Geotour Tarapacá: from Iquique to the Andes: "stairway to heaven"

A unique experience

Few places (if any) in the world offer the opportunity to ascend from 0 to more than 4000 meters of altitude by car, along an excellent road, in little more than three hours, with the extra attraction of crossing the Atacama Desert. The Road 15 from Iquique to Colchane in Chile, and other roads in the region, offer this opportunity and more possibilities, in a geological journey of more than 170 million years from the volcanic Jurassic of the coast to the current volcanoes of the Andean Cordillera, all this in the midst of a spectacular biological and archaeological richness.

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Cretaceous to Miocene rocks in the Gulches (Quebradas) Domain. View to the SW from Road 15 at about 3000 m of altitude.

Dates of visits:

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Aula2puntonet – 2023*

***: English edition of Geotour Tarapacá: de Iquique a la Cordillera de los Andes, escalera al cielo. Una experiencia total (2021), also in Geotours por el Norte de Chile**

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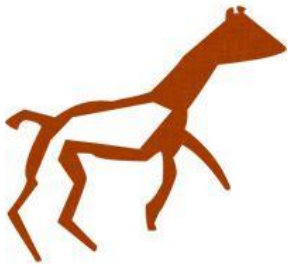


Introduction

From the point of view of tourism, the city of Iquique in northern Chile is known for its beaches, its casino, and the tax-free zone, however, except for the tax-free zone, the others are attractions that can be found in more coastal towns in Chile such as Viña del Mar or La Serena, so in that sense, they are not real competitive advantages of the city with respect to others. However, what other cities cannot offer is the opportunity to 'climb' to over 4000 m above sea level in little more than three hours and along an excellent road (*Road 15*), all this amidst the breathtaking scenery of the Atacama Desert.

One also wonders how many places in Chile or the world offer the opportunity to see sea lions and vultures together without having to travel to a remote location in the middle of nowhere. In Iquique you will have all this and much more at your fingertips.

Sea lions (Otarya flavescens) near and "in" the Iquique fishing terminal. A) females and a vulture ("jote" as they are known in Chile: Cathartes aura) on a rocky outcrop. B) male emerging from the water. C) male and female.

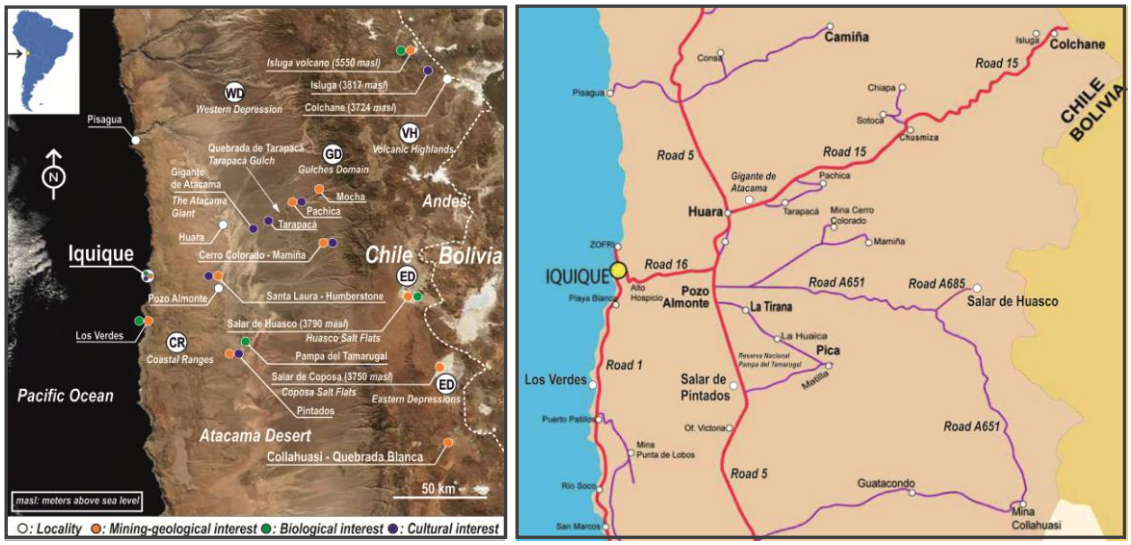
Important:

The sea lions may look "friendly" but they are not.

Males are very aggressive and territorial.

Physiography

The region we will visit is physiographically and climatically divided into a series of north-south belts, which in turn are related to important changes in altitude and, of course, geological and biological features.



Left, main localities, their interest and physiographic features as described in the document (image: NASA Visible Earth); From west to east: CR: Coastal Ranges (Cordillera de la Costa); WD: Western Depression (Depresión Occidental); GD: Gulches Domain (Dominio de las Quebradas); ED: Eastern Depressions: basins with salt flats (Depresiones Orientales); VH: Volcanic Highlands (Altiplano Volcánico). Right, road map of the region (Image[1]).

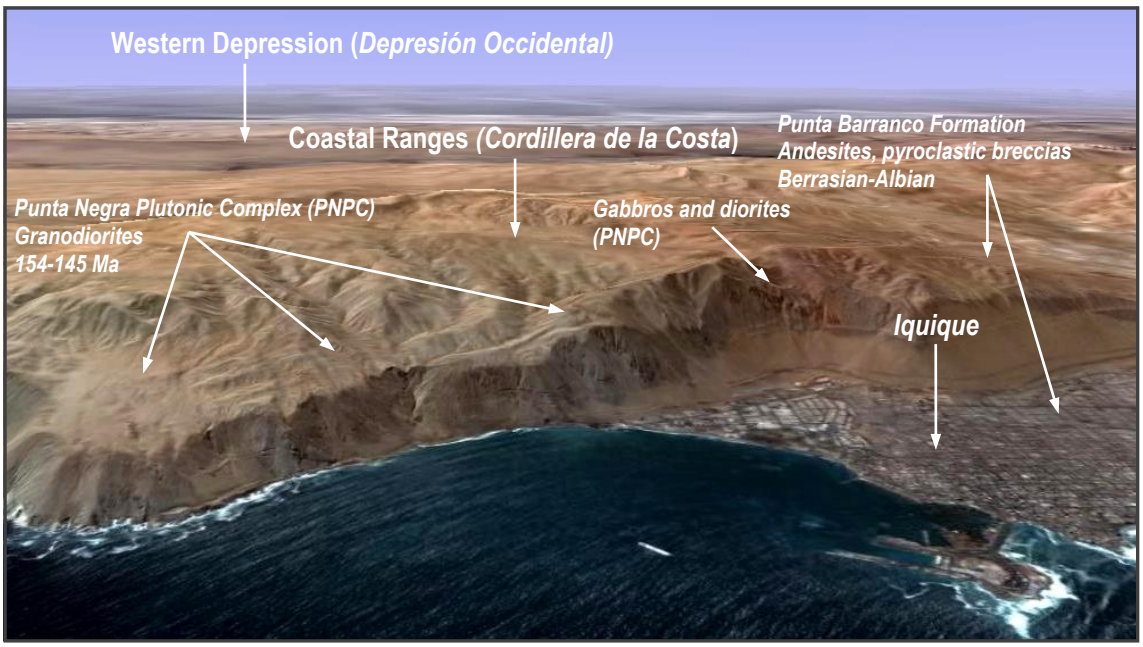
Travelling by car (1)

The places recommended here are on or near roads in very good condition, such as (for example) Roads 1, 5, 15, 16, or the A651. All of them are paved.

It is not advisable to leave the roads and it is of course forbidden to do so in protected areas.

The Coastal Ranges is about 40 km wide at the latitude of Iquique (*20º14'S*) and ends in front of the Pacific in steep cliffs that can reach altitudes of up to about 1000 m.

The coastline is bathed by the cold Humboldt Current, rich in nutrients and therefore in fish, which in turn support important colonies of sea lions (*Otaria flavescens*), pelicans (*Pelecanus thagus*) and cormorants (*Phalacrocorax brasilianus*).



The Coastal Ranges and the Western Depression near Iquique. Image width: 6.56 km (Google Earth oblique). The rocks of the Coastal Cordillera in this image are Upper Jurassic-Lower Cretaceous (plutonic) and Lower Cretaceous (volcanic) (Vásquez & Sepúlveda 2013).

Travelling by car (2)

Better if the car is a 4x4, because of its power and altitude performance.

Take into account the distance to be travelled and the level of the car's fuel tank. Gas stations are not available everywhere.

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Watching seabirds

Although these birds are easily observed from the beach or a rocky outcrop, the use of a telephoto (zoom) lens is necessary.

A rocky beach south of Iquique: A) group of pelicans (Pelecanus thagus) and B) cormorants (Phalacrocorax brasilianus).

To the east of the coastal mountain block we find the Western Depression (*WD*), a westward-sloping plain at an altitude of 1000 to 1500 m, which is important because large nitrate deposits (*Chilean saltpetre*) developed on the western edge of the plain.

The Western Depression, reminiscent (except for the colour of the sky) of a Martian landscape. This desolation, locally known as the "pampa", is carpeted with centimetre- to decimetre-scale boulders of rock that originated from erosion and transport of volcanic rocks from the Andes. The inset shows two rounded boulders of vesicular basalt which are part of the scree overlying finer materials.

It is here, close to the mountais, that we also find the so-called Pampa del Tamarugal, where communities of thorny tamarugo trees (*Prosopis tamarugo*) grow due to the presence of shallow water tables. The vegetation is highly altered by human influence and in its present form corresponds mainly to *P. tamarugo* and *P. alba* plantations (*Gajardo 1994*). More interesting than the Pampa del Tamarugal is the area of Pintados (*adjacent to the Salar de Pintados: salt flats*) where on the eastern slopes of the mountains of the Coastal Ranges there is an important number of large geoglyphs, i.e. the rock art of the pre-Hispanic cultures.

Further east comes the Gulches Domain, which is marked by remarkable E-W trending transversal valleys flanked by a relief that rises to more than 3000 m of altitude. The Tarapacá Gulch (*Quebrada de Tarapacá*) stands out for its importance in the area of this geotour. The gulch has sectors with small oases that allow the existence of a precarious but remarkable existence of pastures and a modest agriculture, that paints with green a relief tinged with brown and ochre colours. The source of the Tarapacá Gulch is to be found in the high Andes and gives rise to the most important watercourse in the area (*Cade-Idepe 2004*).

On the term gulch (quebrada)

Gulch is usually defined as a deep, narrow valley, especially one marking the course of a stream. Its translation into 'Chilean Spanish' is "quebrada". However, quebrada in northern Chile is a loose term that serves for either small ravines, or large valleys.

Entering the Tarapacá Gulch.

Continuing eastwards, there are endorheic basins at 3700-3800 m of altitude, which for the purpose of this document we have named as the Eastern Depressions, that are home to important salt flats such as those of Huasco and Coposa and numerous animal and plant especies.

The village of Tarapacá

"The village of Tarapacá is located some 100 km to the northeast of of Iquique. It is estimated that its occupation dates back to the 12th century, when the village was part of the Inca Trail".

CMN (2021a)

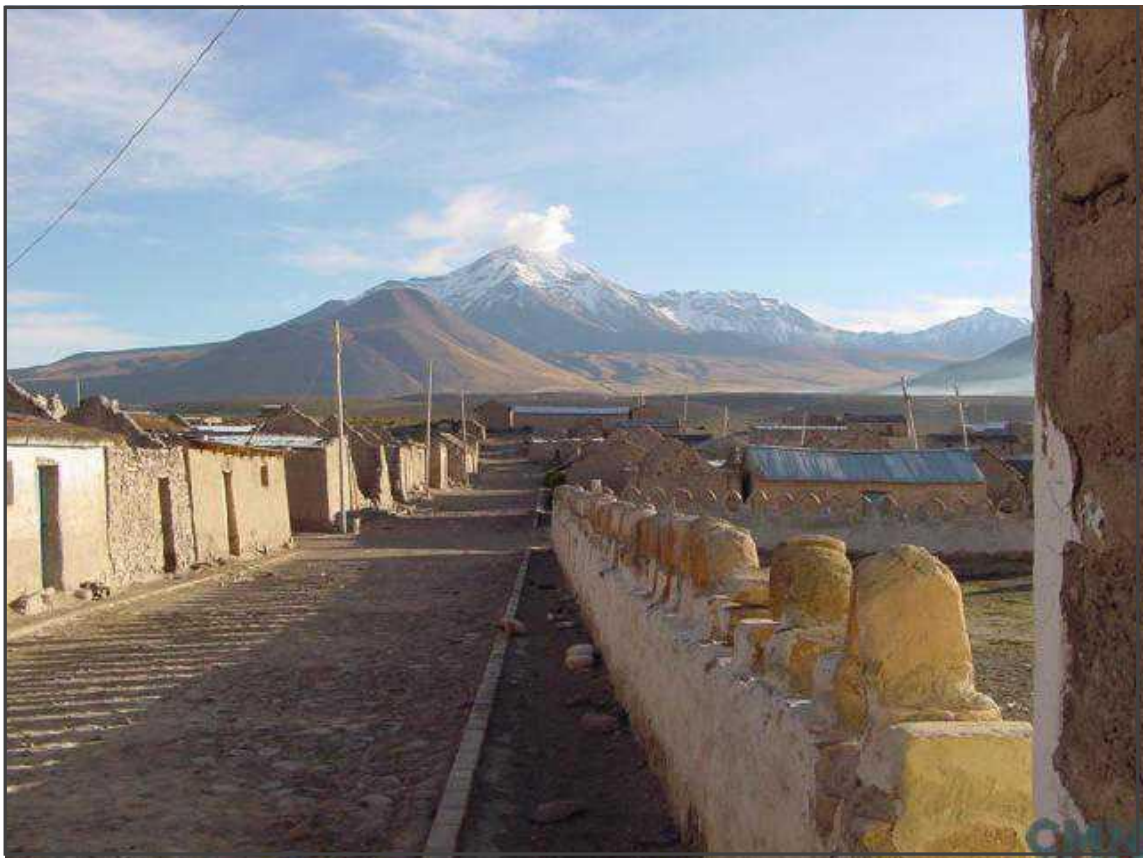
Panoramic view of the Huasco salt flats (3800 m of altitude), in the background there is a series of volcanoes of the Andean Highlands of Mio-Pliocene age.

The Isluga volcano (summit at 5500 m of altitude) (Image[2]). Inset: DEM showing the Volcanic Highlands (VH) (JPL 2003).

The Isluga village

"The village of Isluga is located in the high plateau area of the Tarapacá Region, in the township of Colchane, 276 km northeast of Iquique and at an altitude of 3780 m above sea level. It is characterized for being a ceremonial center of the sector".

CMN (2021b)



Another view of the Isluga volcano, from the town of the same name. Image[3].

Perhaps the most remarkable physiographic belt is that of the Volcanic Highlands (*the volcanic Altiplano*), which rises to about 3800 - 4000 m of altitude. The belt is formed by volcanic materials of Miocene to present age, and the area is crowned by large volcanoes that exceed 5000 m of altitude. It is a diffuse wide region (*in the E-W sense*) in which the so-called "high plateau" and the Andes merge into a single whole. The Spanish name of "Altiplano Volcánico" can generate confusion, since it suggests three ideas: that it is high, flat and volcanic. Of the three statements the first and the last are correct, but let us clarify that at least on the Chilean side, the Volcanic Altiplano is not exactly "a billiard table". Dozens of ancient (*Mio-Pliocene*) or recent stratovolcanoes make up an absolutely magical and unique landscape with no equivalent in the world.

Climate

The change in altitude determines the main spatial zonings between climates. That of the coastal sector is characterized by a large number of sunny days. The months of January, February and March have average temperatures above 24°C, while the minimums (*minima*) temperatures do not fall below 16° to 18°C. This exceptional regime is only disturbed by the "camanchaca" phenomenon, which consists of a very dense coastal fog, which is moved by the winds and can reach the interior beyond the Coastal Ranges. The fog is located between 300 and 800 m of altitude, and moves inland due to the presence of winds from the south and southwest (*Muñoz-Schick et al. 2001*). These fogs present a water potential for obtaining drinking water, which has already been experimented in other regions of Chile (*Román 1999*). This phenomenon occurs in response to the encounter of cold waters (*Humboldt Current*) and warm atmospheric temperatures at sea level. An equivalent phenomenon is observed on the coasts of the Namib Desert, bathed by the Benguela Current, also a cold oceanic current (*Oyarzún & Oyarzun 2007*).

Left, a fog-trap for the camanchaca at Alto Patache, about 63 km south of Iquique. Right, the camanchaca as seen from Alto Patache. Images[4,5].

There is a desert climate in the Western Depression, which extends between 1000 and 1500 meters above sea level. Above this altitude and up to 2800 m of altitude, the desert characteristics are maintained within a more abrupt topography. The lower zone corresponds in most of its extension to absolute desert (*hyper-arid conditions*), with large areas where rainfall is practically non-existent. This hyper-arid core of the Atacama is the driest zone on the planet (*Oyarzún & Oyarzun 2007*).

The climatic conditions within the Gulches Domain are similar to those of the Volcanic Highlands (*Altiplano Volcánico*), except that since precipitation comes from the east, summer rainfall is significantly lower on its western edge, generally not exceeding 200 mm per year, and disappearing almost completely below the 2500 m of altitude. As for temperatures, the limit values are also very similar to those of the Volcanic Highlands, fluctuating around 5ºC as average annual temperature. The ambient thermal sensation is within the range of mountain temperatures, which adds to the thinning of the air due to the altitude. Precipitation in the Volcanic Highlands is characterized by great interannual variability, so that dry years are followed by years of high rainfall. Because the region is located at high altitude, precipitation is in the form of sleet during the summer or snow in the winter, and there is a long season where the surface of the territory is snowy. To this must be added the decrease in atmospheric oxygen pressure

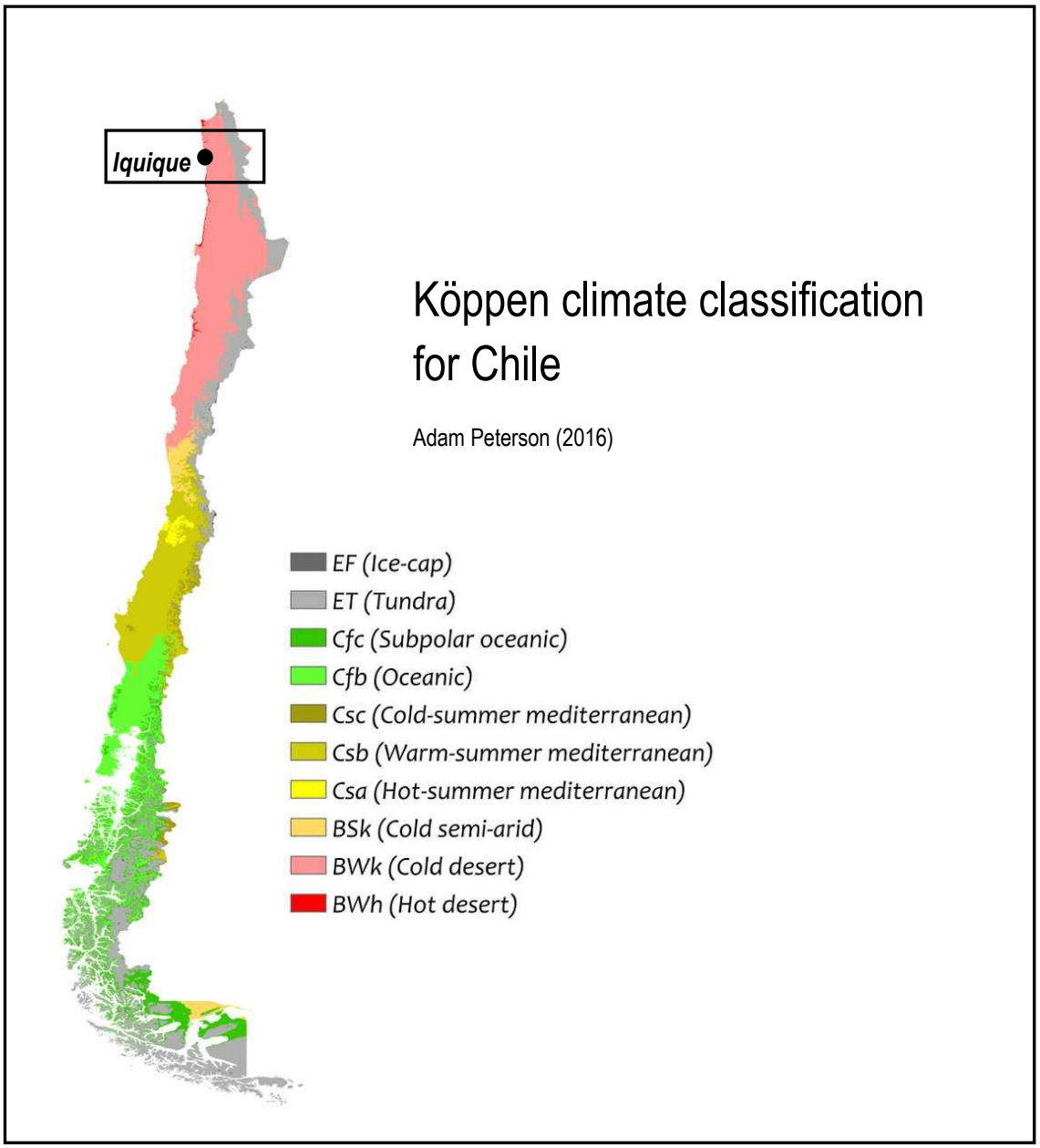
The Atacama desert climate

"In addition to its great aridity, the Atacama desert is characterized by being the oldest desert in the world, at least 20 million years old.
Scientists searching for the place on Earth with the greatest similarity to the surface of Mars, go to the Atacama Desert to determine which are the minimums water levels necessary for life.
With the exception of some remote places in Antarctica this region is, indisputably, the driest place in the world."

M.O. Dillon, en: Orrego et al. (2013)

because of the high altitude, which induces hypobaric hypoxia, commonly known as “puna” in Chile and “soroche” in Bolivia, which can become a barrier for visitors who are not used to these conditions.

This altitude sickness can affect tourists since many places of interest are above 2500-3000 meters above sea level. Mild symptoms are: headache, tiredness, fatigue when walking, slight sensation of shortness of breath, lack of appetite, insomnia. Severe symptoms include: severe shortness of breath, cough with pinkish sputum or traces of blood (*a symptom of pulmonary edema*), extreme tiredness with small efforts and even at rest, nausea and vomiting, etc. Those who suffer from previous pulmonary, circulatory or neuromuscular diseases should refrain from visiting high altitude sites (*Photographing Travel 2020*). Important: Above all, consult your doctor before starting an adventure at high altitude.



The Köppen climate classification

"The Köppen climate classification uses monthly temperature and precipitation for the twelve months, usually averaged over a long period of time (30 years or more). Climate types are represented by a two or three letter combination in which the first letter defines the major type".

Chen (2023)

Plant communities

The existence of plant species in a desert region is by itself remarkable. Due to the strong differences in altitude (*and therefore in climate conditions*) this realm host three exceptional groups of plants. By altitudinal gradient, from west to east we have: 1) the plant formation that develops in the so-called Pampa del Tamarugal to the south of Iquique in the Western Depression; 2) the so-called desert scrub of columnar cacti (*Corryocactus brevistylus* and *Browningia candelaria*), which are located in the high altitude sectors of the Gulches Domain; and finally 3) the high altitude wetlands in the Eastern Depressions and the Volcanic Highlands.

Despite its location in the Atacama Desert, the region has some well-defined habitats where plant life develops, sometimes in extremely precarious conditions. From west to east, four main habitats can be defined. The first are the coastal fog oases where the oceanic influence reduces the aridity of the Atacama Desert thanks to the camanchaca phenomenon (*see Climate*) that configures a coastal desert climate (*Muñoz-Schick et al. 2001*).

The latter authors recognize a total of 72 species of vascular plants in this environment: two pteridophytes, one gymnosperm and 69 angiosperms (*flowering plants*). Within this last group, the asteraceae and solanaceae dominate. Despite the hyperaridity of the Western Depression, in sectors we find the desert ecosystem of the Pampa del Tamarugal that survives thanks to the groundwater of an aquifer (*Chávez et al. 2016*). This ecosystem develops under a climate characterized by high diurnal temperatures, a large daily thermal oscillation, an almost absolute lack of precipitation, occasional presence of fog, low relative humidity and high solar radiation (*Chávez et al. 2016*).

Cultivated tamarugo trees in the Pampa del Tamarugal National Reserve.

In certain areas where groundwater accumulates, the tamarugo (*Prosopis tamarugo Phil*.), a native tree of the legume family that can reach a height of 15 m (*Habit et al. 1980*), is able to survive. The northern carob tree (*algarrobo blanco; Prosopis alba Griseb*.) also grows next to the tamarugos (MMA 2021). At present most of this ecosystem is under protection in the Pampa del Tamarugal National Reserve, administered by the Chilean Forestry Service (*CONAF*) (*Chávez et al. 2016*), although the site does not stand out much for the care or condition of the trees.

To the east we have the desert scrub of cacti and finally on the upper floor, in the foothills (*3200 to 4000 meters of altitude*), we find low scrub on its slopes. The latter habitat includes high altitude 'queñoa' forests (*Polylepis tarapacana Phil*.), and on the highlands (above 3800 m of altitude) there are two types of grasslands: dry and humid, where the 'bofedales' (*wetlands*) stand out.

Next we will discuss in greater detail the desert scrub of columnar cacti (*Corryocactus brevistylus* and *Browningia candelaria*). In the plains and slopes of the Gulches Domain, between 2000 and 3000 m of altitude, an open vegetation grows, whose coverage does not exceed 10%, and is dominated by the presence of columnar cacti and low shrubs. Characteristic plants are *Corryocactus brevistylus* (*guacalla*), *Oreocereus leucotrichus*, *Haageocereus fascicularis*, *Ambrosia artemisioides* and *Browningia candelaria* (*candelabro*), the latter being very scarce.

Oreocereus leucotrichus on the side of the Road 15 at some 3000 m of altitude.

Corryocactus brevistylus (guacalla) in the same sector.

Origin of the term "cacti"

"The word cacti, with which the Cactaceae family is known, is an ancient Greek term, which was used to refer to the "Castilian thistle" (Cynaria cardunculus) in the year 300 BC, because it is a plant with strong thorns, similar to the cactaceae. Later, in 1753, Linnaeus used this term to characterize a genus of plants with thorns, but without any relation to the thistles.
He used this term to characterize 22 species of Cactus L.

Señoret Espinosa & Acosta Ramos (2013)


Corryocactus brevistylus (guacalla) in the same sector.


Ephedra breana (pingo-pingo) in the same sector.


Balbisia microphylla in the same sector.

The most frequent associated species are *Atriplex imbricata*, *Opuntia sphaerica*, and *Notholaena nivea* (*Luebert 2004*). Particularly prominent in the landscape are the guacallas, often arborescent, reaching up to 5 m in height, with thick, jointed branches covered with long thorns (*Hoffmann 1989*).

The cactus vegetation of the plains and slopes disappears as it descends to the bottom of the gulches, until it is replaced by a riparian forest community, which has been greatly modified by human activity. At around 3000 m of altitude, the scrub becomes progressively more complex in terms of the number of species, as many plants from the highlands descend to this altitude.

Flowering in Atacama

"Depending on prevailing conditions, decades may pass between flowering events. But these species, and the conditions in which they live, have been around for a long time. They were there when the first inhabitants arrived in this area, around twelve thousand years ago."

M.O. Dillon, en: Orrego et al. (2013)

Finally, and following the altitude gradient, we find the bofedales in the highlands and basins where salt flats such as the Huasco have formed. The bofedales are high Andean wetlands that can be found in Chile, Peru, Bolivia and Argentina, between 3200 and 5000 m of altitude (*Squeo et al. 2006*). They are composed mainly of pulvinate plants, which form very hard cushions. Unlike the peatlands of the northern hemisphere, they are not dominated by mosses of the genus *Sphagnum* but by two species of sedges: *Distichia muscoides* and *Oxychloe andina*. The fresh and slightly saline groundwater that feeds them originates from glacier streams, snowmelt and rainfall.

Bofedal in the salt flats of the Huasco basin, at some 3800 m of altitude.

The bofedal

Volcanoes, salt flats and wetlands such as the bofedal ecosystem. You will not find many equivalent sites in the world.

Due to their geographic distribution in cold and dry high altitude climates the bofedales are very important ecosystems, as they concentrate life in their environment. The presence of water (*which frequently freezes at night*) generates habitats for a multitude of insects, mammals, birds, vascular plants and also mosses and lichens. In addition, they are ecosystems of great importance for the human communities of the highlands, because they provide water and food for the Andean camelid livestock (*llamas and alpacas*).

Prehispanic Cultures

The so-called Pica-Tarapacá culture flourished in the region from 900 to 1500 AD. In this regard, the large geoglyphs found in various places in the Tarapacá Region, which correlate with the so-called Desarrollo Regional (*Regional Development*) period (*Briones et al. 2005*), can be associated with this time period. According to Poblete (*2003*), the first archaeological investigations in the Arica highlands (*north of the study area*) show an intense occupation since the beginning of 1000 AD. This period of regional development is also known as the Late Intermediate Period, and lasts from 1000 to 1400 AD. Uribe (*2006*) indicates that the landscape conditioned the type of activities developed by the indigenous peoples, and in this regard he differentiates several N-S physiographic belts, that from E to W are:

- The highlands, with hard grass steppes and wetlands and the inland basins and salt flats, ideal for hunting and grazing.
- The inclined plane that descends towards the Western Depression, with gulches (*allowing some subsistence agriculture*) alternating with absolute desert. These gulches interrupt their course in a third area, corresponding to the Pampa del Tamarugal.
- The latter is limited to the west by the Coastal Ranges, with a strong cliff and narrow platforms or beaches, with almost no running water resources. This conditions a very desertic coastline, but highly rich in marine resources for gathering, fishing and hunting, maintained by water holes and the dense coastal fog (*camanchaca*).

The societies that inhabited Pica and Tarapacá during the Late Intermediate Period have been defined as lordships, societies of prestige and rank, a situation supposedly shared by the populations of northern Chile and, in general, by the societies of the Central-Southern Andes. These lordships pursued the basic interest of the Andean populations: social and economic self-sufficiency.

The Atacama Giant, at Cerro Unita (Unita Hill) (Road15). In the inset is the stylized representation of the geoglyph, which corresponds to a shaman or yatiri, although it could also represent the Andean deity Tunupa-Tarapacá, who made a journey from Lake Titicaca to the Pacific Ocean; the geoglyph was probably made sometime in the period: 900-1450 AD (Wikipedia 2021a). GPS (Google Earth): 19º57'11.41" S, 69º38'03.76"' W.

A visit to two archaeological sites with large geoglyphs is a must: the Atacama Giant (*see above*) and Pintados. The Pintados geoglyphs (*Briones and Alvarez 1984; Briones et al. 2005*) are one of

Ariquilda Petroglyph (Huara)

Metal pendant, Guatacondo (Pozo Almonte)

Petroglyph, Tamentica (Pozo Almonte)

Representations of the anthropomorphic being with radiated head, made during the so-called Formative Period.

"This period (two to three millennia ago) corresponds to a time of changes in lifestyles. Experimentation and innovation in agriculture, technology, and architecture began, giving way to the creation of the first villages."

MNCN (2021)

Textile, Chorrillos (Calama)

the most important archaeological sites in Chile and South America. Geoglyphs in this region of the world are the rock art of pre-Hispanic peoples, and their representations can range from abstract-geometric to anthropomorphic and zoomorphic.

A) Path for the visit to the geoglyphs (running over the Pintados salt flats) and some of the geoglyphs (arrows). B) Geometric (e.g. rhombuses) and zoomorphic (e.g. camelids) figures; in the foreground the crust of the salt flats (arrow).

Be "civilized", do not act like some brainless people.

"Three Belgian tourists were arrested today in Chile as alleged perpetrators of causing serious damage to the "Atacama Giant", a petroglyph of large dimensions stamped on a hill in the north of the country.

The tourists were captured by the camera of an archaeologist last Sunday, when they passed with an SUV over the lines that form a human figure 119 meters long on a hillside of the "Unita" hill, in the municipality of Huara, in the Tarapacá region, about 1830 kilometers north of Santiago."

Agencia EFE (2019)

Anthropomorphic figure: a man on a raft with harpoon (interpretation: Briones et al. 2005).

The salt crust of the Salar de Pintados (Pintados salt flats), which covers an area of about 850 km² on the eastern slope of the Coastal Ranges. The crust consists of carbonates, sulfates and chlorides (Vila 1976).

All this was done by those who traveled in caravans along different trails and camped in the vicinity of the geoglyphs (*adding new ones*). The figures were drawn on the regolith, removing loose rocks on the slopes of the hills where the Pintados Formation (*Middle-Upper Triassic*) outcrops. This stratigraphic unit is made up of volcanic and sedimentary rocks consisting of andesitic lavas, breccias and sandstones, with intercalations of shales and siltstones (*Vila 1976*). The geoglyphs cover an area of about 50,000 m², along some 3 km, always to the west of the Salar de Pintados.

Geology

Except for the scarce presence of Paleozoic outcrops at the bottom of gulches in the pre-Andean sector (*e.g. Aroma Formation: Ordovician-Silurian*), the Tarapacá Region is mainly characterized by units of the Andean Cycle ranging from Jurassic to recent. If we move from west to east we find a series of geological units of decreasing age.

The Coastal Ranges

The Coastal Ranges has maximum altitudes of about 1700 m (*e.g. Cerro Constancia*) and in the area around Iquique consists mainly of Upper Jurassic - Lower Cretaceous plutonic rocks (*Punta Negra Plutonic Complex*) and Lower Cretaceous volcanic rocks (*Punta Barranco Formation*) (*Vásquez & Sepúlveda 2013*). A little further south in Los Verdes (*beaches and rocky areas*) we find volcanic and epiclastic andesitic-basaltic rocks belonging to the La Negra Formation *(= Caleta Ligate Formation Vásquez & Sepúlveda 2013*), which in this area has ages of 170-175 Ma (*Middle Jurassic*) (*Oliveros et al. 2006*). To the east crop out Lower to Upper Jurassic sedimentary and volcanic rocks and the Oyarvide Plutonic Complex (*150-144 Ma*) (*Vásquez & Sepúlveda 2013*).

The Coastal Ranges south of Iquique (on the way to Los Verdes along Road 1).

Left, sequence of epiclastic rocks and andesites (basaltic andesites) in the Los Verdes sector south of Iquique. To the left, the sequence is propylitized (with epidote, chlorite, and calcite), taking on a greenish-gray color.

Los Verdes

This place not only offers first class geology, but it is also the ideal place to observe marine life and birds such as pelicans and cormorants.

Los Verdes is also the ideal place to spend the day picnicking or eating at some of the restaurants near the beach.

The Jurassic of Los Verdes includes large massive lava flows, volcanic breccias and epiclastic intercalations, characterized by the formation of stratified banks. This seems to indicate that the

volcanic activity occurred near the coastline and that the volcanic rocks were subject to erosion, removal and sedimentation as epiclastic sediments in an environment of variable energy or with significant variations in sea level as shown by the alternation of coarse and fine facies.

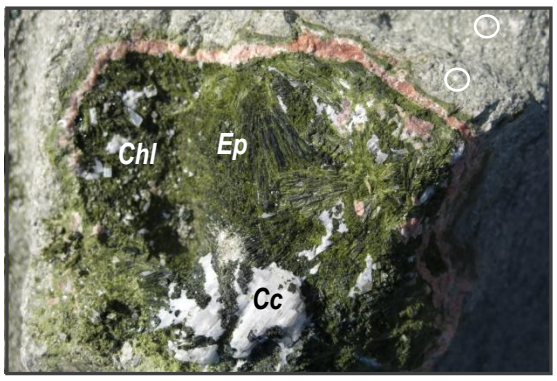
The rocks underwent (*to a greater or lesser degree*) regional alteration phenomena, with the typical greenish coloration induced by the important formation of chlorite-epidote-calcite-pink albite (*propylitization*) in groundmass, veinlets or filling vesicles.

Los Verdes. Sedimentary character of part of the sequence evidenced by differential erosion of layers of coarser and finer epiclastic sediments. Inset, a detail of lithological and grain size changes, PA: porphyric andesite, CE and FE: coarse and fine epiclastic materials. Arrows indicate strongly propylitized beds.

What are epiclastic rocks?

These are fragmented rocks that originate by normal erosion processes of volcanic rocks, regardless of the mode of fragmentation. In a way they can be regarded a proper sedimentary rocks.

A typical epiclastic rock formation environment. Las Gaviotas beach, Tenerife (Spain). Image[7].



Los Verdes. Vesicles in andesite filled with epidote (Ep), chlorite (Chl), calcite (Cc) and probably pink albite (Abr). The plagioclase phenocrysts (circled examples) are about 2 to 4 mm long, the rock being a porphyric basaltic andesite, propylitized during the so-called "regional alteration" (e.g. Oyarzun et al. 1998) of these volcanic materials.

The tides leave pools of seawater that contain abundant plant and animal life. In the images you can see a crab (or "jaiba" as it is known in Chile) and a starfish (Heliaster helianthus).

Los Verdes. Coarse and fine andesitic epiclastic sediments..

Los Verdes. Propylitized massive basaltic andesites (regional alteration). Easily observable planes (arrows) correspond to diaclases. Scale: the youngest member of the geotour (AO).

What is the regional alteration?

The Jurassic and Lower Cretaceous volcanic mega-sequences of Chile present sections with mineral assemblages typical of the propylitic alteration (with chlorite, epidote, calcite, albite), all this at the large (regional) scale of these formations.

What is albitization?

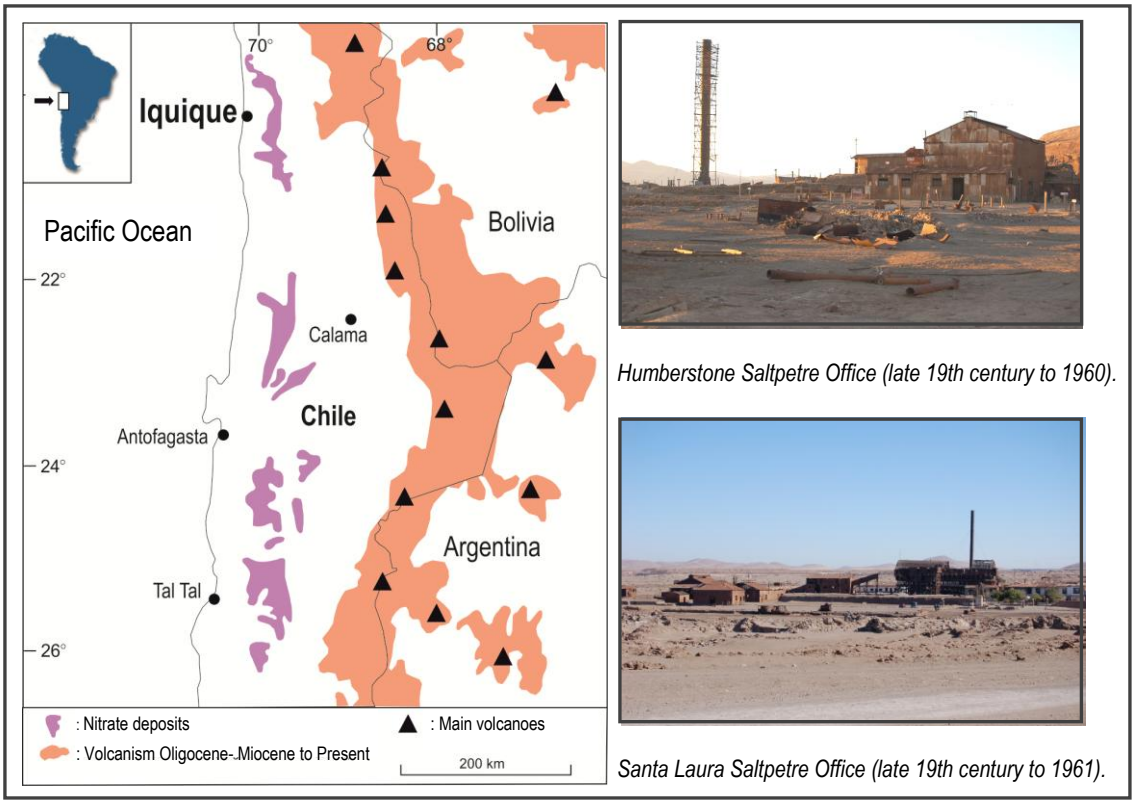
Hydrothermal alteration process involving a replacement of calcium in plagioclase by sodium. If this replacement occurs in the presence of Fe^{3+} (e.g. in the form of very fine grains of hematite), the formed albite may develop a pink color (which can lead to confusion with pink orthoclase).

Oyarzun et al. (1998); Oyarzún & Oyarzun (2014)

The Western Depression and nitrate deposits

This slight depression flanked by the Cordillera de la Costa at 1000-1400 masl, is infilled with Quaternary lacustrine, alluvial and saline sedimentary deposits, including the Salar de Pintados (*Pintados salt flats*). On the western edge of this basin are located the famous Chilean nitrate deposits (*saltpetre*) and the numerous saltpetre "offices" (*e.g. Santa Laura or Humberstone among many others*) from where this unique mineral assemblage was extracted.

These natural nitrate deposits (*$NaNO_3$ as an industrial end product*) are part of a N-S belt of about 700 km with reserves (*before production*) of about 250 Mt. The origin of the large nitrate deposits of the Atacama Desert has been a long debated topic, and it is worth noting that on a planetary scale these deposits are a singularity (*e.g. Oyarzún & Oyarzun 2007*).



Humberstone Saltpetre Office (late 19th century to 1960).

Santa Laura Saltpetre Office (late 19th century to 1961).

Left, distribution of nitrates and the Altiplano volcanism in northern Chile (Oyarzún & Oyarzun 2007). Right, the offices (mines, chemical - treatment plants and mining camps) of Humberstone and Santa Laura.

Previous hypotheses for the origin of nitrates did not globally recognize the importance of the Volcanic Highlands (*Altiplano Volcanic Plateau: AVP*), a geological unit of Miocene to present age, and about 70,000 km^2 in extent. Oyarzún & Oyarzun (*2007*) suggest that the extrusion of a volume of 10^4 km^3 of pyroclastic rocks in the AVP may have generated the necessary conditions to induce the thermal and electrical fixation of about 2800 Mt of atmospheric nitrogen in the form of NOx-type compounds. This figure exceeds the amount of nitrogen required to form the nitrate deposits of the Atacama Desert. Thus, the origin of the deposits could be found in the combination of: 1) hyper-arid conditions (critical for the final stabilization and preservation of the $NaNO_3$ mineral phase) and 2) massive volcanism (*key for the fixation of large amounts of atmospheric nitrogen*). See figure below.

On the term "saltpetre offices"

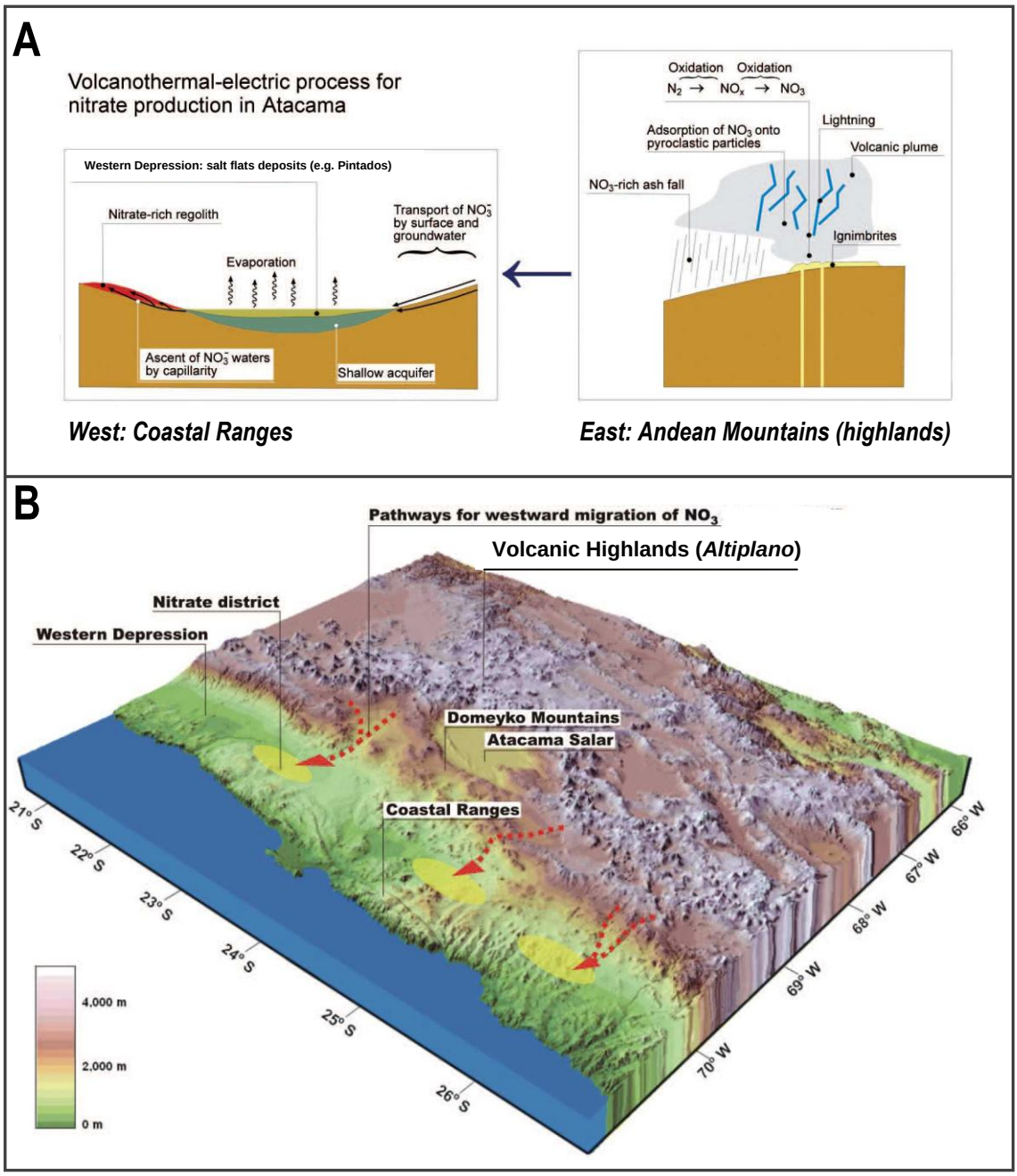
A confusing term was used to designate the saltpetre production plants. In this regard, saltpetre "offices" are not places with desks and employees in collars and ties, but chemical plants in which the raw material (caliche) that was extracted from the mines was transformed into saltpetre.

Humberstone and Santa Laura

For those interested in industrial archeology, Humberstone and Santa Laura are the perfect sites.

They are national monuments and UNESCO World Heritage Sites.

In this regard, it is a pity that the state of conservation is very poor. However, despite this, it is worth visiting Humberstone and Santa Laura, which are only 48 km from Iquique.



A) Schematic model for the generation of nitrate from atmospheric nitrogen via large volcanic eruptions and associated electrical apparatus, which due to thermal energy could have broken the N-N bond and induced nitrogen oxidation. B) Routes of transport and final destination of nitrates transported by ephemeral water courses (Oyarzún & Oyarzun 2007).

Volcanic eruptions may have many more environmental implications than they are usually given credit for, contributing decisively to the global cycles of many chemical elements and compounds (*Oyarzun et al. 2005*). For example, soils of volcanic origin are extremely fertile and perhaps the reason goes beyond the mere uptake of major chemical elements (*e.g. K, Mg, Ca*) by plants, and may reflect an important improvement in the availability of nitrogen, a key nutrient. Thus, volcanic activity would "naturally" fertilize the soil-plant system, which would offset the initial adverse effects of ash fall. Whatever the case, the importance of volcanic activity should never be underestimated (*Oyarzún & Oyarzun 2007*).

Caliche and nitrate

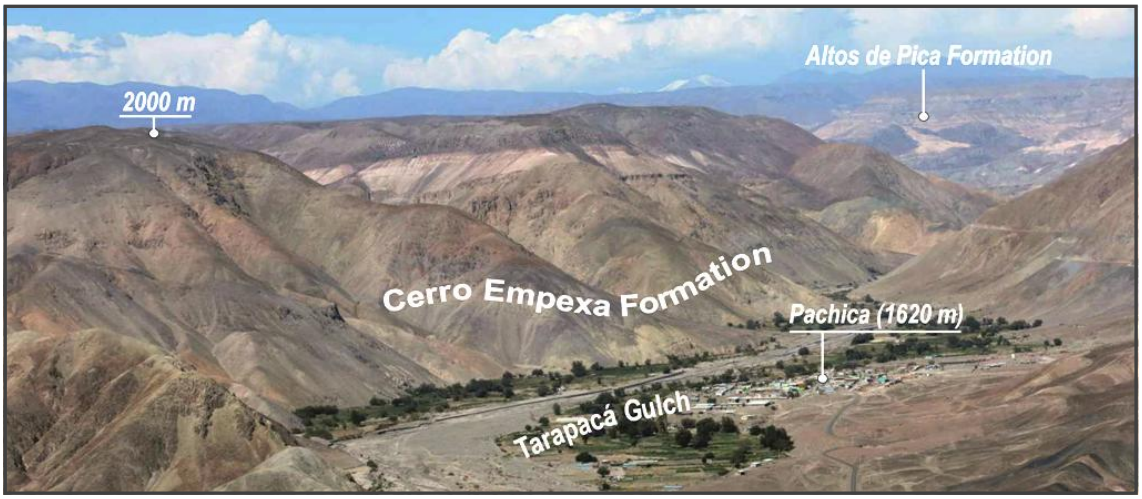
The Atacama nitrate is extracted from layers of caliche (from "cachi": salt in the ancient Quechua language), a deposit containing high concentrations of nitrate and iodine (6-9% and 0.03-0.06%, respectively).

Typical caliche layers are composed mainly of halite (NaCl) and nitratine ($NaNO_3$), with darapskite ($Na_3(SO_4)(NO_3)\cdot H_2O$), humberstonite ($K_3Na_7Mg_2(SO_4)_6(NO_3)_2\cdot 6H_2O$), anhydrite, glauberite and bloedite, along with subordinate iodates, borates, chromates, zeolites and calcite

Oyarzún & Oyarzun (2007)

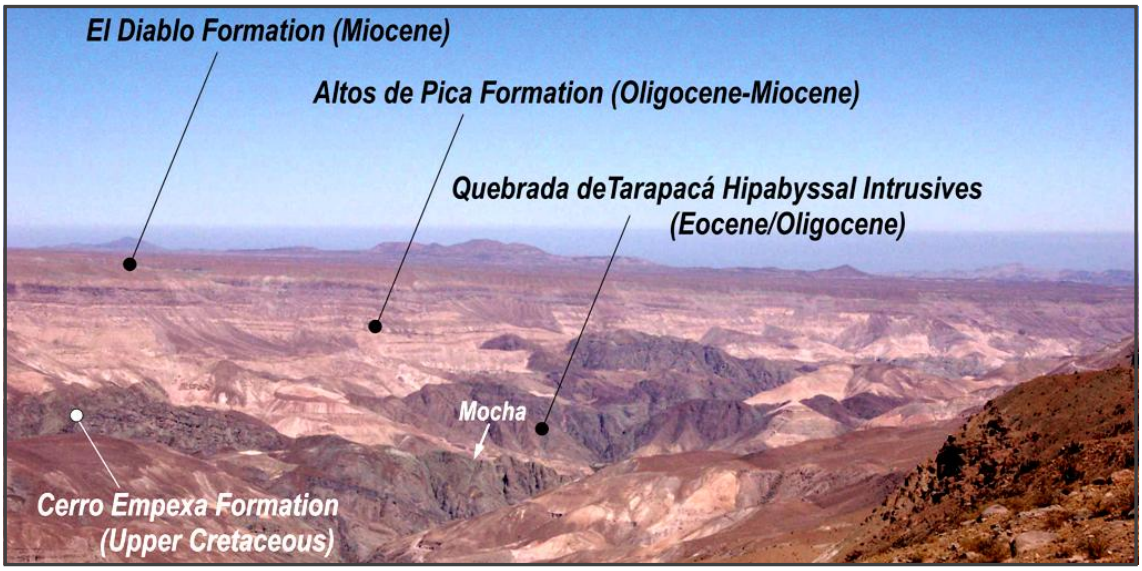
The Gulches (Quebradas) Domain

When we leave the Western Depression, heading east along Road 15 the relief rises above 2000 m and up to about 3000+ m. At the beginning of the Tarapacá Gulch, near Pachica, we find rocks belonging to the Cerro Empexa Formation (*Upper Cretaceous*); this formation consists of a 600 - 1000 m thick sedimentary and volcanic series; the lower portions of the unit include andesitic lavas, auto-breccias, overlain by conglomerates and conglomeratic sandstones, whereas the upper section is composed of poorly sorted sandstones (*Gallardo Cerón 2015; Herrera et al. 2017*).



The locality of Pachica in the Tarapacá Gulch. The rocks correspond to the Cerro Empexa Formation (Upper Cretaceous), Member A: andesites and volcanoclastic rocks. In the background, the Altos de Pica Formation (Oligocene-Miocene) is observed. Interpretation based on Gallardo Cerón (2015)..

In the higher course of the gulch (*observable from Road 15 from about 3000 m of altitude*), younger units are recognized: the so-called Hipabyssal Intrusives of the Quebrada de Tarapacá (*Eocene/Oligocene*) and the Altos de Pica (*Upper Oligocene - Lower Miocene*) and El Diablo (*Middle to Upper Miocene*) Formations (*Gallardo Cerón 2015*).



Awesome geology. Contact relationships between the so-called Hipabyssal Intrusives of the Quebrada de Tarapacá and the Cerro Empexa, Altos de Pica and El Diablo formations. Looking towards the town of Mocha, about 150 m from Road 15, and about 3000 m above sea level. Interpretation based on Gallardo Cerón (2015). The town of Mocha is in the direction of the arrow; the town is hidden in this image by the surrounding mountains.

The Road 15

The Road 15 in its ascent to the heights offers two "must see":

1) A geology that takes your breath away when you look at the bottom of the gulches.

2) A world of Cactaceae by the side of the road.

The Altos de Pica Formation consists of ignimbrites, tuffs and volcanoclastic rocks that in part correspond to base surge deposits. Finally, the El Diablo *("Devil")* Formation constitutes the top of the stratigraphy of this sector with sandstones, conglomerates and shale intercalations and some volcanic ash beds (*Gallardo Cerón 2015*).

El Diablo Formation (Middle to Upper Miocene), an authentic "Martian" landscape on Earth.

The Diablo Formation:

A walk through the canyons of Mars on Earth, without having to wear a spacesuit.

What is a molasse?

"A term of Swiss origin used to describe sediments produced by the erosion of mountain ranges after the final phase of an orogeny." Glosarios (2012)

El Diablo is the product of the erosion of the previous formations (*Gallardo Cerón 2015*). Thus, on the other hand, being El Diablo a formation that was deposited syntectonically, at least its base (*Gallardo Cerón 2015*), it is likely that it represents the "molasse" of the construction phase of the Andean orogen that culminated with the development of Altos de Pica.

The Eastern Depressions: the pre-Andean salt flats domain

The salt flats of the Eastern Depressions, or "salares" as they are known in Chile, consist of evaporite-sedimentary bodies located in endorheic basins at an altitude above 3700 m.The drainage basin of the Huasco salar extends over an area of approximately 1500 km^2, whereas the salt flats cover an area of about 50 km^2 (*López Julián & Garcés Millas 2002*).

The Salar de Huasco has been declared a Ramsar Site because of its high value as a habitat for plants (the bofedal ecosystem), animals (*camelids and flamingos among others*) and landscape (*Acosta & Custodio 2008*). The mineralogy is dominated by carbonates, sodium salts (sulfates and chlorides). The free shallow water surface is very small compared to the dimensions of the salt flats (*Garcés Millas & López Julián 2010; SERNAGEOMIN 2021*).

The Salar de Huasco (looking east). In the background, eroded stratovolcanoes of Mio-Pliocene age (SERNAGEOMIN 2021).

The Salar de Huasco: importance

"Closed basins are watersheds whose drainage networks converge to lakes, salt flats or floodplains. The salt flats in the closed basins of the arid northern Chile are extremely important as ecological niches. The Salar de Huasco, one of these salt flats located on a high plateau (Altiplano), is a Ramsar site that is located in a national park and is composed of a wetland ecosystem rich in biodiversity."

Uribe et al. (2015)

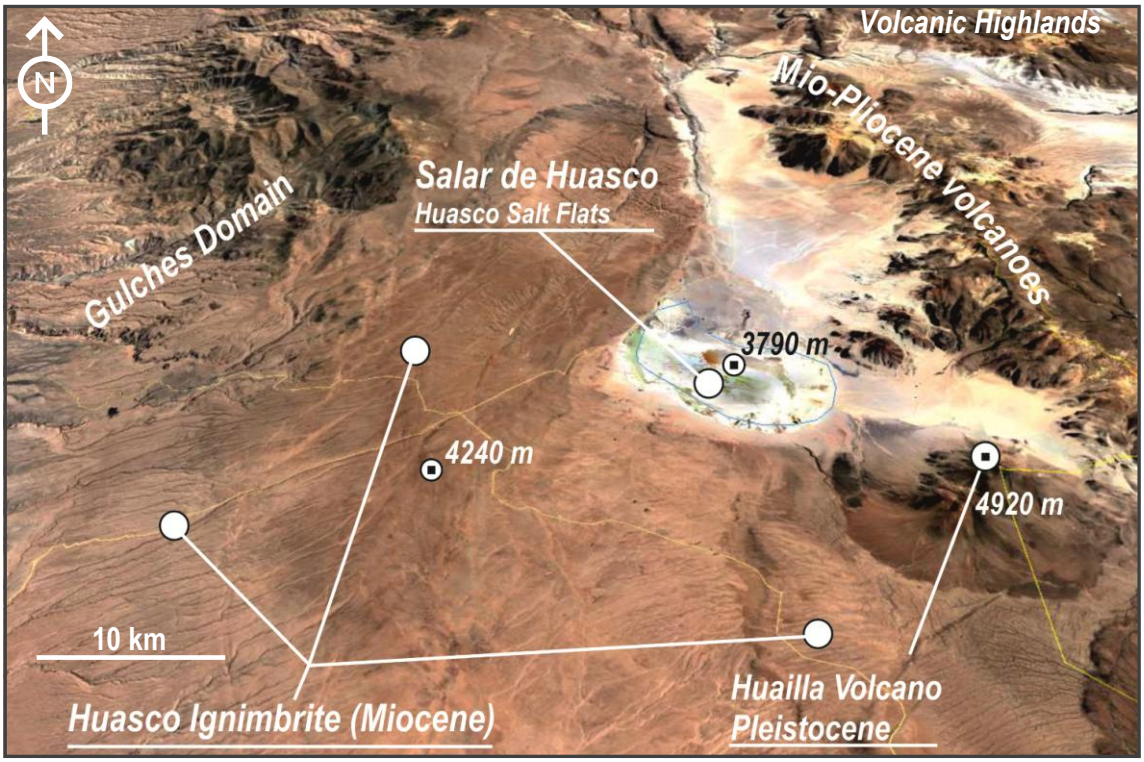
Precipitation of salts during the drying of the brine sheet and death of the plants. These pseudo-circular structures appear as a consequence of the desiccation of the water sheet and death of clumps of cespitose plants whose edges are the last to disappear, resulting in a periphery with greater protrusion. Inset: forming circles (arrows and ovals) that during total desiccation will take the appearance shown in the main figure.

What are the Ramsar sites?

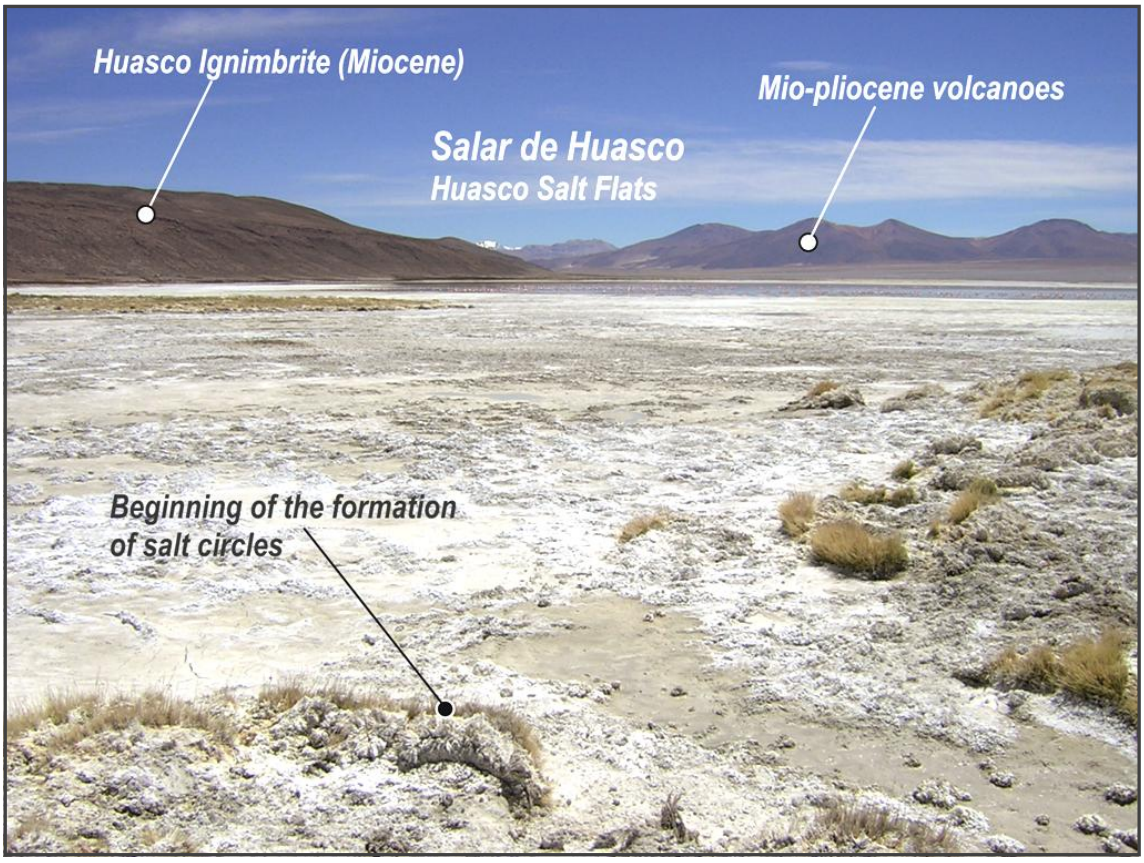
"Ramsar sites are designated because they meet the criteria for identifying wetlands of international importance."

These are sites that contain rare or unique wetlands, for the conservation of biological diversity.

Ramsar (2021)



Basic geology of the salt flat environment (I); heights determined with Google Earth.



Basic geology of the salt flats environment (II); looking north.

El Salar de Huasco: national and international recognition

"The Salar del Huasco is located in the township of Pica, Tarapacá Region. It is located between two mountain ranges that go from north to south and reach over 4500 meters. Its surface area is 9950 hectares (24576 acres). Scientific studies have determined that the Salar is a vestige of what was once a Pleistocene lake that stretched from Lake Titicaca in southern Peru to the Antofagasta Region in Chile. Climatic change caused this lake to gradually recede, leaving as proof of its existence the wetland that today makes up the Salar de Huasco. Its geomorphological and climatic conditions did not favor human settlement, however, the Aymara culture, located in the surrounding area, integrated it as part of their myths and religious rituals. Recognized as one of the most pristine wetlands of the altiplano, it is an important water reserve in one of the driest places in the world."

"The Salar is an essential habitat for the development of biodiversity in the area, attracting countless species, including mammals such as the Andean fox and the puna guinea pig, among others. Its location transforms it into a relevant scenario in one of the most important migratory routes of birds, being essential for the nesting of various species such as the Chilean flamingo, the Andean flamingo, the small parina, the eagle owl or horned owl and the rhea. Its climatic conditions also favor the proliferation of shrubs and plants characteristic of the altiplano. In 1996, it was declared a protected area as a Wetland of International Importance, in accordance with the RAMSAR Convention, an agreement that seeks to preserve wetlands around the world."

"Due to its singularities and ecological value, on May 9, 2005, the Salar de Huasco was declared a National Monument in the category of Nature Sanctuary, becoming administered by Bienes Nacionales. Furthermore, on June 5, 2010, at the request of CONAF, it acquired the category of National Park, becoming part of the 100th unit of the National System of State Protected Wildlife Areas (SNAPE). At present, various educational, recreational and sporting activities can be carried out inside the park, for tourism and leisure purposes."

CMN (2021c)

More reasons to visit the Salar de Huasco and its ecosystem. A) flamingos, B) suries or also called Puna rheas (Rhea pennata subsp. tarapacensis), C) vicuñas (Vicugna vicugna), D) llareta (Azorella compacta). The llareta is a spectacular plant that adds a touch of color to these sites."

The Volcanic Highlands (the Altiplano)

The outcrop area of the Altiplano is about 70,000 km^2 (*Chile-Argentina-Bolivia*), with more than 10^4 km^3 of emitted materials, making it the largest ignimbrite province on Earth (*e.g. Allmendinger et al., 1997; Babeyko et al. 2002*). Emission of ignimbrites began about 10 Ma ago and continued strongly until about 1 Ma ago (*Babeyko et al., 2002; Schmitt et al., 2002*). Single ignimbrite eruptions of andesitic to dacitic composition (63-68% SiO_2) exceeded 1000 km^3 in volume (*De Silva 1989; Allmendinger et al. 1997; Schmitt et al. 2002*).

The volcanic altiplano (ignimbrites and fall deposits) in the Isluga National Park. See map (Wikipedia 2021b) of the park in Fact Sheet 2 (III). Image[8]: Till Niermann.

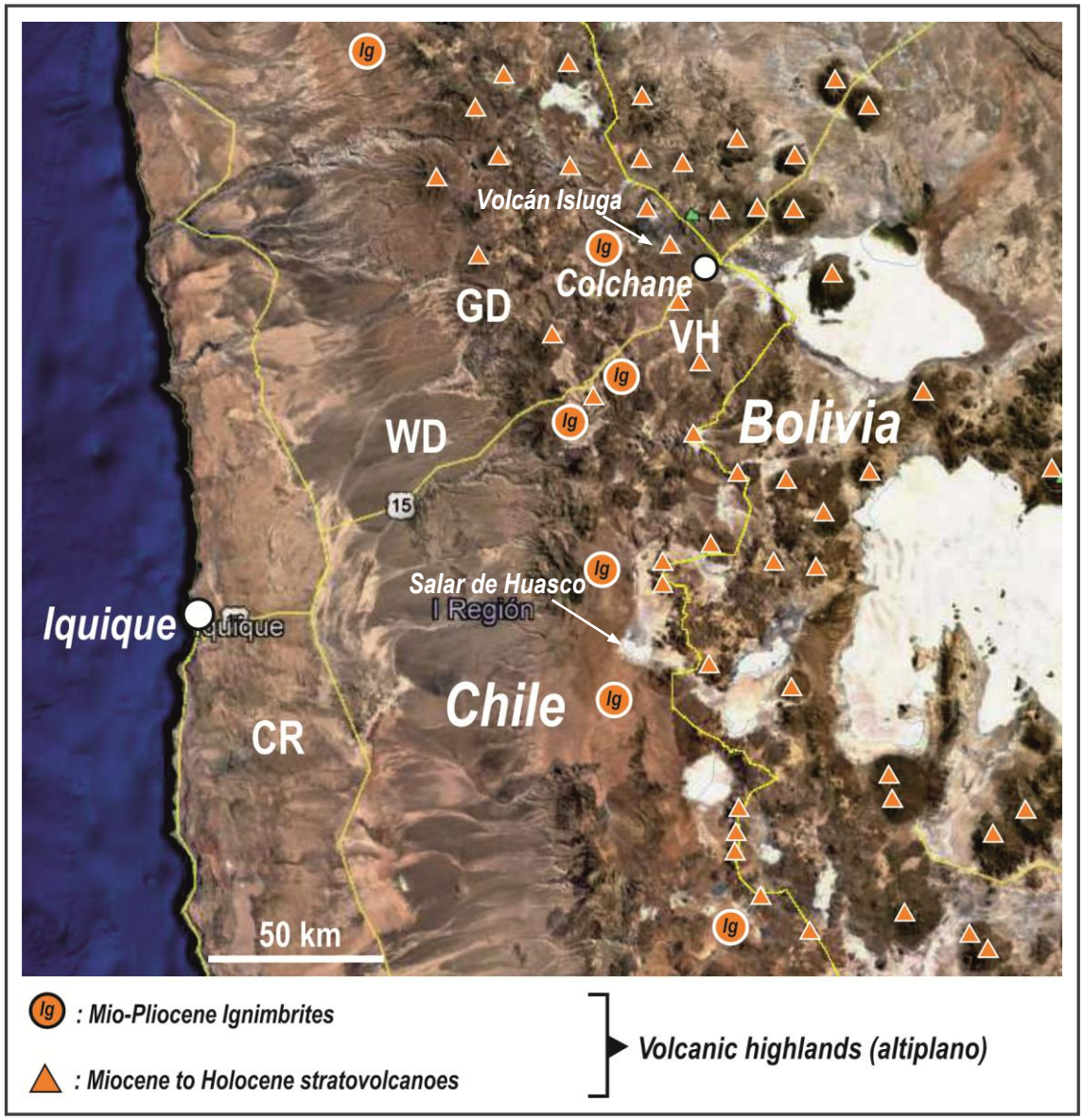
In turn, a mafic to intermediate Pliocene to Quaternary volcanism concentrated in the western boundary of the Altiplano-Puna Volcanic Complex *(between 21º10' and 22º50'S*) and gave rise to lava flows from stratovolcanoes and monogenetic cones; the volcanic rocks vary in composition from basaltic andesite to dacitic with a great compositional heterogeneity in terms of the contents in major and trace elements (*González-Maurel et al. 2019*).

The Isluga volcano and a herd of llamas.

"The Volcanological Observatory of the Southern Andes (OVDAS) belonging to the National Geology and Mining Service of Chile, installed in October 2012 two volcanic monitoring and surveillance stations on the slopes of Isluga volcano, which recorded seismic activity.

In addition, the presence of fumarolic activity (characterized by a column of white-colored gases) was observed."

Volcano Discovery (2012)



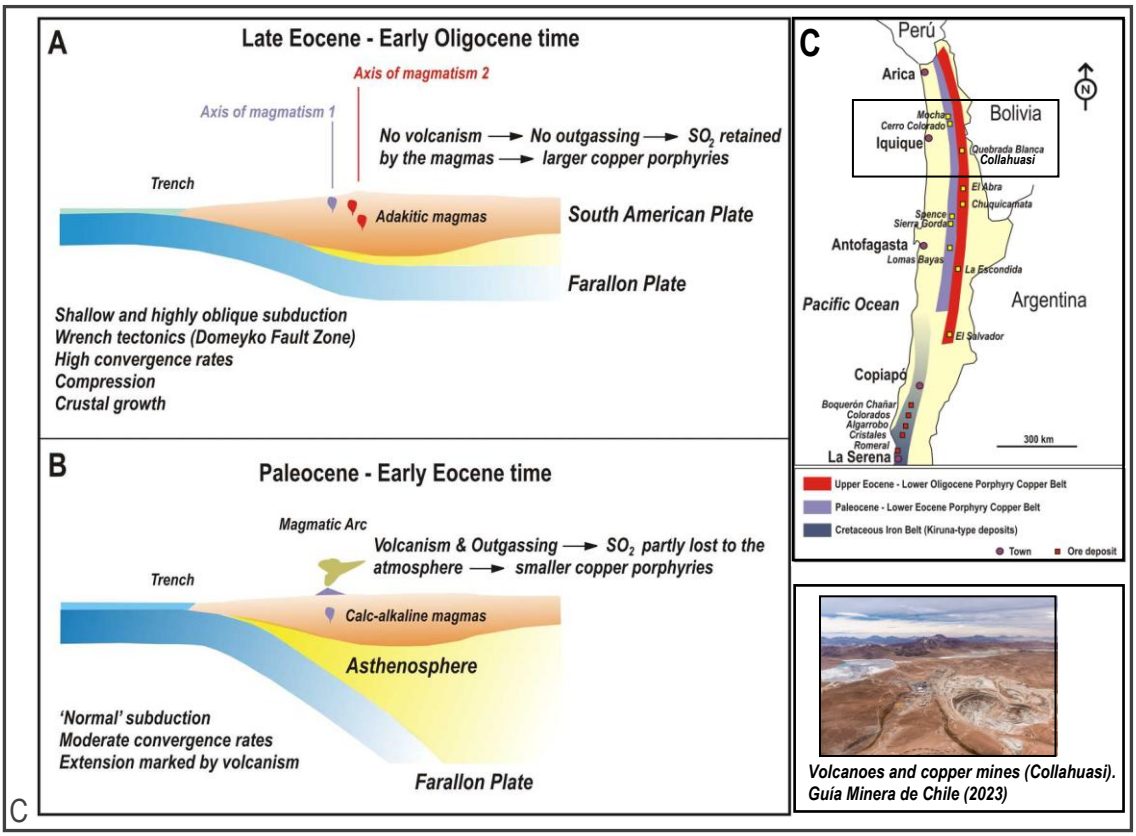
Stratovolcanoes and ignimbrites of the highlands on a Google Earth image. The presence of the Isluga Volcano has been highlighted with an arrow; see also (below) the last paragraph of this section. VH: Volcanic Highlands, CR: Coastal Ranges, GD: Gulches Domain, WD: Western Depression.

An example of this volcanism is Isluga volcano (*Volcano Discovery 2012*), with large historical eruptions in 1868, 1869, 1877 and 1878, and small eruptions in 1863, 1885 and 1913. Recent eruptions were phreatomagmatic and produced emissions whose deposits can be found around the active crater. Holocene lava flows cover the northernmost flank of the volcano. A dacite flow from the northwest side of the volcano has been dated at 96,000 years. The Isluga lavas overlie the rocks of an older volcano (*Quimsachatas*) to the north and northeast. The latter erupted some 566,000 years ago (*Volcano Discovery 2012*).

Ore deposits

The metallogenic world of porphyry copper deposits in northern Chile

Two parallel N-S oriented metallogenic belts (*provinces*) of copper-bearing porphyries are recognized in northern Chile. From West to East we have one of Paleocene - Lower Eocene age, and another one immediately to the East of Upper Eocene - Lower Oligocene age. This is the result of the eastward advance of Andean magmatism, i.e., the younger a volcano-plutonic belt is, the more eastward it will be located.



A and B) Schematics of the plate tectonic framework related to the formation of copper-bearing porphyries in northern Chile. C: Some of the metallogenic provinces in northern Chile. Adapted from Oyarzun et al. (2001).

The following are examples of porphyry Cu-(*Mo*) deposits in the region:

- **Cerro Colorado** is a porphyry copper deposit located in the Gulches Domain and is part of the Paleocene - Lower Eocene metallogenic province (*e.g. Oyarzun et al. 2001*) (*see above*) whereas **Collahuasi** - **Quebrada Blanca** are part of the Upper Eocene - Lower Oligocene copper porphyry metallogenic province (*see above*).
- Quebrada Blanca is simply a porphyry Cu-(*Mo*) deposit whereas Collahuasi is a more complex case, hosting in addition to porphyry Cu-(*Mo*) deposits such as Ujina and Rosario, a high sulfidation (*Cu-Ag*) vein type deposit (*Rosario West*) and a distal oxidized copper (*exotic type*) deposit: Rosario South (*MDO 2020a*).

What are adakites?

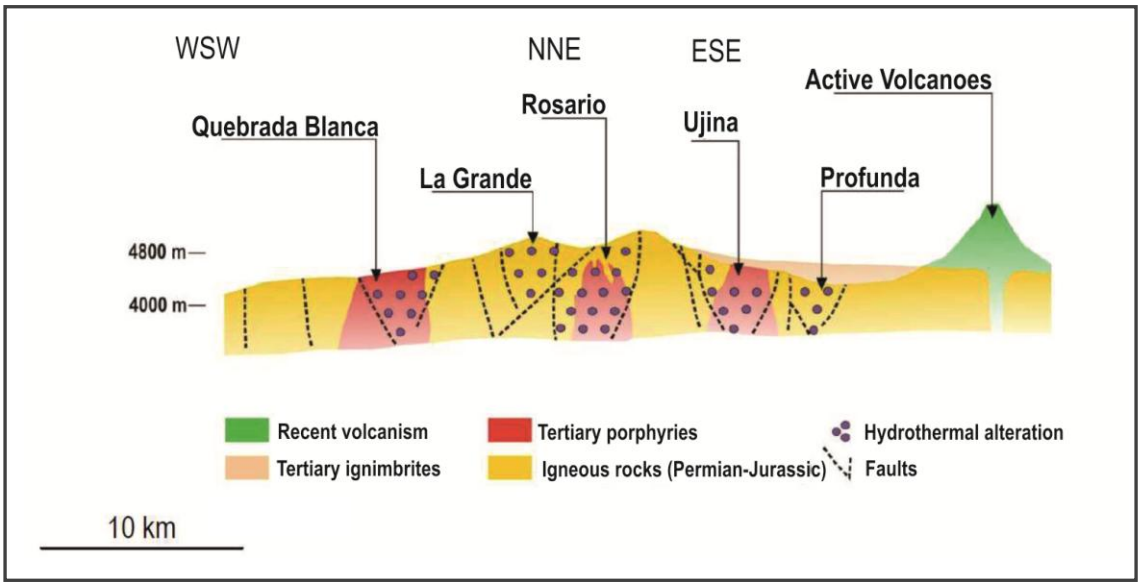
The term adakite comes from Adak Island (Aleutian Islands, Alaska) and was defined by Defant & Drummond (1990) to describe magmatic arc volcanic rocks of Cenozoic age with geochemical characteristics including $SiO2 \geq 56\%$, $Al_2O_3 \geq 5\%$, MgO: 3-6%, $Y \leq 18$ ppm, $Sr \geq 400$ ppm

(Oyarzun et al. 2001).

What are calc-alkaline magmas?

"The use of the term has evolved considerably since then, and today it is variably used for the subalkaline assemblage of basalt-andesite-dacite- rhyolite, or any rock assemblage containing andesites, island arc rocks, or rocks with high ratios of large ion lithophile elements (LILE) (e. K, Rb, Cs, Sr, Ba) to high field strength elements (HFSE) (e.g. Zr, Nb, Hf, rare earths)."

(Sheth et al. 2010).



Schematic geological section along the Collahuasi - Quebrada Blanca district. Adapted from Dick et al. (1994).

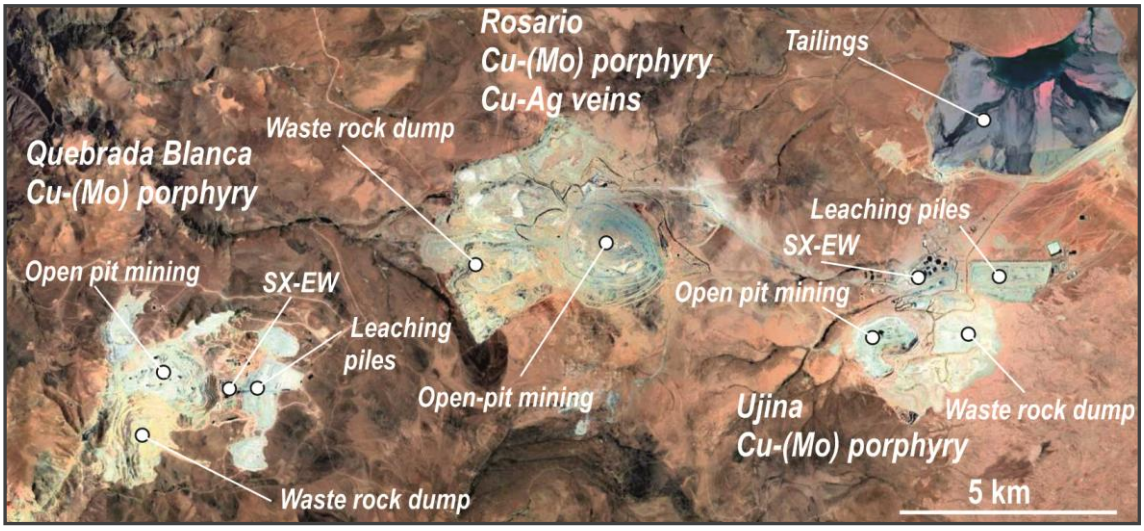
The district porphyries

The porphyries were emplaced in Paleozoic rocks of the Collahuasi Formation (sedimentary and volcanic rocks) and plutonic rocks; the Collahuasi Formation is considered to be of Permo-Triassic or Carboniferous-Permian age. The porphyries would have been emplaced in the Upper Eocene, almost at the boundary with the Oligocene

Masterman et al. (2004); Barrios & Maksaev (2015)

Mining at Collahuasi – Quebrada Blanca

Mining activity in the Collahuasi district (*Collahuasi 2021*) dates back to 1880 when its high grade copper and silver lode systems began to be mined. These operations continued for fifty years until they were interrupted by the Great Depression. Work in the area resumed in 1978 when the key components of the Rosario deposit were identified. In 1991, a combination of geological studies, along with a drilling campaign, resulted in the discovery of the Ujina deposit. The feasibility and environmental impact studies for the Collahuasi Project were approved in 1995, and in late 1996, once the financing and commercialization agreements were signed, the construction and development phases of the project began.



The Collahuasi-Quebrada Blanca mining-metallurgical complex. Google Earth image of 12/23//2018.

Prehispanic mining at Collahuasi

"Copper metallurgical production was practiced in the Collahuasi district from the beginning of the Late Intermediate Period through the use of a technology based on stone-backed furnaces, something apparently uncommon in northern Chile. In that mining district, the Inca took advantage of the pre-existing mining-metallurgical system and maintained the use of local technology."

Figueroa et al. (2002)

The Company began commercial operations on April 7, 1999. Since then, it has sought to develop its activities in accordance with policies and practices of excellence that contribute to the well-being of the society, economic development and care for the environment (*Collahuasi 2021*).

In 2020 Collahuasi produced 629,100 t of copper (*cathodes and concentrates*) (*Mining Journal 2021*).

Mining operations in Collahuasi (Collahuasi 2021).

The Quebrada Blanca mine is at 4400 m of altitude, approximately 10 km southwest of Rosario. Quebrada Blanca is a smaller open pit operation, which leaches oxidized ore to produce copper cathodes through processing in an SX-EW plant; Quebrada Blanca produced 25,500 tons of copper cathodes in 2018, compared to 23,400 tons in 2017 (*Teck 2021*). The copper cathodes produced at Quebrada Blanca are transported by road to Iquique for shipment to buyers.

Important:

Mining operations are not open-access tourist sites.

If you do not have a duly authorized express invitation, you will be denied access to the site.

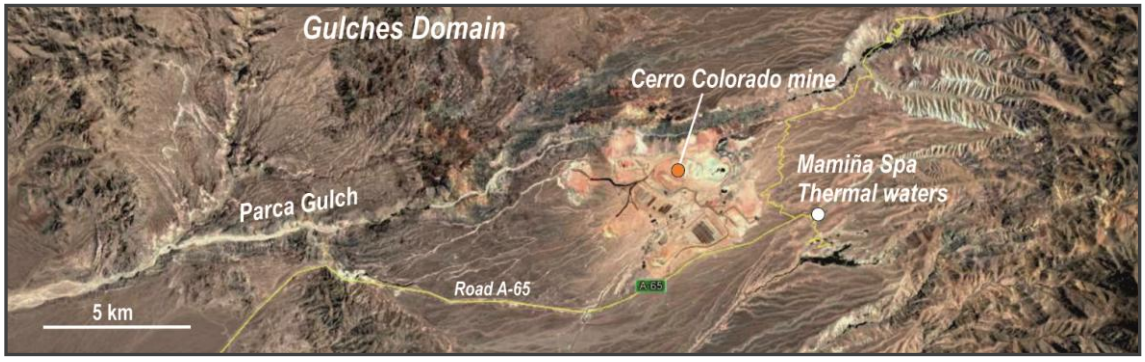
The Quebrada Blanca open pit operation (Teck 2021).

A common roster in mining (*worldwide*) is two weeks "on", one week "off" (*LISA 2022*). While "in mine" personnel live in a camp and from there, once they have completed the working period most of them will travel back to the towns and cities from where they came from. This is neither easy for the personnel nor for their families, but the pay can be good to extremely good.

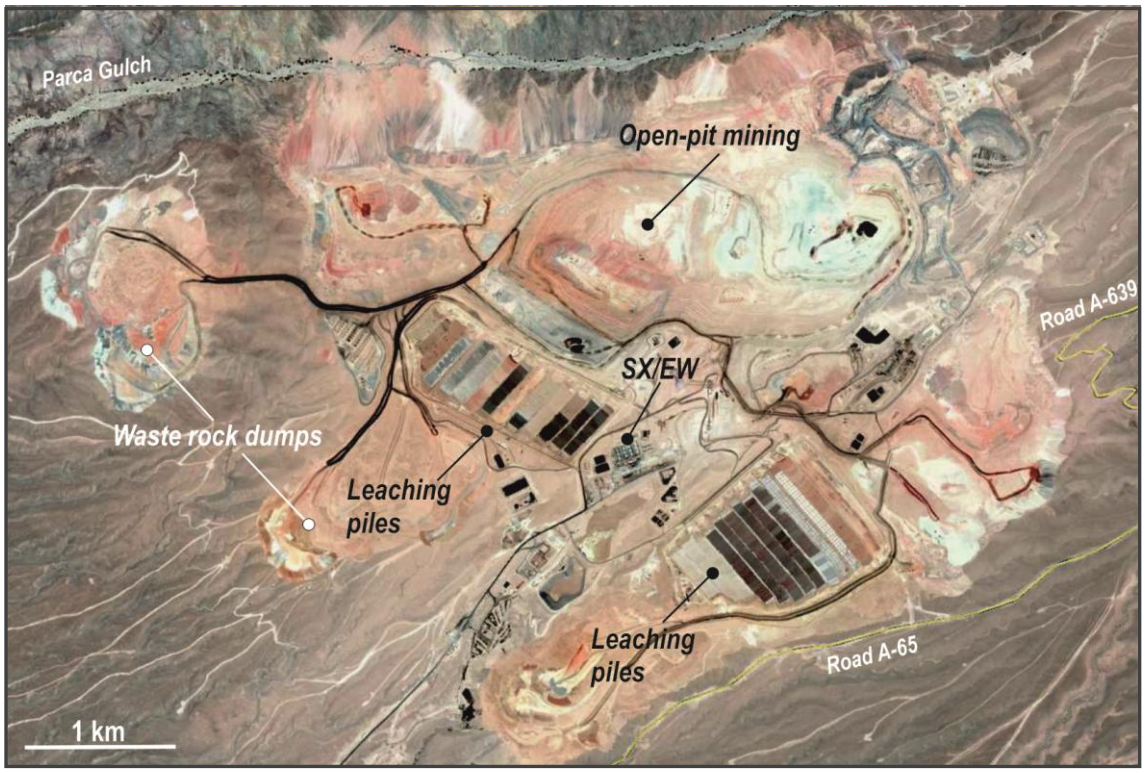
Collahuasi: Camp Pioneer expansion consisting of 3 Modular Buildings of 2 and 3 stories with metal staircases on the outside (ATCO Sabinco 2017).

Cerro Colorado and the Mamiña Spa (a happy coincidence)

The Cerro Colorado deposit (*Moreno Ibarra 2021*) is located in the Gulches Domain, about 130 km to the NE of Iquique at about 2600 m of altitude. It is a porphyry copper deposit of Lower Eocene age (*52 Ma*), and the hydrothermal system is related to the emplacement of an intrusive complex in volcanoclastic rocks of the Cerro Empexa Formation (*Upper Cretaceous*).



The Cerro Colorado mining complex and the Mamiña Spa.



The Cerro Colorado mining-metallurgical complex. SX/EW: "Solvent Extraction-Electrowinning".

The distribution of the mineralization is typical of the copper porphyries of northern Chile (*Moreno Ibarra 2021*):

- A 80 m thick leached zone.
- An oxidation zone, with oxidized copper minerals (*brochantite-crysocolla*): 25 to 125 m thick.

Mining and spa facilities

It is by a very fortunate coincidence that Cerro Colorado miners can enjoy the presence of a hot springs spa practically "just around the corner". This is the case of the Termas de Mamiña hot springs, only half an hour's drive from the mining facilities.

- A zone of supergene enrichment, with a majority presence of chalcocite, reaching a thickness of up to 100 m.

The mine is operated on an open pit basis and the ore is processed by SX/EW to obtain copper cathodes, with a production of 130,000 t of cathodes/year (*2018*) (*MDO 2020b*).

Surroundings of Mamiña village, cultivation plots. Note the erosion of the rocks in the form of a regolith on the hills. Image[9].

As a final curiosity, the Cerro Colorado mining complex is only 30 minutes (*20 km*) from the famous Mamiña spas along Road A-65. These are at more than 2,700 meters of altitude and include several hot springs at temperatures between 45ºC and 57ºC.

The Mamiña thermal waters are an excellent alternative for those who enjoy natural life, adventure, sun and desert landscapes.

Termas (2021)

Modern facilities in one of Mamiña's spas. Image[10].

Important: mining facilities are not tourist attractions and cannot be visited, but the Mamiña spas are, and there you can also be in contact with the local geology, partly dominated by the Upper Cretaceous Cerro Empexa Formation.

This would be all for now, although there are still many things to tell, many other landscapes to describe. We hope that someday you will be able to visit these places, and if you have already done it, we hope you will come back: there is always something new to see, to explore, to discover.

Roberto, Paloma & Fernando

The Tarapacá Gulch

Tres Cantos (Madrid) – Iquique

March 2023

So, so you think you can tell, heaven from hell? Blue skies from pain? (Roger Waters & David Gilmour)

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***Note**: Internet documents that do not have a date of publication on the network were generically assigned the date 2021, the year in which these pages were accessed for the Spanish edition of this document. Some http addresses have been split.*

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