The cold desert of Atacama – Mapping previously unknown cryophenomena in the Ojos de Salado Region

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ABSTRACT

The volcano-surrounded endorheic basin of the Valle de Barrancas Blancas in the Chilean High Atacama belongs to the *Dry Andes*. The basin displays and preserves a unique suite of active and paleocryogenic processes. In this contribution an attempt is made to describe their physical and temporal interaction. Permafrost occurs in the Valley of Barrancas Blancas. Regarding its climatic conditions the study area represents an extremely cold desert region with particular microclimatic characteristics on the bottom of the valley which allow for an active layer of 30 to 45 cm in depth (at approximately 5000 m ASL). At some higher sites, such as the top of the Llanos de Rivera towards the south of the study area and in cryoplanated areas, however, the permafrost table was found at greater depth (e.g., at an altitude of roughly of 5400 m ASL at approximately 65 cm). The cryogenic geomorphology of the study area shows most varied micro (patterned ground) and mesoforms (rock glaciers, cryoplanation surfaces). Gelifluction strongly affects the slopes. Moreover, and for the first time in the Southern Hemisphere two new types of cryophenomena are described: a specific type of a small pingo, the Atacama pingo (*pingo atacamensis*), and the frosted dunes (*dunas heladas*). At the same time, the conducted research provides excellent clues for the comprehension extraterrestrial environments. Furthermore, it has an impact on the exploration of the urgently needed water reserves in the High Atacama.

1 INTRODUCTION

The Valle de Barrancas Blancas is an endorheic basin situated at elevations above 4850 m, west of the Ojos del Salado Massif (6893 m), east of the Nevado Tres Cruces Massif (6748 m) and south of the Cerros de Barrancas Blancas (Cordón Foerster, 6119 m), in the High Atacama Andes of Chile (68°39'W, 27°02'S; Figure 1A). The valley trends more or less in NNW–SSE direction, with its Y-branches running in ENE–WSW and SSE–NNW directions. The study area (approximately160 km^2) contains a series of well-preserved landforms resulting from a unique combination of slope (aero-gravitational), aeolian, lacustrine/littoral, fluvial, glacial and periglacial regimes. A broad spectrum of cryogenic geomorphic landforms has not yet been described in this entire region (Buchroithner et al. 2010). Following the general geomorphological interest in cryospheric landforms in the Arid Diagonal of South America, and in the Atacama Desert specifically (cf. García et al. 2017), our results reveal subrecent subsurface features, which were not documented before and may be crucial for water management within the specific area and beyond.

The geological background of the Valle de Barrancas Blancas Region is covered by the Hydro-Geological Map of the Chilean Servicio Nacional de Geología y Minería (Santibáñez et al. 2006) and also described in Baker, Gonzalez-Ferran and Rex (1987). The study area displays mountain permafrost in situ (Trombotto 2000) and also creeping permafrost. It is a periglacial macro-environment where interdependent processes, such as cryogenic processes together with erosion, eolian deposition and the action of fluvial washout mainly caused by precipitation, accumulation, retransportation/redeposition and melting of snow, play an important role (Buchroithner et al. 2010).

As defined on the basis of temperature Andean permafrost is ground (soil or rock and included ice and organic material) that remains at or below 0 °C for at least two consecutive years, which according to Trombotto Liaudat et al. (2014) shows altitudinal zonification.

Permafrost is synonymous with perennially cryotic ground. Permafrost related with temperature descending due to the altitude is called *mountain permafrost*; in the case of the Andes, it is called *Andean Permafrost*. Garleff and Stingl (1986) called this type *quasi continuous permafrost* because of the difficulty in distinguishing continuous and discontinuous permafrost in the Andes, as they are described for the lowlands of the Northern Hemisphere. It is a cold permafrost type, reinforced on south-exposed slopes and particularly restricted to the mountain topography of the Andean Cordillera and their mean annual air temperature (MAAT) and an annual precipitation of 300 mm/y involved landforms. According to Garleff and Stingl (1986) it occurs in the Argentine Puna up – 1/-2 °C MAAT.

Permafrost appears because of topographic as well as thermal conditions. The mountain summits are generally frozen if the MAAT is below -2 °C and they show tors as well as sediments from cryogenic weathering.

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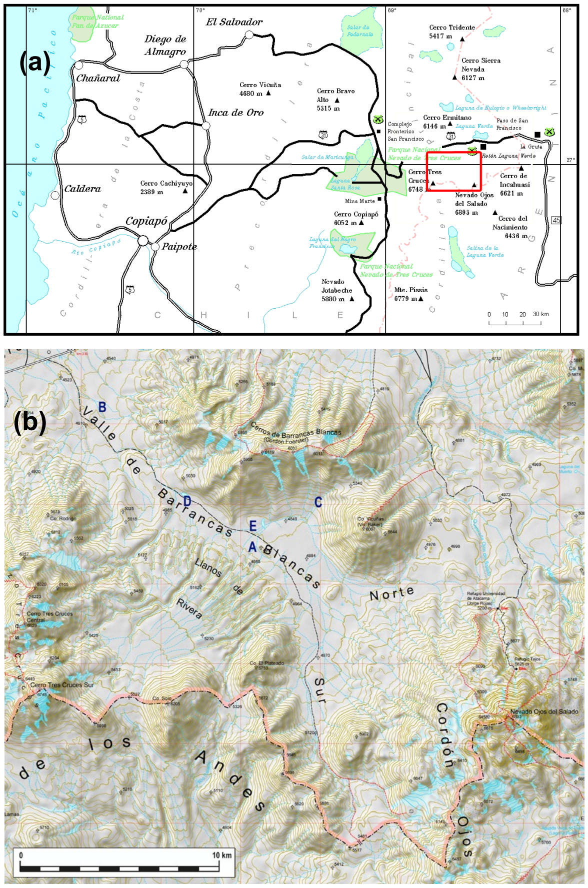

Figure 1. (a) Location of Valle de Barrancas Blancas (red rectangle), Buchroithner et al. 2004. (b) Locations mentioned in paper: A Valle de Barrancas Blancas; B patterned ground; C embryonic rock glacier; D Pingo atacamensis; E frosted dunes

Permafrost is denominated in situ if it is found below the surface without any sign of movement (Trombotto 2000). Another type of permafrost is rock glacier permafrost, which is characterized by downslope creeping movement caused by gravity and its rheological properties. Small micro landforms like gelifluction lobes are also related with the occurrence of permafrost, but with the movement of the active layer, which is the layer that covers permafrost and which thaws in summer.

The cryogenic geomorphology of the Valle de Barrancas Blancas is most varied and contains all kinds of examples known for the Andes, which were mentioned above, from microforms such as sorted and unsorted patterned ground, patterned ground with extrusion forms caused by cryoturbation (Figure 1B) to mesoforms like rock glaciers and cryoplanation surfaces (Figure 1C). Slopes are strongly affected by gelifluction. Nagy Et al. (2018; 2020) made an important contribution to ground ice and the presence of permafrost in the region. In the study area important niveo-eolian processes (van Straelen 1946, *in fide* Jahn, 1972) occur which not only participate in the erosion of pre-existing landforms in the sense of Jahn but also in the formation of subterraneous ice layers and the retransportation/redeposition of sediments as already described by Cailleux (1972) for Nouveau-Quebec and Victoria Land.

The aim of this paper is to describe landforms that have not been previously documented from the South America context and from the Southern Hemisphere as a whole.

2 METHODOLOGY

The work consisted of making a periglacial geomorphological survey. The cryogenic landforms were interpreted by taking soil temperatures at different depths with data loggers. These temperature recordings were only carried out for very short time, from 14 to 20 February 2011. Pits were dug specifically in each new landform to recognize the cryogenic sedimentology, origin of the landform and to find ground ice. Geophysical sounding (Ground Penetrating Radar) was also used to interpret the presence and depth of the ground ice. With terrestrial laser scanning at one of the Atacama pingos, work to know its evolution or growth was begun.

3 RESULTS AND DISCUSSION

3.1 Conditions of the Periglacial Environment

The mean annual air temperatures (MAAT) of the Valle de Barrancas Blancas, an endorheic basin according to the Hydro-Geological Map (Santibáñez et al. 2006), vary between -2 and -4 °C. Lower temperatures occur with increasing elevation and on south-facing slopes. The valley bottom consists of pebbles, predominantly of pumice (piedra pómez) and other volcanic and sedimentary materials. Data loggers installed close to the surface at a few sites (in the shade) indicate daily mean air temperatures of -2 to -3 °C (Figures 2 and 3).

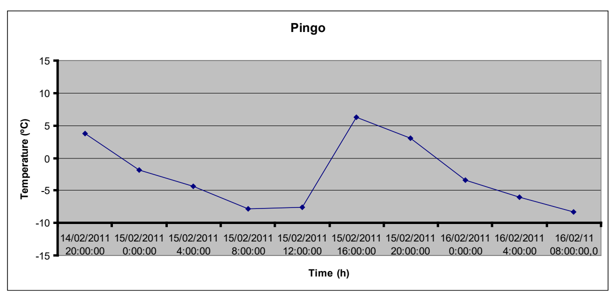

Figure 2. Representative temperature (36 hours during Austral summer) of a pingo at the valley bottom of the Valle de Barrancas Blancas at an elevation of approx. 4900 m ASL at the ground/air interphase (Figure 1b, location D). This temperature > 0 °C favours the adherence of snow to the ground and the generation of frosted dunes (Figure 1b, location E).

According to the hydrogeological map (Santibáñez et al. 2006) and according to field observations precipitation in the study area is approximately 150 mm/year. Snowfall is frequent, but the snow is quickly sublimated, redeposited and/or covered by cryosediments, i.e., mainly pumice pebbles.

The climatic conditions in the study area stand for an extremely cold desert region with particular microclimatic characteristics on the bottom of the valley, which allow for an active layer of 30 to 45 cm in thickness.

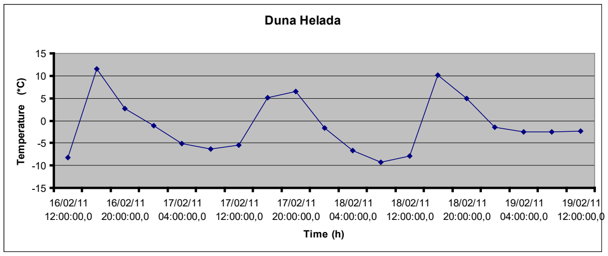

Figure 3. Temperature of a *duna helada* (Figure 1b, location E) at the valley bottom of the Valle de Barrancas Blancas at approximately 4860 m ASL at the ground/air interphase.

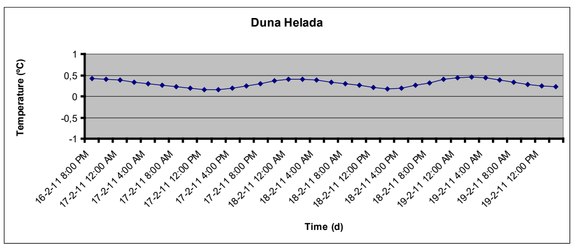

Figure 4. Temperatures at approx. 70 cm depth at a "*duna helada"*, at the valley bottom at 4860 m ASL (Figure 1b, location E)

Along some south-facing slopes the thickness of the active layer increases. In those cases, typically a dark-coloured sediment occurs and facilitates higher absorption of energy resulting in high temperatures at the interphase zone (ground/air). Wherever an excavation was made to study the subsoil (i.e., at numerous locations), the permafrost table was found close to the surface, or temperatures around 0 °C indicated its proximity.

At some higher sites, like the top of the Llanos de Rivera (6205 m; Figure 1) towards the south of the study area and in cryoplanated areas, the permafrost table was found at greater depth (e.g., at 65 cm at an altitude of approximately 5400 m ASL). It is assumed that due to its topography and location the bottom of the main valley of the Valle de Barrancas Blancas keeps pockets of very low temperatures over a long period of time.

Along the contact between the permafrost table or the detected massive, pure sediment-covered ice bodies and the sedimentary layer, thermistors showed temperatures close to 0 °C, which may be explained by the phenomenon of the 'zero curtain' documented in this region (Batbaatar et al. 2020) where the latent heat has not completely dissipated because of the summer conditions during the field campaign. This is possibly also true for the influence of snowfall and the air temperature variations (cf. Figures 4 and 5).

The bottom of the Valle de Barrancas Blancas does not only act as a reservoir of sediments with cryogenic weathering origin due to transport by melting water from higher altitudes and eolian transport. Snow fall throughout the year in this valley is one of the key agents of erosion and deposition in this landscape.

During the measurement expedition in February 2011 (La Niña year) it snowed frequently at different times of the day and sastrugis or snow-sand dunes were shaped. The sand layers of the dunes are interbedded with snow. Granule-pebble ripples like in Antarctica (Selby et al. 1974) are also present in the valley.

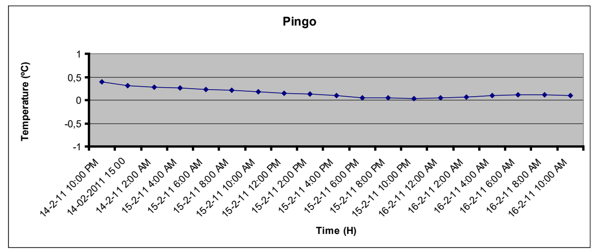

Figure 5. Temperatures at approximately 45 cm depth below the top of a pingo at the valley bottom of the Valle de Barrancas Blancas at 4900 m ASL (Figure 1b, location D).

It is worth mentioning though, that the snow is generally either quickly redeposited by wind, it sublimates, or melts and percolates through the mentioned thin active layer where possible, or otherwise helps to build puddles where proximate permafrost impedes permeability. This is often the case in many parts of the valley but particularly in its lowest parts. The pH of the puddles, ranges between 4 and 5, and the temperatures in the shallow areas, where samples were taken, were 8 to 10 °C (at midday). This process formed two lakes of remarkable size (Figure 8): one in the lower and one in the upper part of the Valle de Barrancas Blancas (Figure 1b, location B). The latter one showed a pH of > 6 and hosts a type of copepods, similar to the extremophile microfauna observed in the Lagunita del Plata in Mendoza, Argentina, at approximately 4000 m ASL (Trombotto 1991). All water bodies presented icings. In deeper ones like the larger lake in the SE part, ice is present on the rims. The bottom of the valley seems to have been the bottom of a former lake. Hence, different terraces can be distinguished and are likely associated with more humid and warmer Quaternary conditions. The prevailing pumice and its physical characteristics of low specific weight help to delimit former coastal lines as well as the perimeter of the bottom of the valley associated to a comparatively big lake that previously existed. In this context, GPS and TLS (terrestrial laser scanner) measurements are still waiting to be analyzed.

When snow is blown away by wind, the moving snow mingles with sediments which also experience eolian transport. This process allows for bodies of snow to remain in dunes in closed basins and are covered by sand and smaller pebbles (mainly of pumice). These landforms display an interstratified profile like the one Jahn (1972) presented for Sudetenland. Subsequently, part of the snow is transformed into firn and finally into ice (Schwikowski et al. 2010). This special condition facilitates the rise of the permafrost table and enhances the presence of different types of ice, such as layers of massive pure ice, bodies altering with sediments from the transversal side valleys that end up in the valley bottom of the Valle de Barrancas Blancas, or massive ice present as cores, inside the permafrost itself on the bottom of the main valley.

On the other hand, snow increases erosion of the slopes, shapes the landscape of the volcanics, predominantly pumice and lapilli, and the formation of steep side valleys, more or less transversal to the main valley of Barrancas Blancas. These, constitute the Llanos de Rivera plains and dissect the pumice formations with a predominant SSW-NNE orientation. The erosive shaping of the valleys creates a typical landscape of subpyramidal landforms at their endings at the main valley that can mimic desert barchans.

At approx. 4000 m ASL permafrost table was found to be at varying depths in the Valle de Barrancas Blancas (Figures 6, 7 and 8).

Figure 6. Physical sounding of permafrost table (see metal avalanche probe sticking in sediment) and clearing of cryoforms from sedimentary veneer.

3.2 Cryogenic forms of the region

3.2.1 Patterned ground

In particular at the relief threshold of the “entrance pass” (Figure 1b, location B) many examples of patterned ground can be found. They are characterized by their irregular shape and a length of various meters with extrusion cryoforms or nubbins as a result of the expulsion of the sediments towards the surface caused by cryoturbation and the presence of a near-surface permafrost. The diameter of these nubbins is 20 cm and more. When they are found on soft slopes of more than 2°, the soil displays the typical shape of a comet as described by Büdel (1978). Other types of patterned ground also frequently found in this region are irregular unsorted polygons delimited by thermal contraction cracks. The latter may create extended lines of several meters with collapse structures of cryosediments as explained by Trombotto (1991). In rather peneplanated areas, desert (stone) pavements are frequently observed (Figure 8; Dietze et al. 2011).

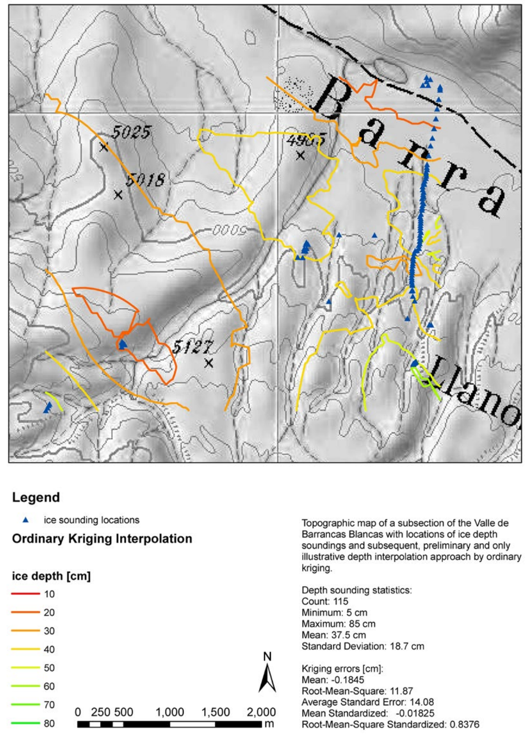

Figure 7. Location of February 2010 sounding profiles of the permafrost table in the Valle de Barrancas Blancas with areal extrapolation of its depth (extrapolation and visualization courtesy Michael Dietze (University of Göttingen).

Figure 8. View from the western slopes of Cerro Vicuñas (6007 m) towards the west onto the Tres Cruces Massif (left: Cerro Tres Cruces Sur, 6748 m). The larger of the two cryo-lakes mentioned in the text above appear in the middle ground.

3.2.2 Rock glaciers

The rock glaciers found in the area are of the cryogenic type; they originate through the contribution of cryosediments and snow from the slopes through niveo-detritic runnels or hollows, in particular at the range of the Nevados de Barrancas Blancas (Figure 1b, location C).

There are cases, however, where the niveo-detritic hollows are not well delimited, and the cryoforms seem to be related with subterranean creeping of 'ice slopes'

Trombotto et al. (1999) proposed that melted active layers of mountain permafrost, frozen in winter, snowfall and graupel mainly feed the discharge of mountain rivers. It is possible that with continuing global warming, water melting may also occur in supra-permafrost. On the other hand, important recent geophysical studies in the Central Andes have corroborated the coexistence and movement of supercooled water in the structure of the rock glacier, promoting high dynamics (Blöthe et al. 2021; Halla et al. 2021). What is quite unique though in the Valle de Barrancas Blancas, is the occurrence of a cryoform like a small rock glacier at the lower slopes of the Cerros de Barrancas Blancas created from a colluvial cone, the front of which show clear signs of creeping (Figure 1C).

3.2.3 Gelifluction lobes

The south facing slopes of the 'Cerros of Barrancas Blancas' are mainly composed of rhyolite type eruptives with gelifluction lobes and terrace landforms modified by snow patches (see Trombotto 1991).

3.2.4 Debris slopes

The slopes with gelifluction lobes are debris slopes formed by cryosediments of varied thickness correlated with the corresponding thickness of the active layers. The slopes are usually sorted with surface blocks of a diameter of 10–40 cm, although isolated blocks of a size of 1 m and more are also common. Below, coarse sand is found altering with the aforementioned blocks.

3.2.5 Cryoplanation surfaces

The southern part of the study area called "Llanos de Rivera" reaches up to an altitude of approximately 5400 m and reveals cryoplanation surfaces and cryopediments shaped by the action of cryogenesis and nivation on top of the *pumice* formations on which it is built (Figure 8). The transport of the material can be explained by gelifluction, although wind and subaquatic action may also be involved. Snow generates melting water during some part of the day, as was observed during summer expeditions. It is remarkable that between 4 and 8 pm data loggers registered positive temperatures that would explain this phenomenon of considerable transport of cryosediments.

3.3 New Cryoforms in South America

3.3.1 Atacama pingo (Pingo atacamensis)

This new type was defined by Buchroithner and Trombotto 2012).

This new geomorphological feature can be described as an oblong cryoform, mainly composed of pumice pebbles with varying sizes of tens of meters in planimetric extension. It is the first time that this kind of pingo has been discovered in South America in the Valle de Barrancas Blancas, at the foot of the south-eastern slopes of Cerro de Barrancas Blancas Central (27°01'26"S, 68°40'48"W) which are composed of rhyolithic eruptives (Figure 8).

It is a cryoform composed of different units, and due to its shape is hardly comparable to an open-system pingo like those of the northern hemisphere. However, the Atacama Pingo appears to be comparable to other known pingos in terms of its possible hydraulic genesis (Porsild 1938; Müller 1959).

In the NE sector of the discovered pingo and on the top of the cryoform, the permafrost table was detected at a depth of 65 cm with dry permafrost until 76 cm of the excavation. The temperature registered among the cryosediments was -0.1 °C.

In the SW sector of the relatively flat top of the pingo, the permafrost table was found at a depth of 46 cm and without dry permafrost. No massive ice was found. In the center of the landform a slight depression was identified which might be indicating permafrost degradation as part of its evolution.

Figure 9. Terrestrial laser scanning of one of the *Atacama Pingos.*

Small varieties of hydrolaccoliths, with a hydraulic genesis of the pingo type, were described by other authors (Porsild 1938; Müller 1959). These were denominated 'open system pingos' or East Greenland pingos, but of much smaller size with a contribution of the lateral injection of subterraneous water through the active layer of rhyolithic debris slopes, also exist. Three of these cryoforms were studied in more detail.

One of the analyzed forms had a size of 12 × 8 m and a height of approximately 0.6 m (Figure 9). With a remarkable comet-like shape that links the cryoform with the slope indicating the flow of subterranean waterways towards the endorheic basin or the main valley. A detailed geometric analysis of an Atacama Pingo (Pingo atacamensis) uncovered from sediment revealed that massive and pure ice grew in convex botryoidal shape on the permafrost table (Figure 1b, location D).

The analysis of a profile made of the Atacama Pingo (Pingo atacamensis, Figure 10) revealed that massive and pure ice grew in convex botryoidal shape on the permafrost table.

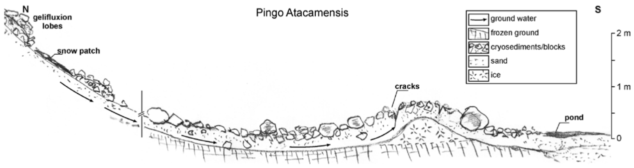

Figure 10. Proposed cross-section of the Atacama Pingo.

Its surface corresponds to the characteristics of the debris slopes at the edge of the bottom of the valley where it is located. Large blocks on the surface have a diameter of 30 to 85 cm. The cryogenic open fabric is complemented by smaller blocks of 4 or 5 and up to 8 cm in the matrix of the major ones. Below those blocks there is a sorted layer of sand similar to the 'kora' of the pingos found in the northern hemisphere (Davis 2000), with a thickness of approximately 45 cm. This layer is in contact with the massive pure ice that characterizes the cryoform. Large blocks with a length of up to 85 cm have been lifted by cryostatic pressure and are located in the upper part of the cryoform. Longitudinal, i.e., W–E trending, and lateral near-surface cracks characterize the surface.

The pingo formation is correlated with the flow of subterranean water which moves through an active layer. The active layer can have a significant thickness on the debris slope, in some cases a thickness of 70 to 80 cm was measured at this one particular feature. The debris slope 'crashes' with the pingo's perimeter at the bottom of the valley, and with a permafrost top at minor depth (30–45 cm, see above) which hinders the water to flow into the Valle de Barrancas Blancas and hence produces its accumulation and rises the piezometric level. Cryostatic pressure subsequently causes the generation of ice bodies on the permafrost table.

In another case of this type of cryogenic landform a 'kora', with an average thickness of over 30 cm was completely removed to observe different units with rounded convex forms of considerable size, indicating that the cryoform may be composed of various units of ice growth (Figure 11). This Atacama Pingo behaves like a secondary pingo next to the big one derived from the detritic slope shown in Figure 8.

The ice of the Atacama Pingos in both of the two studied cases was massive and transparent. The measured ice crystals that grow at the top layer of the permafrost reached a length of up to 12 cm and a diameter of about 3 cm, displaying growth in the typical hexagonal system (Figure 12). In one of the cases the ice allowed to distinguish different planes of growth, and it may be assumed that these correspond to different ages. The Atacama Pingos of this area developed after the emptying or drying of the ancient lake mentioned above.

Figure 11. Botryoidal ice core of a secondary Pingo atacamensis.

Figure 12. Typical hexagonal ice crystals in the top layer of the permafrost showing sizes up to 12 cm length and 3 cm in diameter.

3.3.2 *Frosted Dunes ("Dunas heladas")*

Frosted dunes or 'dunas heladas' are eolian-induced cryoforms (Figure 13) in the relief of the bottom of the Valle de Barrancas Blancas, rooting in the permafrost of the "*bajo sin salida"* or main valley.

A profile through a comparatively mighty '*duna helada*' shows a total height above the surrounding terrain close to 150 cm. The sediment cover (active layer) reaches from 35 to 50 cm on the western windward side.

It shows 55 cm on the crest of the ice core, and varies from 70 cm down to 55 cm on the leeward side, resulting in a depth of ±35 cm at the plain ground immediately east of the frost dune. The length is about 10 m. “Dunas heladas” facilitate the upheaval of the permafrost table. At the same time the permafrost helps to anchor the dune, preferably at

Figure 13. Digging a sediment-free profile of a ‘duna helada’ (frost dune). The grainsize gradation is clearly visible Frosted Dunes (Dunas heladas).

its base, in the periglacial landscape of the Barrancas Blancas Valley. “Dunas heladas” were also found in Victoria Land and were studied by Selby et al. (1974). It should be noted that in the present case their cryogenic origin through cryogenic weathering is affecting the pumice formations. The sand cover of the “dunas heladas” is loose and sorted. It represents the active layer and reaches a thickness of up to 70 cm. The lateral parts show an active layer thickness of up to 46 cm. Similar values have been registered at various frosted dunes in the main valley of the Valle de Barrancas Blancas. It is worth mentioning that their structure resembles that of classical desert dunes.

The layers of cryosediments at the peak of the dune are subhorizontal and the flanks preserve the angularity of the asymmetrical slopes, but due to the lee effects on the extended slope and to that of the windward side, in a rather limited and abrupt way. The frequent, nearly daily winds loaded with sediments and snow are either impeded or rasp on their way and produce an accumulation of sediments, in this case cryosediments (as they are the product of rocks from cryogenic weathering) and snow.

The permafrost table of dunas heladas shows an oblong perimeter and a relatively stepped tendency at the lee side, presumably associated to different accumulation events of snow during various episodes which have gradually been transformed into ice. In some sectors apparently more intense than in others, the presence of massive ice in form of cores or “eyes” within some parts of permafrost has been detected. The snow has delivered the percolated melting water which intruded into the upper part of the permafrost and enriched it with ice.

4 Conclusions

Studies of this periglacial environment are crucial for the understanding of past environments such as the Tundrean paleoenvironment of Patagonia (Trombotto 2002) and that of the European Doggerland. At the same time, this kind of research gives excellent clues for the comprehension of extraterrestrial environments. Furthermore, they have an impact on the exploration of the urgently needed water reserves in the High Atacama.

Note: as observed during a field check in 2017 the formerly remote and untouched area had become a subject of mineral exploration. Hence, the condition described in this paper present conditions which do not exist anymore.

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