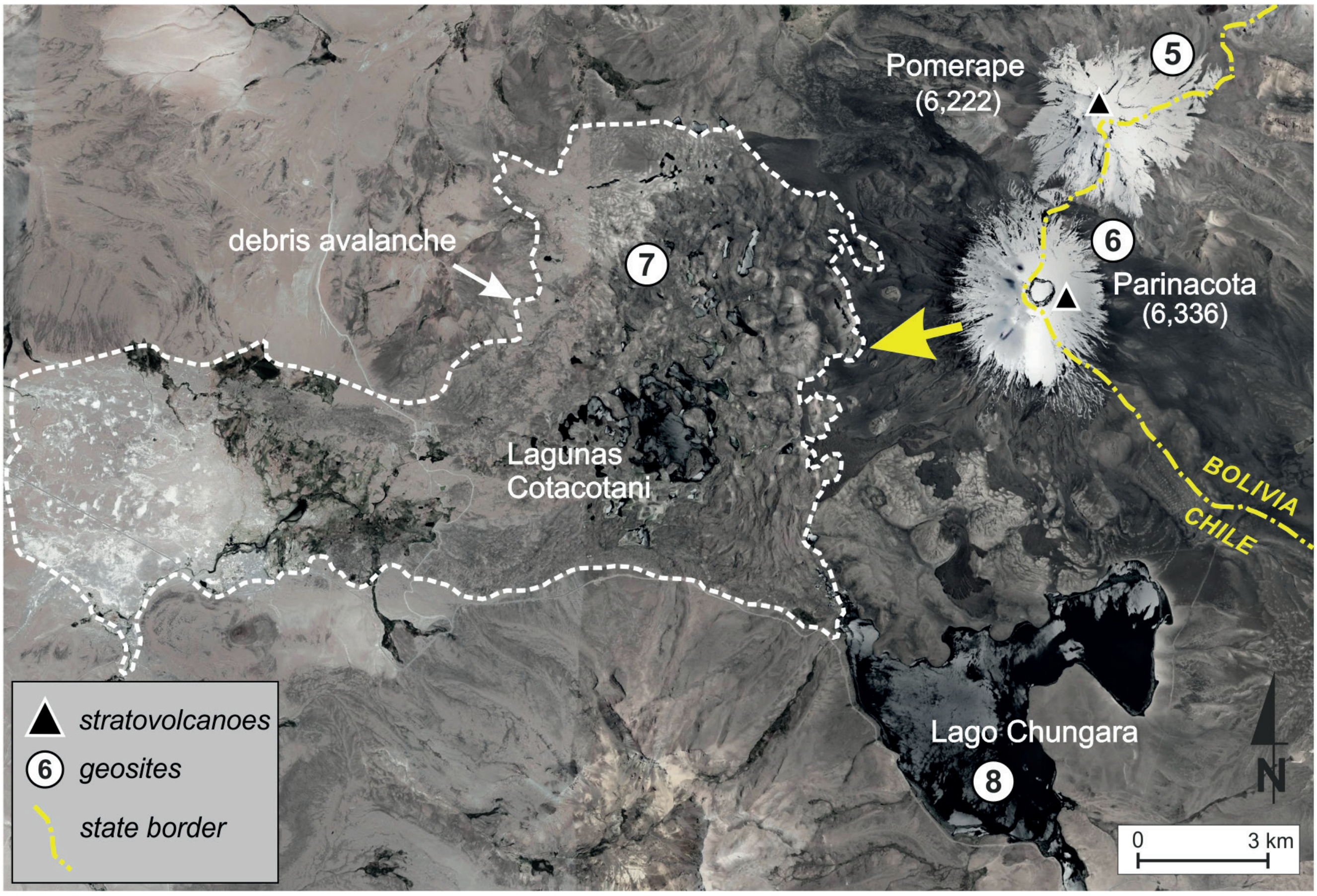

Fig. 4. Google Earth aerial photograph of the vicinity of Parinacota and Pomerape volcanoes. The yellow arrow shows the direction of debris avalanche, white dotted line marks the range of deposit after Cleavero *et al.* (2002)

On the Altiplano, there are cultural monuments of the Aymara Indians who still live in these areas. The majority, in the form of chapels and churches originate from the times of the Spanish conquest. Following the colonial epoch, i.e. from the XVIth–XIXth centuries. However, numerous geoglyphs found here come from the pre-Inca times (Valenzuela & Clarkson, 2014; Birge, 2016). The livelihood basis for the inhabitants living in the Carahuara de Carangas territory is still pastoralism (72%), while only 19% of residents are engaged in tourism (Villarroel *et al.*, 2014). The basic livestock animals are *llamas* and *alpacas* kept for wool and meat. This requires a rational management of *bofedales* peat bogs by shepherds (Villarroel *et al.*, 2014). The vegetation of plants on *bofedales* depends menaced by the water outflowing from rapidly melting snow caps, glaciers and on minor precipitation (Vuille *et al.*, 2008; Rangecroft *et al.*, 2013, Schoolmeester *et al.*, 2018).

Stratovolcanoes

Since the Jurassic period, the area of Andes has formed the active margin of the South America continental plate over subducted oceanic plate (Fig. 2). An initial Mesozoic magmatic arc in the Coastal Cordillera, was partly eroded. The Paleogene sub-volcanic intrusions of the Toquepala Group and diverse Oligocene-Miocene volcanic formations of the Tacaza Group are better-preserved. The Neogene-Quaternary Barroso Volcanic Arc (10–1 Ma) was initially some 100 km wide, but over time, its range and activity have decreased (Wörner *et al.*, 2000). Contemporary volcanoes in northern Chile and Bolivia belong to the Central Volcanic Zone (CVZ), which extends parallel to the continental margin from south Peru to central Chile, and includes 44 stratovolcanoes (De Silva & Francis, 1991).

The Nevados de Payachata comprise two typical stratocones: Parinacota and Pomerape (Fig. 5A). Both are currently covered with ice caps, which eroded volcanic rocks in elevated areas. Their area measures about 170 km^2 with a topographic prominence reaching about 2,000 m. The Pomerape Volcano is older and more eroded. On the slopes, smoothed andesite lava flows and undercut pyroclastic layers are observed (Fig. 5B), whereas near the extended peak a dacite dome is visible (Fig. 5C). Lava composition ranges from basaltic andesites to rhyodacites.

Due to a rarely observed landform, i.e. the debris avalanche, the Parinacota Volcano (Fig. 5D) is better known among the volcanologists (Fig. 5D, E). According to Wörner *et al.* (1988), activity of that volcano was dated at the end of the Pleistocene (300–10 ka). These authors identified five stages (I–V) of the stratovolcano activity. The oldest andesite lavas (I stage) were dated at 0.264 Ma. Their activity manifested itself in the extrusion of the andesite dome. The second stage (0.011 Ma) was the eruption of dacitic-rhyolitic dome. The subsequent III stage included mainly lava effusions. In the III stage, which took place about 13 ka years ago, the Plinian lateral eruption occurred, which clearly placed the Parinacota Volcano among the most hazardous eruptive centers discussed in this paper.

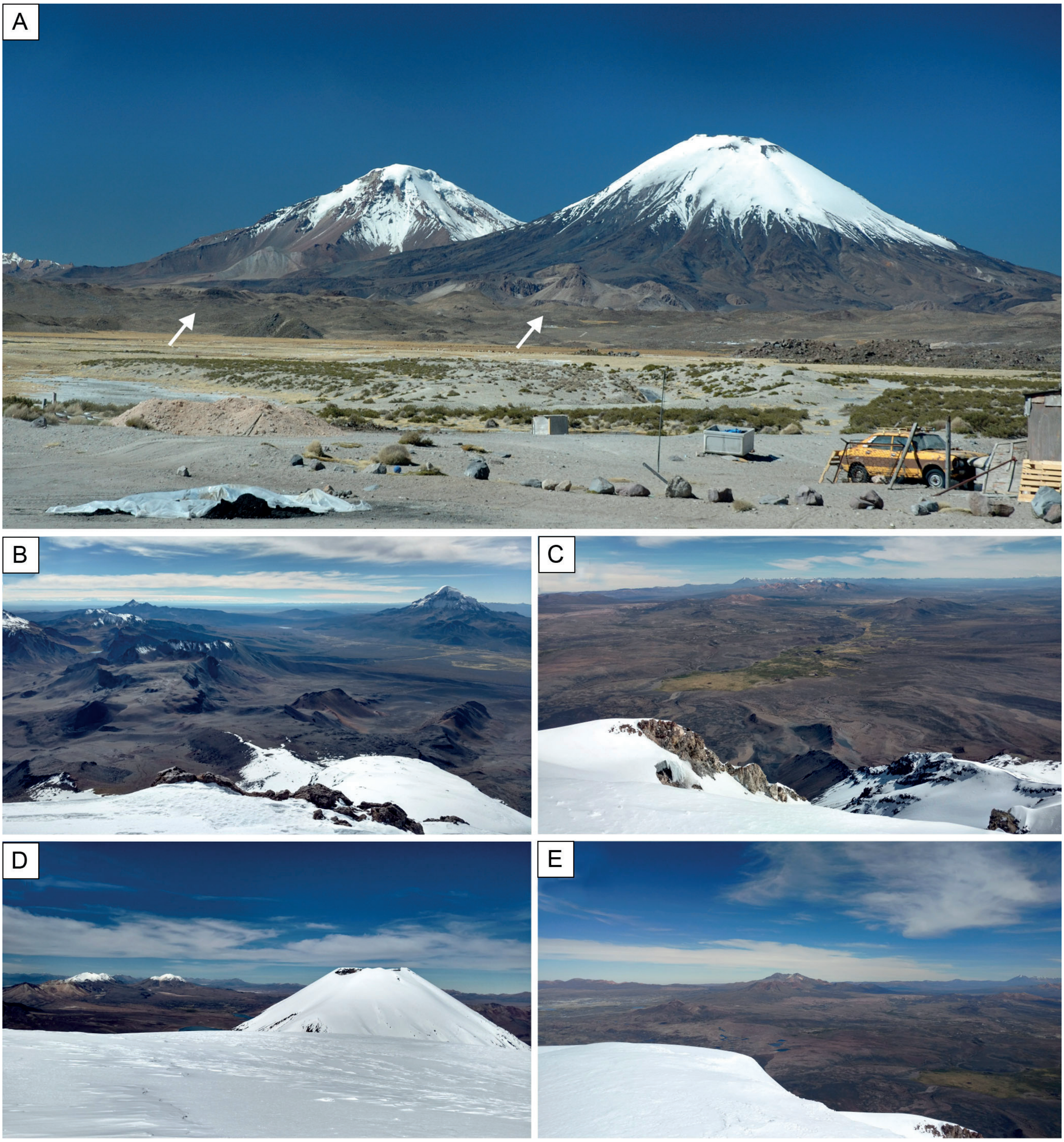

Fig. 5. Geotouristic objects described in the text: A – SW slopes of Pomerape (left) and Parinacota (right) volcanoes, arrows indicate position of debris avalanche triggered by the collapse of Parinacota cone in the Holocene; B – view from Pomerape summit towards the E, lava flows eroded by glacier are exposed on the slope, peak on the far right is Nevado Sajama; C – view from Pomerape summit towards the W, fragment of dacite dome is seen on the left, and green bofedales peat bogs occur in the centre, in front of debris avalanche; D – view from ice cap of Pomerape summit towards the S with Parinacota summit seen in the foreground and ice-capped Acontago and Guallatiri volcanoes in Nevados Quimsachata Massif seen on the far left; E – view from Pomerape summit to the SW, towards Altiplano fragment covered with debris avalanche. Lagunas Cotacotani lakes are visible in the central part of debris avalanche. Photos P. Panajew unless otherwise noted

An effect of this lateral eruption was a huge debris avalanche (Figs. 3, 4), similar to that known from the eruption of Mount Saint Helens volcano in the USA, in 1980. The mass of rocks and ice, which slid down the slopes of the volcano showed an unexpected mobility, as it climbed up an opposing slope with 270 km/h velocity (Lipman & Mullineaux, 1981).

It is interesting to add that some extremely large debris avalanches in the world may have traveled even faster (Siebert, 1996). Both the shape and volume of the Parinacota debris avalanche show that it was three times larger than that of Mount Saint Helens avalanche from 1980 eruption. Moreover, the interesting feature is that the Parinacota cone shows no signs of collapse after the avalanche descent.

At the IV stage of the Parinacota activity, the cone has been rebuilt, which masked the source area of that terrible catastrophe. The last, V stage of Parinacota development comprised the formation of parasitic vents with main one the Ajata Volcano (Fig. 6A) (González-Ferrán, 1995).

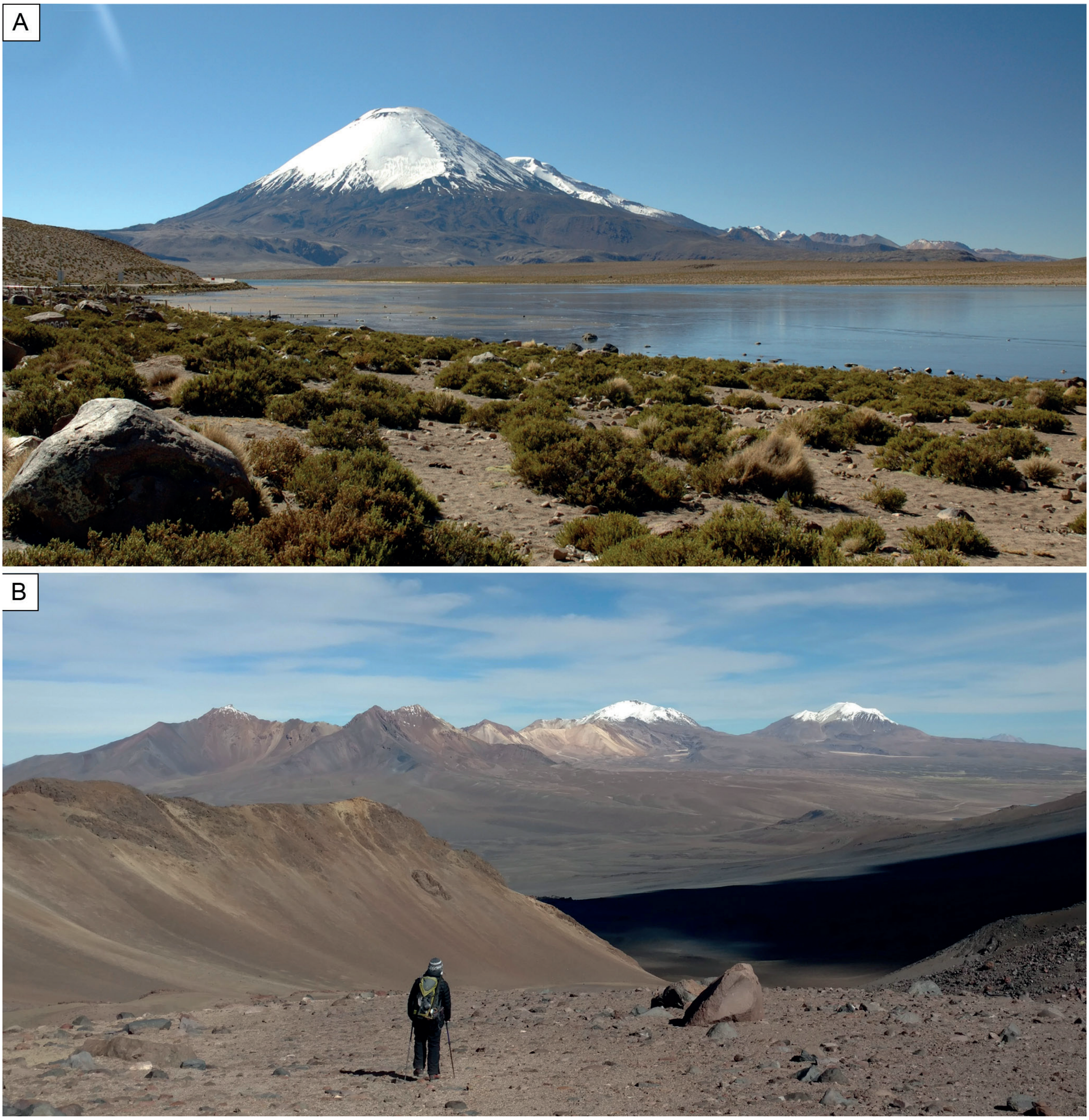

Fig. 6. Geotouristic objects described in the text: A – southern shore of Lago Chungara covered by *Parastrephia lepidophylla* shrubs and Parinacota Volcano in the distance; B – view of Nevados de Quimsachata and Cerro Quisiquisini volcanic massifs from the S slopes of Pomerape Volcano. From the right: Guallatiri, Acotango and Humarata volcanoes, and the Quisiquisini Ridge

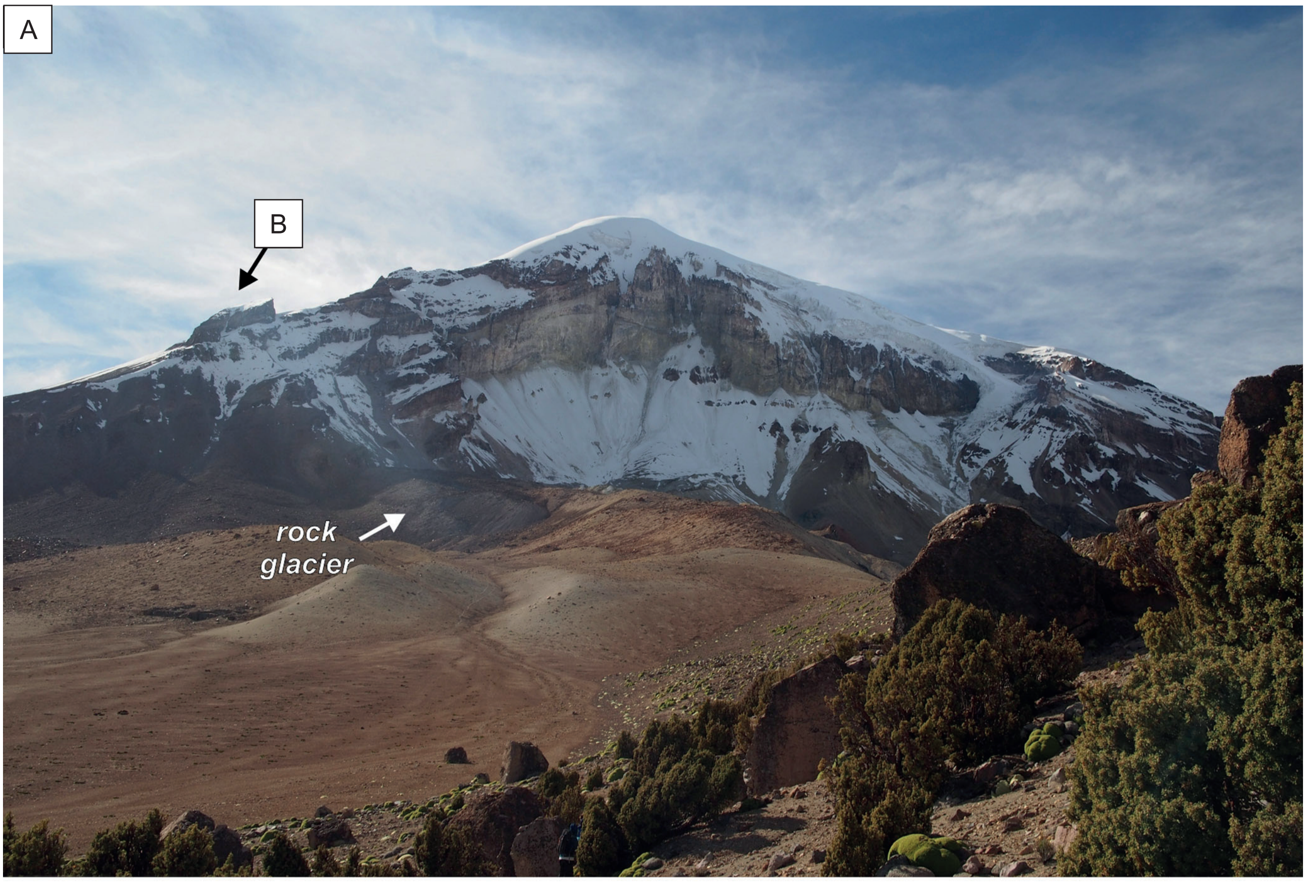

Fig. 7. Geotouristic objects described in the text: A – Nevado Sajama Volcano seen from the SW, with active rubble glacier in the centre; B – enlarged fragment of Figure 7A: approach from the SW to the intermediate camp at 5,600 m a.s.l. located at the foot of lava flow on the trail leading to Sajama summit

The other eruptive complex within the area of Nevados Quimsachata (Fig. 6B) comprises the Gualatiri, Acotango and Capurata volcanoes (González-Ferrán, 1995). The first two are definitely older than the third one, and the Acotango was certainly active in the Holocene. A significant part of the Acotango cone slid downslope towards the north, leaving a huge niche incised in the northern slope of the volcano. Moreover, the sediments laid down by its lateral eruption were observed 10 km away from the source.

The Gualatiri is the youngest volcano in the Quimsachata complex and is also the southernmost volcano in the Central Andes, which has a permanent ice cap. There is evidence that the Gualatiri was active 6 times during the period 1825–1985. Numerous fumaroles seen in the main crater and on the eastern slope of the mountain testify to its recent activity. A "Jet-type" fumarole is also active, the name of which comes from the roar sound similar to that of the aircraft engine.

Similarly to the Pomerape, the Sajama Volcano forms a stratocone, exposing glacially-eroded slopes (Fig. 7A), covered with numerous lava flows (Fig. 7B). The composition of eruptive products ranges from andesites to rhyodacites. Below the ice cap, elements of glacial relief can be observed on the slopes: moraines, boulder moraines, rock glaciers and lakes. It should be noted that these are typical forms of insulated ice caps developed in a dry and semi-tropical climate.

Volcanic eruption hazard

The hazard of stratovolcano eruptions is monitored primarily for large cities in the Andes, e.g. Arequipa (Peru), Quito (Ecuador) and Pasto (Colombia). Close to the study area, the Huaynaputina, Tutupaca and Gualatiri volcanoes have been active in historical times (Simkin & Siebert, 1994).

In the Andes, the largest volcanic event in historical time was the eruption of the Huaynaputina Volcano, which took place in February, 1600. This is assumed to be the Plinian eruption, with an estimated height of the ash column ranging up to 43 km (Oppenheimer, 2011).

Generally, the activity of the Gualatiri Volcano is regarded as far more dangerous to the Altiplano communities in the study area. Recently, it has been manifested by fumaroles located on the eastern slope and in the summit crater. Also, the described historical eruptions were not very dangerous, grading only two on the Volcanic Explosivity Index (VEI) scale. It is assumed that a possible future eruption will be of sub-Plinian type, although it cannot be excluded that its VEI may be one degree stronger.

However, the real danger is revealed by sediments that surround both the Acotango and Parinacota volcanoes. Considering the volcanic events recorded in these sediments, the following forms of activity can be predicted: ashfalls, pyroclastic flows, lahars and debris avalanches. Moreover, the intensity of these forms indicates that in the case of the Parinacota Volcano, the eruptions of VEI = 5–6 can be expected.

Geosites

In the article, the authors propose 11 trips to the SNP and geoattractions located in its immediate vicinity (Tab. 2). The longest hike (Trip 1) is at Nevado Sajama. The time needed to reach the summit of Nevado Sajama depends on your physical condition, acclimatization and the actual weather. Usually, it requires 2 to 3 days. Trips 2, 3, and 4 near Pueblo Sajama (4,245 m a.s.l.) are aimed at getting to know the immediate area and obtaining adequate acclimatization necessary to stay at an altitude of over 4,000 m a.s.l. The longest hike to Geysers in the Junthuma River Valley (Trip 4) is approx. 15 km. For people planning to climb the nearby stratovolcanoes over 6,000 m a.s.l., an acclimatization trip (No. 9) to the nearby volcano Cerro Quisiquisini (5,542 m a.s.l.) with beautiful views of the highest volcanoes is proposed. For people planning to reach the highest volcano in Bolivia – Nevado Sajama (6,542 m a.s.l.) (Trip 1), authors suggest an earlier acclimatization trip to one of the lower volcanoes: Pomerape (6,222 m a.s.l.) (Trip 5), Parinacota (6,336 m a.s.l.) (Trip 6), Acotango (6,052 m a.s.l.) (Trip 10) or Guallatiri (6,071 m a.s.l.) (Trip 11). These are full-day trips lasting from 12 hours to 20 hours. Their starting points can be reached by a rented 4 × 4 car. During a break between volcano visits, one can go on a day trip to Lauca National Park on the Chilean side, to see the remains of a stone avalanche (Trip 7) and rest at Lago Chungara (Trip 8).

In addition to the joy of overcoming your own weaknesses and seeing extraordinary landscapes, these tours provide cognitive values by exploring geosites of volcanic and postglacial landforms, fumaroles and hot springs, typical high-Andean plant habitats, mysterious geoglifs, as well as local culture monuments and folklore.

Trip 1: Nevado Sajama (6,542 m a.s.l.)

The Sajama Volcano is the 15th highest peak of the Andes (Biggar, 2005) and the highest mountain in Bolivia (Fig. 7A). This is a perfectly shaped volcanic cone covered with an ice cap and valleys incised in the slopes (Karátson *et al.*, 2012). The ice cap at the summit and the rubble glaciers on its southern slope constitute an important water reservoir for the whole region (Rangecroft *et al.*, 2013). Its melting feeds numerous streams that are tributaries of the Sajama, Tomarapi and Esquillani rivers. The range of *bofedales*, which provide the basis for the existence of the SNP fauna and flora depends on the amount of water in rivers and streams. While climbing the Sajama, visitors cross one of the active rubble glaciers (Fig. 7A) covering an area of 0.103 km^2 (Rangecroft *et al.*, 2015). The snow-free slopes of the Sajama are of great ecological value, where visitors can meet the plants typical of biotic zones from 4,100 m a.s.l. to 5,400 m a.s.l.

Together with the neighbouring volcanoes: Pomerape, Parinacota, Acotango and the still active Guallatiri towering over the Altiplano Plateau, the Sajama group presents a typical volcanic landscape.

The first Europeans visited this region in 1939. They were Austrians: Wilfrid Kühm and Josef Prem (Brain, 1999). Among the volcanoes mentioned above, Sajama is technically the most difficult mountain to climb. Depending on the chosen route of entry, difficulties, according to the IFAS climbing scale, are rated at PD, AD grades (Brain, 1999; Biggar, 2005). Thus, to reach the top, visitors must have trekking experience, mountaineering equipment and warm clothes, must be in good physical condition and acclimatized. Climbing the volcano takes 2–3 days. Tourists who do not have the appropriate technical skills and experience in trekking the high mountains and lack the appropriate mountaineering equipment can hire a local guide, transport and necessary equipment in Pueblo Sajama. Climbing the remaining volcanoes mentioned in the article is not very technically demanding and does not exceed the IFAS grade F (Biggar, 2005).

During long ascents, exposed massive andesite lava flows and endless slopes made of pyroclastic deposits are observed.

Trip 2: Mirador Montecielo (4,550 m a.s.l.)

The Mirador Montecielo (Fig. 8B) is a traditional ritual site of the Caranga people, located on a hilltop, in the immediate vicinity of Pueblo Sajama (Fig. 8A). The outlook is located about 250 m from the stone altar (Fig. 8C), at the end of the linear geoglyph, which is one of the ritual paths (Trip 3d). The square is surrounded by a stone wall (Fig. 8D). In its central part, there is a stone plaque informing about the purpose of this site and its elevation (Fig. 8B). The whole surrounding area, up to about 4,800 m a.s.l., is covered with the *queñua* dwarf forest (Fig. 8B) (Kessler, 2006). From this site, there is a broad view of the plateau covered with green peat bogs, and of the towering volcanoes. Looking towards the W, visitors can admire the Nevados Payachata Massif with the Pomerape and the Parinacota volcanoes (Fig. 8C). Towards the SW, there is the volcanic Nevados Quimsachata Massif and the Cerro Quisiquisini Volcano (Fig. 8D). During windless weather, towards the NE, a white plume of water vapor can be seen over the geyser field in the Junthum Valley (Fig. 8C).

Fig. 8. Geotouristic objects described in the text: A – view from Pueblo Sajama outskirts to the E, towards Nevado Sajama, black arrow (B) marks a viewpoint located on a hilltop (4,550 m a.s.l.). In the foreground, llamas stand among clumps of *Festuca orthophylla* grass; B – view of Nevado Sajama slopes covered with high-mountain *queñua* forest (*Polylepis tarapacana*) from Mirador Montecielo viewpoint (Fig. 10A); C – panorama from viewpoint B to the W: in the foreground stands a stone altar built by the Caranga people as their ritual site, in the centre there is Pueblo Sajama surrounded by *bofedales* and in the far distance there are Parinacota and Pomerape volcanoes; D – panorama from viewpoint B to the SW: from the left are Nevados Quimsachata and Cerro Quisiquisini volcanic massifs, in the foreground there are dwarf trees *Polylepis tarapacana*

Towards the E, above the mouth of the gorge named Quebrada Kohuiri, the Nevado Sajama glacier rises (Fig. 8B).

Near the mirador square, there are bits of land intended as camping sites for climbers getting acclimatized before climbing the Nevado Sajama peak.

Trip 3: Pueblo Sajama (4,245 m a.s.l.)

Pueblo Sajama is a small village located in the Carahuara de Carangas territory, in the Sajama Province of the Oruro department. The village is entirely located within the SNP area. It provides a modest, but reliable accommodation base. Tourists can also hire local guides. The residents speak Spanish. There are trailheads to thermal pools (Trip 3a) and to *bofedales* in the vicinity (3b), as well as to the monuments of local architecture (3c) and geoglyphs (3d).

Trip 3a: hot springs (approx. 6 km distant from Pueblo Sajama)

In the lower part of the Rio Junthuma, near its confluence with the Rio Sajama, there are hot springs of slightly brackish water, with temperatures from 39.3°C to 45.2°C, and following ions in mg/dm^3: Ca (27.1–43.5), Mg (17.1–28.3), Na (300–439), K (49–56), Cl (319–476), SO_4 (163–188), SiO_2 (148–155) and average pH of 7.1 (Scandiffio & Rodriguez, 1992). Approximately 5 km from Pueblo Sajama, there are the Manasaya hot springs, with bathing facilities, accommodation and a restaurant (Fig. 9B).

Trip 3b: bofedales (peat bogs of alpine biotic zone)

In the immediate vicinity of Pueblo Sajama, there is a wetland (*bofedale*) covered with evergreen vegetation, which is a unique ecosystem, typical of the Altiplano Plateau. Such areas are natural pastures for *llamas*, *alpacas* and wild *vicuñas*. Three types of *bofedales* occur in the SNP: 1. permanently wet (Fig. 9C) and 2. periodically drying (Fig. 9D) and 3. salt flats (*collpares*) (Fig. 9B). The dominant plants in the wetlands are: *Oxychloeandina*, *Distichiamuscoides* and *Calamagrostis rigescens*, but there are also several other species (Alzérreca *et al.*, 2001; Ruthsatz, 2012). In recent decades (1986–2016), with progressive climate warming, a decrease in the *bofedales* area has been observed, related to lower water supply and resulting drying (Yager *et al.*, 2019).

Trip 3c: Pueblo Sajama, historical buildings

While in Pueblo Sajama, tourists can visit the colonial church (Iglesia de la Natividad) from 1886 (Fig. 10A), located at the central square. The church is built of stone, on a rectangular plan with two transepts: in the northern and the southern parts.

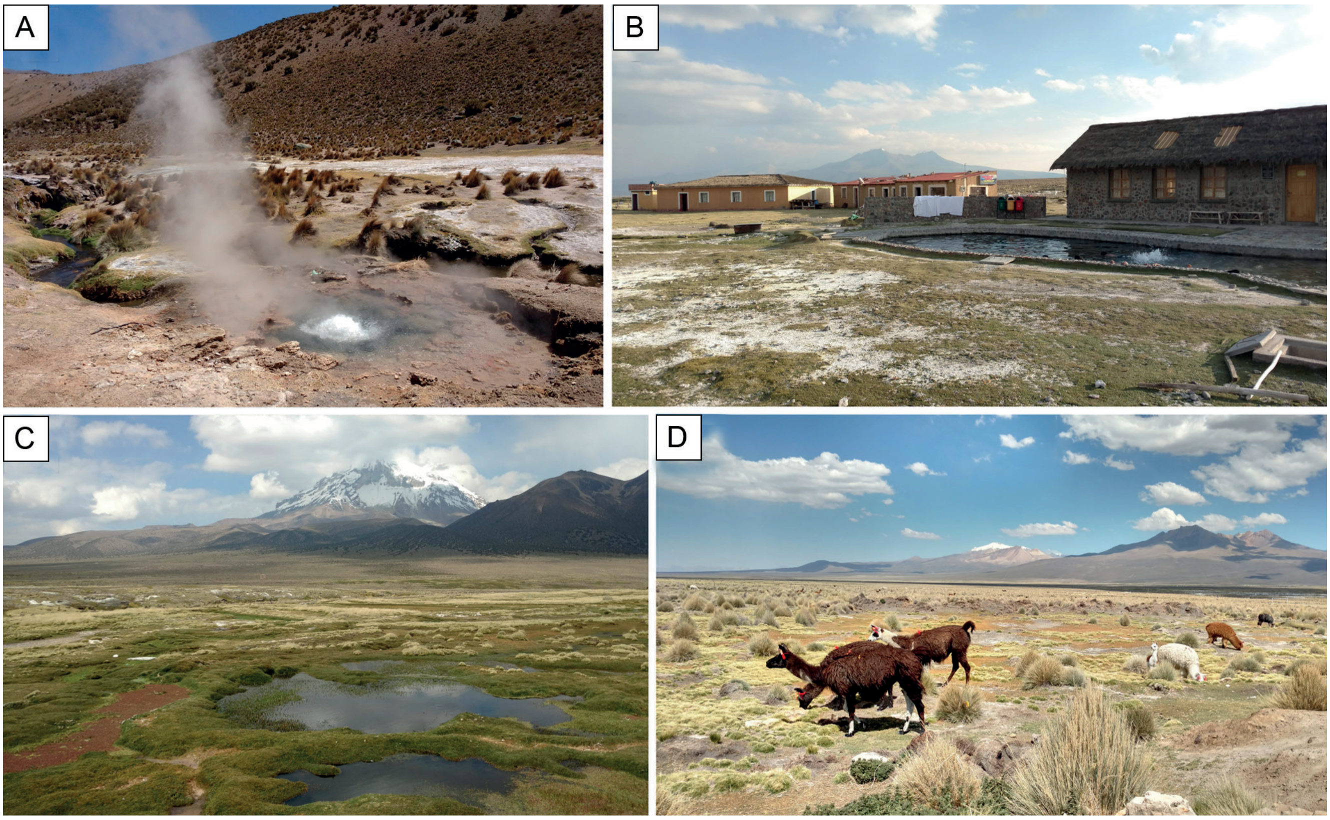

Fig. 9. Geotouristic objects described in the text: A – one of geysers in Rio Junthuma Valley (photo N. Utnicka-Łydek); B – thermal pool in Manasaya hot springs area located on the border between *bofedales* and Salar de Collpares near Pueblo Sajama; C – view of permanent wetlands (*bofedales*) providing pastures for *llamas* and *alpacas* with Nevado Sajama Volcano in the far center; D – *llamas* and *alpacas* grazing on periodically drying *bofedales* with Cerro Quisiquisini Massif visible on the far right

Outside, on each side, the body of the building is supported by three side buttresses, which give the entire structure a massive and stable appearance (Fig. 10B). The roof is thatched and the whole complex is surrounded by a stone wall, with a bell tower built in the NE corner. In the inner courtyard, in front of the entrance to the church, there is a small stone chapel (Fig. 10C).

Near Pueblo Sajama, about 3.7 km from the central square, there is another small chapel (Fig. 10E), built in the immediate vicinity of one of the family farms (*Aymara sayaña*) that tourist pass on the way to the Manasaya hot springs. The chapel is built of brick and covered with clay tiles. Its architecture resembles that of the church in Pueblo Sajama.

Trip 3d: geoglyphs

Near Pueblo Sajama, visitors can examine over a hundred linear geoglyphs (Fig. 11), originated from pre-Inca times (Valenzuela & Clarkson, 2014; Birge, 2016). Straight lines of geoglyphs cover an area of about 22,000 km^2 and extend up to several kilometers, covering the slopes of the surrounding hills. These objects combine the material remains of the Carangas Indians culture, such as ruins of mountain fortresses (*Aymara pucaras*), tomb towers (*Aymara chullpas*), as well as modern villages and chapels (Birge, 2016). However, these forms differ from the numerous geometric, zoomorphic and anthropomorphic geoglyphs found in northern Chile (Briones, 2006). These also do not resemble the geoglyphs known from the Paracas Peninsula (Fig. 11E). However, some similarity can be noticed with the linear geoglyphs from the Nasca Plateau in Peru (Fig. 11F), located between the zoomorphic geoglyphs (Reinhard, 1988; Ruggles & Saunders, 2012). Just like the Nazca geoglyphs, the Sajama objects probably served as ritual processional pathways. Nowadays, the path (Fig. 11B) connecting the church in Sajama (Fig. 10A) with the altar on the top of nearby hill (Fig. 11C) is used by local Aymara people for occasional processions (Birge, 2016). Straight lines of geoglyphs connect the churches, chapels and altars on the Altiplano, and the surrounding hills lying at the foot of towering volcanoes, creating a perfectly harmonized, ritualized landscape.

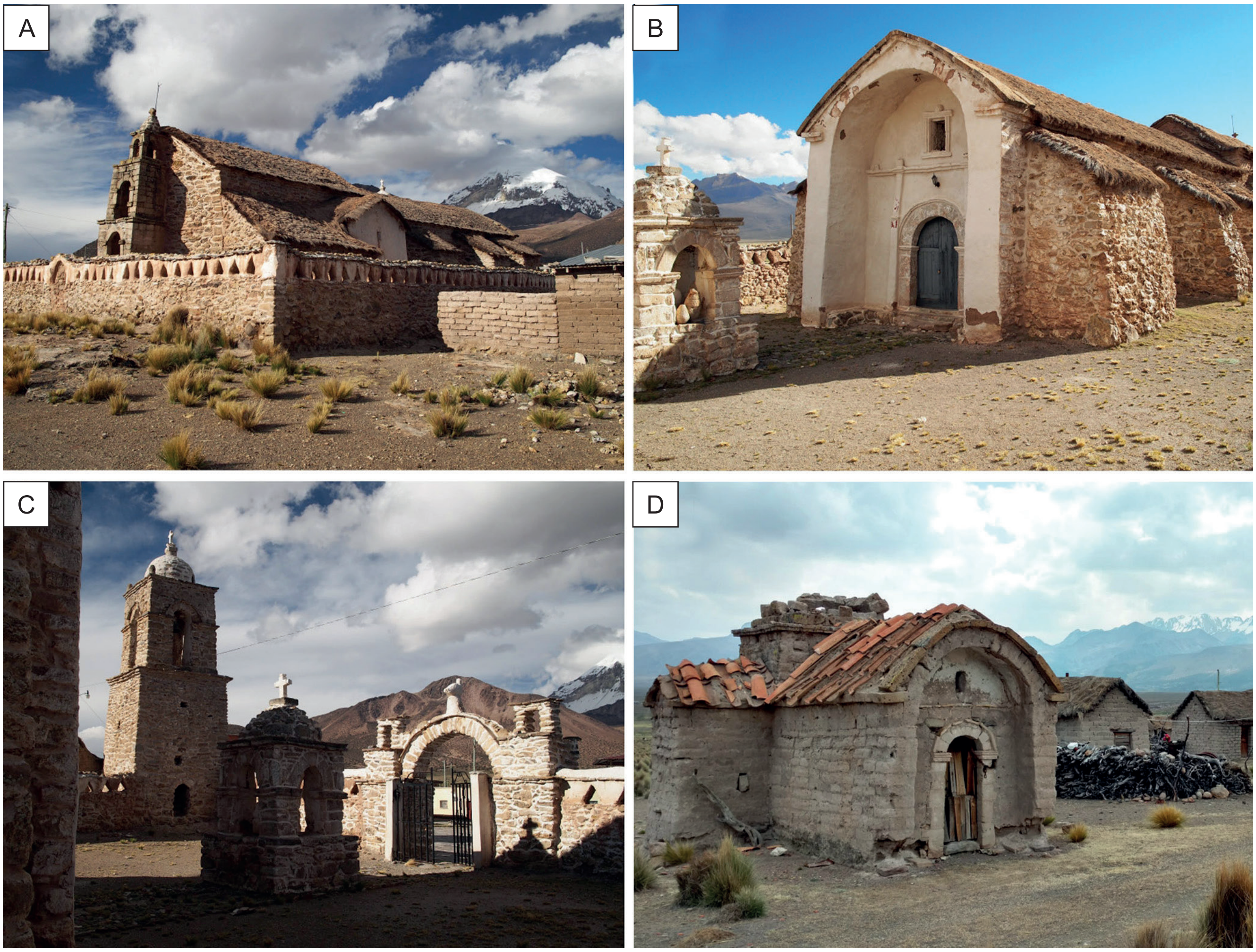

Fig. 10. Geotouristic objects described in the text: A – Iglesia de la Natividad Church (built in 1886), located on the central square of Pueblo Sajama; B – pediment of Iglesia de la Natividad Church with side buttresses strengthening the structure; C – stone chapel close to bell tower of Iglesia de la Natividad Church; D – chapel at one of the family farms near Pueblo Sajama

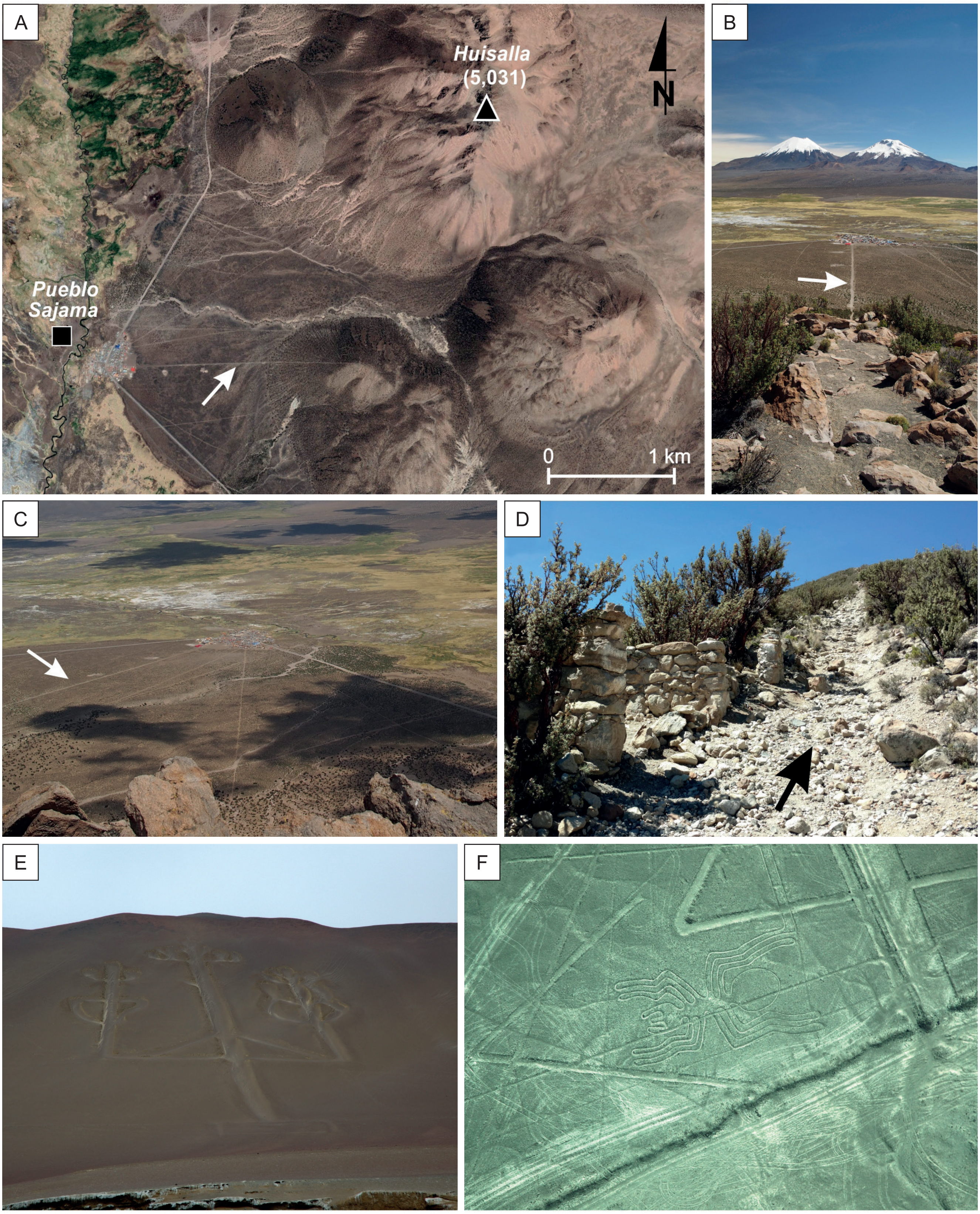

Fig. 11. Geotouristic objects described in the text: A – Google Earth aerial photograph of Pueblo Sajama area with straight geoglyph lines stretching across the Altiplano (white arrow marks position of scenic viewpoint shown in Figure 9B); B – view from the approach to viewpoint marked in Figure 9A along the W-E-heading geoglyph line (arrow) with distant Nevados de Payachata Massif; C – view from Cerro Huisalla (5,031 m a.s.l.) towards the SW with Pueblo Sajama in the centre and geoglyph lines radiating from the village; far distant are green *bofedales* peat bogs bordering the Salarde Collpares (white arrow marks position of scenic viewpoint shown in Figure 9B); D – concave relief of geoglyph line leading (black arrow) through *queñua* bushes to the viewpoint; E – "Chandelier" geoglyph located approx. 190 m above the level of Paracas Peninsula in Peru; F – "Spider" geoglyph (approx. 45 m long) from the Nazca Plateau in Peru

Trip 4: geysers in the Junthuma River Valley

The Junthuma Valley is a glacial landform originated from the Pleistocene. Its bottom is located from 4,700 to 5,000 m a.s.l. and is covered with wet grasslands dominated by *Oxichloeandinae*, *Distichiamuscoides* and *Calamagrostis rigescens* (Alzérreca *et al.*, 2001). Due to scarce vegetation, clearly marked lateral moraines and erratic boulders, which are typical of the postglacial landscape, can be easily identified in the terrain. In the Junthuma valley, about 8 km to the NW from Pueblo Sajama, one of the world's highest geyser fields can be observed, located at an average elevation of 4,400 m a.s.l. (Fig. 9A). Geyser clusters stretch along the Rio Junthuma, over several dozen of meters. Temperatures of the ejected water varies from 50°C to 85°C (Scandiffio & Rodriguez, 1992). The principal hydrochemical components analyzed in the geyser water are (all concentrations in mg/dm^3): Ca (7.4–43.4), Mg (0.07–7.6), Na (1,130–1,140), K (115–144), Cl (1,560–1,950), SO_4 (294–374) and SiO_2 (192–243). The pH values fall into the range of 6.19–7.43 (Scandiffio & Rodriguez, 1992). For centuries, the geyser water has traditionally been used by the Aymara people of the Altiplano for household purposes.

Trip 5: Pomerape (6,222 m a.s.l.)

The Pomerape Volcano (also named: Pomerata, Pomeratu, Payachata Norte, Huarmi Payachata or Payachata II) is one of the two snow-capped volcanoes in the Nevados Payachata Massif located on the Chilean-Bolivian border (Fig. 12A). Currently, Pomerape is inactive and has evident signs of erosion in the terrain. On the SW slope, there is an active rubble glacier covering an area of 0.196 km^2 (Rangecroft *et al.*, 2015). On the NE slopes, clear remnants of glacier activity can be observed in the form of valleys and embankments of lateral and terminal moraines (Fig. 5B). Both the snow cap covering the summit and the rubble glaciers on its SW slope provide an important water reservoir for the region (Rangecroft *et al.*, 2013). The Pomerape is the 36th tallest peak of the Andes. It was first ascended in May, 1946 by Edmundo Garcia and René Zalles (Brain, 1999). Hiking difficulties are rated F on the IFAS climbing scale (Biggar, 2005).

Trip 6: Parinacota (6,336 m a.s.l.)

The Parinacota Volcano (also known as: Payachata I, Payachata Sur, Muru Payachata or Payachata Grande) is the younger and higher of the twin volcanoes of the Nevados Payachata Massif (Fig. 5A). It is located just on the Chilean-Bolivian border, by the Lago Chungará mountain lake (Fig. 6A). The Parinacota is a young, symmetrical volcanic cone with a clearly marked oval crater covered with a snow cap (Fig. 5D), which shows no visible signs of erosion (Karátson *et al.*, 2012). Due to its almost perfect conical shape, it is called the "Little Cotopaxi" as it resembles that "ideal" volcanic cone from the Ecuadorian Andes. Just as in the neighboring Pomerape, the permanent snow covering the Parinacota is a reservoir of fresh water and feeds the nearby Taypi Puchuni and Fisarata streams. Parinacota is the 32nd highest peak of the Andes (Biggar, 2005). The first ascent to the summit was made on December 12, 1928 by Josef Prem and Carlos Terán (Brain, 1999).

Trip 7: debris avalanche

The huge debris avalanche is located on the western, Chilean slope of the Parinacota Volcano (Fig. 4). This is the most important geosite in the study area; very rare on the global scale. This type of geoform can only be seen at a few geosites around the world (e.g. Mount Saint Helens, USA; Socompa, Chile; and Tata Sabaya, Bolivia). It was formed between 8,000 and 18,000 years ago, as a result of the collapse of the Parinacota cone (Francis & Wells, 1988; Wörner *et al.*, 2000; Clavero *et al.*, 2002). Estimated volume of the avalanche is 6 km^3 (for comparison, volume of the Parinacota cone itself is about 25 km^3). It covers an area of 140 km^2 and extends over the distance of 20 km west of the source cone. The terrain represents classic hummocky topography: countless small hills, scattered rock block (Fig. 5A) and a closed depression, filled with small lakes named the "Lagunas Cotacotani" (Fig. 5C). Many andesite blocks show small-scale impact marks, resulted from the collision of two large rock fragments or left by fast-moving rock chunks hitting the andesite surface like projectiles (Clavero *et al.*, 2002). The Lagunas Cotacotani were probably formed by melting of ice blocks that ended up within the debris avalanche mass (Francis & Wells, 1988; Clavero *et al.*, 2002). The water that seeps through the avalanche sediments feeds the Lauca River and the surrounding *bofedales* (Fig. 5C). The increase of water level in the Lago Chungara is associated with the action of debris avalanche. The lake was formed by blocking the runoff of waters from surrounding areas.

Trip 8: Lago Chungará (4,520 m a.s.l.)

Located in the territory of Chile, within the Lauca National Park (Fig. 3), at the foot of the Parinacota Volcano, the Lago Chungará is one of the highest Alpine lakes in the world (Fig. 6A). Its area covers 21.5 km^2 and the maximum depth is 40 m (Bao *et al.*, 2015). The surroundings of the lake represent a typical high-mountain volcanic landscape. The lake has a volcanic-tectonic origin and is classified as a tropical polymictic salt lake (Mühlhauser *et al.*, 1995). It was formed about 13.5 ka ago, as a result of the Parinacota Volcano collapse (Fig. 4), which triggered debris avalanche (Trip 7), that blocked water drainage of the Lauca basin (Francis & Wells, 1988; Wörner *et al.*, 1988; Clavero *et al.*, 2002; Jicha *et al.*, 2015). Both the Lago Chungará and the Laguna Cotacotani are homes to a rich population of waterfowl and wader species. Among the numerous bird species, the giant coot (*Fulica gigantea*), the yellow-billed teal (*Anas flavirostris*), the silver-crested grebe (*Podiceps occipitalis juninensis*) and three species of flamingos: Chilean (*Phoenicopteris chilens*), Andean (*Phoenicopteris andinus*) and short-beaked (*Phoenicopteris jamesi*) can be found (Rundel & Palma, 2000).

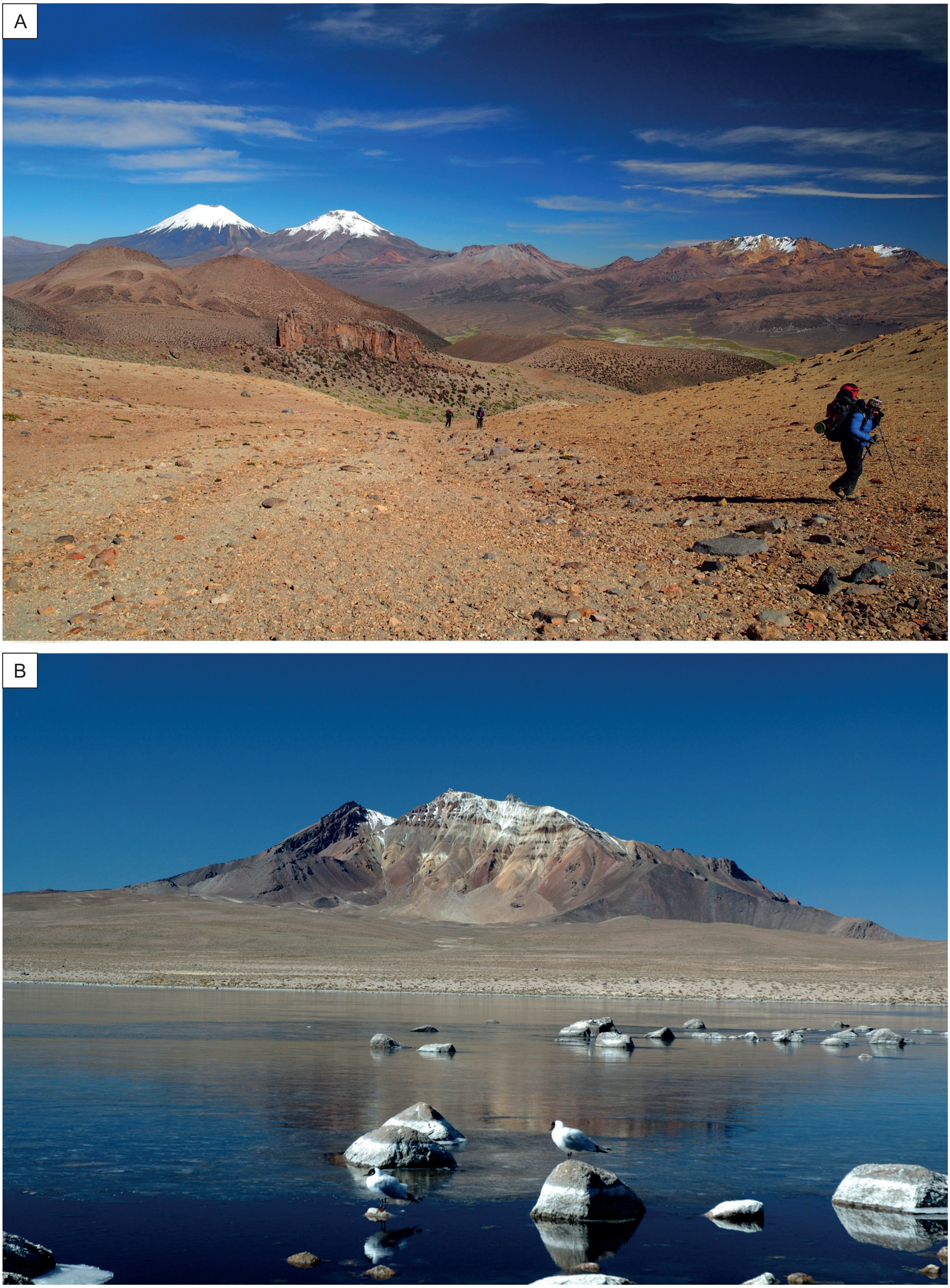

Fig. 12. Geotouristic objects described in the text: A – ice-capped Parinacota (left) and Pomerape (second from the left) volcanoes in the Payachata Massif, seen from Nevado Sajama; B – view of SE slope of Cerro Quisiquisini from the shore of Lago Chungara

Trip 9: Cerro Quisiquisini (Quisi Quisini) (5,542 m a.s.l.)

The Quisiquisini is a heavily eroded Pliocene volcano, only periodically covered with snow cap (Fig. 12B). On its southern slope, there is an active rubble glacier of an area 0.033 km^2 (Rangecroft *et al.*, 2015). On the slopes, visitors can observe elements of postglacial relief, such as. lateral moraines and less marked terminal moraines (Fig. 6B). Originally covered by the *queñua* forest, the Quisiquisini slopes were deforested by human activity. The northern slopes of the volcano reach the *bofedales* peat bogs, which are important pasturelands for numerous *vicunas*.

Trip 10: Acotango (6,052 m a.s.l.)

The Cerro Acotango (Volcán Acotango) is the second highest volcanic peak in the Nevados Quimsachata (Quimsallatas) Massif (Fig. 6B) located just on the Chilean-Bolivian border (Fig. 3). It is covered with a snow cap. The climb to the summit is not difficult and is graded F on IFAS scale (Biggar, 2005). The remains of a construction at the top indicate that Incas were the first humans who ascended the summit (Echevarría *et al.*, 2009). As mentioned above, the Andean people have worshiped the mountains since ancient times, primarily because of the belief in their control of both the weather and the water resources, which have an impact on food production. The highest-found remains of Inca structures were discovered on the Llullaillaco Volcano (6,739 m a.s.l.) Northern Chile and, so far, these are the highest archaeological sites in the world (Reinhard, 1985). The first known ascent to the summit took place in October, 1965 by Sergio Kunstmann, Claudio Maier and Pedro Rosende (Echevarría *et al.*, 2009).

Trip 11: Guallatiri (6,071 m a.s.l.)

The Guallatiri (Huallatire) is the only active stratovolcano in the Nevados Quimsachata (Quimsallatas) Massif, in the Chilean-Bolivian Andes (Fig. 6B). Moreover, it is currently considered the second most active volcano in CVZ, after the Lascar (5,592 m a.s.l.) in Chile. The Guallatiri is located entirely on the Chilean side of the state border (Fig. 3). The first ascent to the summit was made by Friedrich Ahlfeld in 1926. The climb is not technically difficult (grade F on the IFAS scale) (Biggar, 2005) although the summit is covered with permanent snow. Fields of fumaroles can be observed in the area of the summit and on its SW slopes (Inostroza *et al.*, 2020). When climbing the active volcanoes, tourists should take into account the risk of poisoning by gases and vapors emitted from crater or from rock crevices.

Hazards in high mountain regions

Visiting high mountain regions can inflict numerous human health and life hazards. The main risks associated with climbing high volcanoes include low atmospheric pressure, low temperatures, strong winds, icing, snowfall and strong sun exposure. These factors may lead to altitude sickness, frostbite, hypothermia, fractures, sunburn and/or snow blindness (Krzeszowiak *et al.*, 2014; Janus & Piechocki, 2016). When climbing during the Andean summer, tourists can meet atypical snow and ice cover on the slopes of volcanoes. These are penitents (*penitentes*) forming fields of penitents (*campo de penitentes*) or penitent snow (*nieves penitentes*). Their shape resembles rows of kneeling, hooded monks. These forms, usually ranging in size from 0.5 m to 2.0 m, are formed as a result of the slow melting of snow and ice under the influence of wind erosion, rain and sunlight on the glacier surface. The penitent fields can be a serious obstacle while climbing, often making the climbers exhausted. While climbing the active volcanoes, such as the Guallatiri, there is an additional risk of poisoning by volcanic gases emitted from the crater or from rock crevices. Additionally, there is a risk of burns caused by hot vapors and gases released from fumaroles.

Tourist traffic and practical information

In the Sajama National Park, the tourist traffic is low and the number of visitors to this place does not exceed 5,200 people per year (Tab. 3).

Table 3. Comparison of number of tourists visiting the Sajama National Park (SNP) (www1) and the Tatra National Park (TPN) in southern Poland (www2) in 2012–2018

Year	SNP	TPN
2012	4,694	–
2013	4,435	–
2014	1,507	2,926,012
2015	1,327	3,180,644
2016	4,350	3,500,142
2017	3,720	3,593,754
2018	5,189	3,782,610

Compared to the number of tourists visiting the Tatra National Park in Poland, this is a very small number. The fastest way to get to SNP is by bus, minibus or a rented car from the capital of Bolivia – La Paz via Patacamaya. The La Paz–Pueblo Sajama route is approx. 280 km long and takes approx. 4–5 hours. Peueblo Sajama is the perfect place for a base camp for exploring the SNP and visiting the proposed geosites. The accommodation base in Sajama is not very extensive, but there are several hostels offering affordable accommodation in 2–6 bed rooms, equipped with bathrooms with hot water (www3). The hostels offer meals, the possibility of renting camping and climbing equipment and hiring a mountain guide. It should be noted that the offered climbing equipment is quite old and shows signs of wear. In Pueblo Sajama, you can stock up on basic food and industrial products and eat a tasty, warm, but simple meal. If one does want to use the services of a local guide while climbing, one can rent a 4 × 4 car with a driver who will take the tourists to the starting points of the nearby volcanoes and then pick them up at the agreed time. In the period from April to September, the SNP area has the lowest amount of rainfall, and it is the most convenient time to visit Sajama.

Conclusion

Despite high altitudes, the stratovolcanoes in the Andes remain an underappreciated geotourism attraction (Paulo, 2015; Mariño *et al.*, 2021). Physical and mental preparation is crucial for potential visitors to avoid possible health and life hazards.

The area on the Chilean and Bolivian borders has an underestimated geotourism potential. The main attractions are various volcanic forms, typical of the Central Andes. The opportunity to see a volcanic debris avalanche is a real rarity. The second type of attraction comprises glacial forms, in particular glaciers associated with tropical and desert climatic zones. Historical and ethno-cultural values are excellent supplements, available in simple, modest forms, allowing the visitors to forget about the drawbacks of the global tourism industry.

Acknowledgements

We would like to thank the Andrzej Paulo (AGH UST) and other anonymous reviewer for their careful reading of our manuscript and their insightful comments and suggestions. We would like to thank Wojciech Mayer (AGH UST) for help in improving the language of the text. The authors are very much indebted to the participants of the 2019 Tres Pablos y Chicas sport expedition to Bolivia for the time spent together. Sincere thanks are due to Mrs. Natalia Utnicka--Łydek for sharing the photos of geyser from the Rio Junthuma Valley.

References

Alzérreca H., Prieto G., Laura J., Luna D. & Laguna S., 2001. *Características y distribución de los bofedales en el Ámbito Boliviano.* Report, El Programa de las Naciones Unidas para el Desarrollo. La Paz, Bolivia.

Bao R., Hernández A., Sáez A., Giralt S., Prego R., Pueyo J.J., Moreno A. & Valero-Garcés B.L., 2015. Climatic and lacustrine morphometric controls of diatom paleoproductivity in a tropical Andean lake. *Quaternary Science Reviews*, 129: 96–110.

Beck S., Domic A., Garcia C., Meneses R.I., Yager K. & Halloy S., 2010. *El Parque Nacional Sajama y sus Plantas.* Herbario Nacional de Bolivia-Fundacion PUMA, La Paz.

Biggar J., 2005. *The Andes. A Guide for Climbers.* 3rd ed. Andes, Scotland.

Birge A., 2016. *Ritualized Memory and Landscape at Pueblo Sajama, Bolivia: A Study of a Sacred Landscape and Colonial Encounter.* The University of Texas at San Antonio [MA thesis].

Brain Y., 1999. *Bolivia. A Climbing Guide.* The Mountaineers, Seattle.

Briones L., 2006. The geoglyphs of the north Chilean desert: an archaeological and artistic perspective. *Antiquity*, 80(307): 9–24.

Clavero J.E., Sparks R.S.J., Huppert H.E. & Dade W.B., 2002. Geological constraints on the emplacement mechanism of the Parinacota debris avalanche, northern Chile. *Bulletin of Volcanology*, 64(1): 40–54.

De Silva S.L. & Francis P.W., 1991. *Volcanoes of the Central Andes*. Springer-Verlag Berlin Heidelberg.

Echevarría E., Kiełkowska M., Kiełkowski J. & Sas-Nowosielski K., 2009. *Wielka encyklopedia gór i alpinizmu*. T. 4: *Góry Ameryki*. Kiełkowska M., Kiełkowski J. (red.), Wydawnictwo "Stapis", Katowice.

Francis P.W. & Wells G.L., 1988. Landsat thematic mapper observations of debris avalanche deposits in the Central Andes. *Bulletin of Volcanology*, 50(4): 258–278.

González-Ferrán O., 1995. *Volcanes de Chile*. Instituto Geográfico Militar, Santiago, Chile.

Hoffmann D., 2007. The Sajama National Park in Bolivia. *Mountain Research and Development*, 27(1): 11–14.

Inostroza M., Tassi F., Aguilera F., Sepúlveda J., Capecchiacci F., Venturi S. & Capasso G., 2020. Geochemistry of gas and water discharge from the magmatic-hydrothermal system of Guallatiri volcano, northern Chile. *Bulletin of Volcanology*, 82(7): 1–16.

Janus T. & Piechocki J., 2016. Wybrane stany zagrożenia zdrowia i życia związane z przebywaniem na dużej wysokości. *Anestezjologia i Ratownictwo*, 10(1): 103–111.

Jicha B.R., Laabs B.J.C., Hora J.N., Singer B.S. & Caffee M.W., 2015. Early Holocene collapse of Volcán Parinacota, central Andes, Chile: Volcanological and paleohydrological consequences. *Geological Society of America Bulletin*, 127(11–12): 1681–1688.

Kadwell M., Fernandez M., Stanley H.F., Baldi R., Wheeler J.C., Rosadio R. & Bruford M.W., 2001. Genetic analysis reveals the wild ancestors of the llama and alpaca. *Proceedings of the Royal Society B: Biological Sciences*, 268(1485): 2575–2584.

Karátson D., Telbisz T. & Wörner G., 2012. Erosion rates and erosion patterns of Neogene to Quaternary stratovolcanoes in the Western Cordillera of the Central Andes: An SRTM DEM based analysis. *Geomorphology*, 139–140: 122–135.

Kessler M., 2006. Bosques de Polylepis. In: Moraes M., Øllgaard B., Kvist L.P., Borchsenius F. & Balslev H. (eds.), *Botánica económica de los Andes Centrales*. Universidad Mayor de San Andrés, La Paz.

Krzeszowiak J., Michalak A. & Pawlas K., 2014. Zagrożenia zdrowotne w środowisku górskim. *Medycyna Środowiskowa*, 17(2): 61–68.

Lipman P.W. & Mullineaux D.R., 1981. *The 1980 eruptions of Mount St. Helens, Washington*. Geological Survey Professional Paper 1250.

Mariño J., Cueva K., Thouret, J.C., Arias C., Finizola A., Antoine R., Delcher E., Fauchard C., Donnadieu F., Labazuy P., Japura S., Gusset R., Sanchez P., Ramos D., Macedo L., Lazarte I., Thouret L., Carpio J., Jaime L. & Saintenoy T., 2021. Multidisciplinary study of the impacts of the 1600 CE Huaynaputina eruption and a project for geosites and geo-touristic attractions. *Geoheritage*, 13(3): 64.

Mühlhauser H.A., Hrepic N., Mladinic P., Montecino V. & Cabrera S., 1995. Water-quality and limnological features of a high-altitude Andean lake, Chungará, in northern Chile. *Revista Chilena de Historia Natural*, 68: 341–349.

Oppenheimer C., 2011. *Eruptions that Shook the World.* Cambridge University Press, Cambridge.

Paulo A., 2015. Parki narodowe Andów dorzecza Amazonki w południowej Kolumbii, Ekwadorze, Peru i Boliwii. *Pamiętnik Polskiego Towarzystwa Tatrzańskiego*, 23: 163–202.

Pugnaire F.I., Morillo J.A., Armas C., Rodríguez-Echeverría S. & Gaxiola A., 2020. *Azorella compacta*: Survival champions in extreme, high-elevation environments. *Ecosphere*, 11(2): 1–5.

Rangecroft S., Harrison S., Anderson K., Magrath J., Castel A. & Pacheco P., 2013. Climate change and water resources in arid mountains: an example from the Bolivian Andes. *AMBIO*, 42(7): 852–863.

Rangecroft S., Harrison S. & Anderson K., 2015. Rock glaciers as water stores in the Bolivian Andes: an assessment of their hydrological importance. *Arctic, Antarctic, and Alpine Research*, 47(1): 89–98.

Reinhard J., 1985. Sacred mountains: An ethno-archaeological study of high Andean ruins. *Mountain Research and Development*, 5(4): 299–317.

Reinhard J., 1988. *The Nazca lines, water and mountains: An ethno-archaeological study.* In: Saunders N., Montmollin O., de (eds.), *Recent Studies in Pre-Columbian Archaeology.* British Archaeological Reports, Oxford: 363–414.

Reinhard J., 1999. Zaklęte w lodzie. *National Geographic Polska*, 2: 56–75.

Reinhard J. & Ceruti C., 2005. Sacred mountains, ceremonial sites, and human sacrifice among the Incas. *Archaeoastronomy*, XIX: 1–43.

Ruggles C. & Saunders N.J., 2012. Desert labyrinth: lines, landscape and meaning at Nazca, Peru. *Antiquity*, 86(334): 1126–1140.

Rundel P.W. & Palma B., 2000. Preserving the unique puna ecosystems of the Andean Altiplano: a descriptive account of Lauca National Park, Chile. *Mountain Research and Development*, 20(3): 262–271.

Ruthsatz B., 2012. Vegetación y ecología de los bofedales altoandinos de Bolivia. *Phytocoenologia*, 42(3–4), 133–179.

Ryn Z., 1977. Sanktuaria na szczytach Andów. *Wierchy*, 46: 37–64.

Scandiffio G. & Rodriguez J., 1992. Geochemical report on the Sajama geothermal area, Bolivia. In: *Estudios geotérmicos con técnicas isotópicas y geoquímicas en América Latina*. IAEA-TECDOC 641, Organismo Internacional de Energia Atomica: 141–167.

Schoolmeester T., Johansen K.S., Alfthan B., Baker E., Hesping M. & Verbist K., 2018. *Atlas de Glaciares y Aguas Andinos. El impacto del retroceso de los glaciares sobre los recursos hídricos.* UNESCO, GRID-Arendal.

Siebert L., 1996. Hazards of large volcanic debris avalanches and associated eruptive phenomena. In: Scarpa R., Tilling R.I. (eds), *Monitoring and Mitigation of Volcano Hazards*. Springer-Verlag Berlin Heidelberg: 541–572.

Simkin T. & Siebert L., 1994. *Volcanoes of the World – A Regional Directory, Gazetteer and Chronology of Volcanism During the Last 10,000 Years*. 2nd ed. Geosciences Press, Tucson.

Stern C.R., 2004. Active Andean volcanism: its geologic and tectonic setting. *Revista Geológica de Chile*, 31(2): 161–206.

Valenzuela D. & Clarkson P.B., 2014. Geoglyphs. In: Smith C. (ed.), *Encyclopedia of Global Archaeology.* Springer Science+Business Media New York: 3017–3029.

Villarroel E.K., Mollinedo P.L.P., Domic A.I., Capriles J.M. & Espinoza C., 2014. Local management of Andean Wetlands in Sajama National Park, Bolivia: Persistence of the collective system in increasingly family-oriented arrangements. *Mountain Research and Development*, 34(4): 356–368.

Vuille M., Francou B., Wagnon P., Juen I., Kaser G., Mark B.G. & Bradley R.S., 2008. Climate change and tropical Andean glaciers: Past, present and future. *Earth-Science Reviews*, 89(3–4): 79–96.

Wheeler J.C. & Laker J., 2009. The Vicuña in the Andean Altiplano. In: Gordon I.J. (ed.), *The Vicuña: The Theory and Practice of Community Based Wildlife Management*. Springer New York: 21–33.

Wörner G., Harmon R.S., Davidson J., Moorbath S., Turner D.L., McMillan D.L., Nye C., Lopez-Escobar L. & Moreno H., 1988. The Nevados de Payachata volcanic region (18°S/69°W, N. Chile). *Bulletin of Volcanology*, 50(5): 287–303.

Wörner G., Hammerschmidt K., Henjes-Kunst F., Lezaun J. & Wilke H., 2000. Geochronology ($^{40}Ar/^{39}Ar$, K-Ar, and He-exposure ages) of Cenozoic magmatic rocks from Northern Chile (18–22°S): implications for magmatism and tectonic evolution of the Central Andes. *Revista Geológica de Chile*, 27(2): 205–240.

Yager K., Valdivia C., Slayback D., Jimenez E., Meneses R.I., Palabral A., Bracho M., Romero D., Hubbard A., Pacheco P., Calle A., Alberto H., Yana O., Ulloa D., Zeballos G. & Romero A., 2019. Socio-ecological dimensions of Andean pastoral landscape change: bridging traditional ecological knowledge and satellite image analysis in Sajama National Park, Bolivia. *Regional Environmental Change*, 19(5): 1353–1369.

Yensen E., Tarifa T. & Anderson S., 1994. New distributional records of some Bolivian mammals. *Mammalia*, 58(3): 405–414.

www1 – http://sernap.gob.bo/sajama/ [accessed: 2022.05.19].

www2 – http://tpn.pl/zwiedzaj/turystyka/statystyka/ [accessed: 2022.05.19].

www3 – http://sernap.gob.bo/sajama/atractivos-turisticos/ [accessed: 2022.05.21].