Characteristics of two Rock Glaciers in the Dry Argentinean Andes Based on Initial Surface Investigations

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ABSTRACT
At high elevations of the Argentinean and Chilean Andes permafrost conditions can frequently be found in various forms. Its characteristics are of great importance to any development in these areas, particularly the role of the ground ice within the hydrological cycle. Preliminary investigations were initiated by Xstrata Copper San Juan, including surface geophysics, shallow boreholes, ground temperature monitoring, and test pit excavations. With focus on two active rock glacier, multi-faceted investigations confirmed the permafrost setting and evidenced presence of subsurface ice. These initial results help studying the hydrological setting of the El Pachón valley of the San Juan Province, Argentina.

RÉSUMÉ
À haute altitudes de l'Andes de l'Argentine et du Chili pergélisol peuvent être trouvées fréquemment dans diverses formes de pierres sèches aux sols riches en glace. Les caractéristiques et les conditions son d'une grande importance pour les développements dans ces domaines, en particulier le rôle de la glace de sol dans le cycle hydrologique. Enquêtes préliminaires ont été initiées par Xstrata Copper San Juan, y compris de la surface géophysique, de forage peu profonds et de surveillance de la température au sol, et les tranchées de test. Glaciers rocheux actif et les conditions de pergélisol riche en glace ont été confirmés dans la vallée El Pachón de la province de San Juan, Argentine.

1 INTRODUCTION

In the dry Andes of Argentina and Chile, permafrost conditions frequently exist at high altitudes. These permafrost conditions range from dry rock to ice-rich soils. The ground ice in these latter permafrost zones is often the only source of multi-year ice in the absence of substantial surface snow and ice areas, such as glaciers or perennial snow patches. In fact, Ammann et al. (2001) noted for desert Andes that today the limiting factor for glaciers to exist is exclusively the lack of humidity, not temperature. In combination with geo-topographical settings, these climatic conditions are favourable for the formation and preservation of rock glaciers[1]. Several talus and valley shaped rock glaciers as well as protalus ramparts can be found, at different evolution stages.

A characterisation of high Andean permafrost, in particular ice-rich conditions, which may be found in active rock glaciers, is of great importance to potential mine developers and regulators. The role of the existing ground ice within the hydrological cycle and in the general regional hydrology needs to be understood in detail for proper environmental assessments or feasibility studies.
Xstrata Copper San Juan initiated a periglacial environment investigation program to better understand rock glacier behaviour. Two rock glaciers were therefore analysed in more detail. The rock glaciers are located within the El Pachón valley in the San Juan Province, Argentina, which is part of the study area for the proposed mine development and located about five kilometres from the Chilean border (Figure 1). Copper and other metals were discovered in the area in 1964. Since then, several companies have carried out geological, environmental and economic studies to evaluate the possibility of extracting ore from the deposit. Pre-feasibility work conducted by Xstrata Copper has included an extensive drilling programme, geotechnical studies, hydrogeological studies and environmental baseline studies in both Argentina and Chile. Today, next level studies for a future mining operation to be permitted are in preparation.

This paper presents the findings from initial cryosphere investigations that included near surface geophysical investigations, shallow boreholes and ground temperature measurements, as well as test pit excavations.

[1] Some authors prefer to use the term *rockglacier* as suggested by Barsch (1996) to better differentiate them from 'normal' glaciers. For this paper we decided to go with the NSDIC definition proposed by van Everdingen (1998).

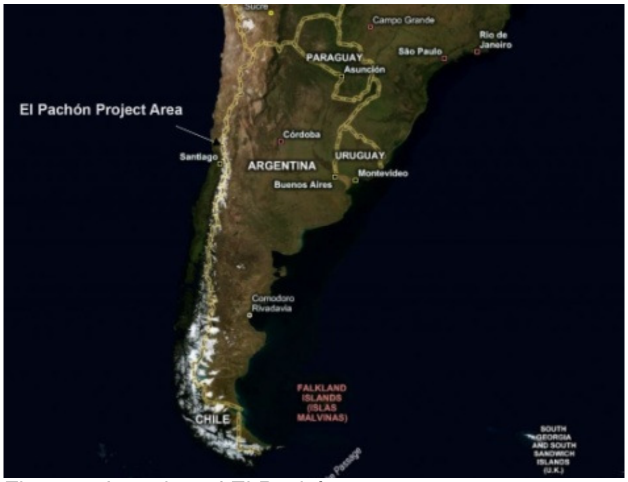

Figure 1. Location of El Pachón.

2 CRYOSPHERE INVESTIGATIONS

Current cryosphere investigations concentrated on providing data and information to be used in the environmental impact assessment and feasibility studies. No detailed investigations were carried out, for example, tailored towards mine development, pit slope designs, access route or pipeline routing. However, the data currently available will become an important basis in the development of any future study and therefore the initial planning also must keep this staged approach in mind. In this paper we concentrate on two rock glaciers located within the project area and information will therefore be primarily presented on these two locations.

2.1 Aerial Images and Surface Geomorphology

Several periglacial features, such as rock glaciers, gelifluction slopes and patterned grounds, were identified in the project area that clearly indicate the presence of permafrost. The area is located in a mountain permafrost environment (approximate continuous permafrost, Trombotto Liaudat et al., 2010) where the lower permafrost boundary varies in elevation as a function of air temperature and solar radiation, which is controlled by the topography, the aspect and the slope angles. Further, potential snow accumulation and surface characteristics play a role in the permafrost distribution.

Numerous rock glaciers have been identified in the area from high resolution aerial images (Figure 2) but also from satellite images (e.g. LandSat 7). Figure 3 shows a rock glacier that is probably active located in the Pachón Valley. Most likely the majority of the rock glaciers in the area are still active, i.e. they contain ice-rich zones and are creeping downslope. However, without any measurements, the amount of deformation as well as the deformation pattern cannot be determined. Often active rock glaciers are located at the lower elevation boundary of permafrost with the source area situated within a permafrost environment and the toe at an elevation where no ice-rich permafrost would form under current climate conditions and scarce permafrost in isolated patches would occur. Active rock glaciers are therefore helpful indicators to determine the permafrost limits in the area. It may be possible that some rock glaciers in the area are inactive (no deformation) or even relict (no ground ice). But additional investigations would be required to gain a better overview on the local rock glacier dynamics, which is not of importance to the project at this stage.

In addition to the rock glaciers, which can often be located from aerial images, several additional periglacial features were identified in the field and used as indirect indicators for the existence of permafrost (e.g. French, 2007). These include gelifluction slopes (Figure 4), detachment failures (Figure 5) or patterned ground (Figure 6). Detachment failures are failures in the active layer resulting from thermal disturbances or water flow. Several sorted ground features were recognized in the area. However, such forms only occur due to frost action, which requires soil moisture, fines and typically a hydraulically impermeable layer (permafrost table). Based on the surface expression alone, it is not possible to determine the volumetric ice content of the soil.

2.2 Climate Data

Due to its high elevation and geographic location, the climate of the study area is in general a tundra climate characterized by a thermal field with a strong topoclimatic component because temperatures mirror the spatial field of the contour lines of the topography at elevation. During the austral summer months, the mean temperature can reach 9ºC while in winter the mean temperature descends to -7ºC, with extreme minimum temperatures reaching -20ºC. The annual mean temperature is 1.3ºC.

Active weather fronts occur mainly in winter associated with the passage through the area of low pressure zones that move overhead from the Pacific Ocean with winds blowing from the north to northwest and releasing their moisture content in the form of snow. This gives rise to a regime of precipitation that is primarily of nival nature and is concentrated in the winter months when the maximum precipitation occurs. According to data extrapolations to the study area, total precipitation is estimated between 300 and 400 mm per year.

The circulation pattern for weather in the study area is strongly influenced by the Subtropical high pressure center of the Southern Pacific, which results in very clear skies in this area with low humidity and predominant west and southwest winds at annual average wind speeds of 3 m/s (10.8 km/h) and with monthly maximum gusts of 26 m/s (93.6 km/h). The atmospheric pressure at the elevation of the station averages 664.2 HPa, and the average relative humidity is 31%.

Figure 2. Aerial view of parts of the project area (section is approximately 4.7 km x 2.8 km). Various rock glaciers and protalus ramparts are indicated with arrows. Rock glaciers 1 and 2 are the focus of this study.

Figure 3. Unnamed active rock glacier located in project area.

Figure 4. Typical gelifluction slope.

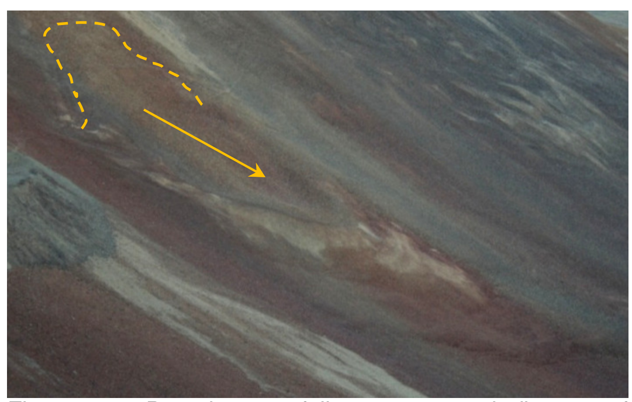

Figure 5. Detachment failure as an indicator of permafrost.

Figure 6. Patterned grounds found in the project area: a) sorted stripe; b) sorted circles.

Making use of the climate classification according to Koeppen (1948), the type of climate at El Pachón area can be characterized as "Tundra" (ET), i.e., an Andean upland type of climate with occurrences of precipitation predominantly in the form of snow, with a maximums in the wintertime, very cold winters, and summers with cool nights and persistent occurrences of winds of high wind speeds.

Air temperatures recorded on rock glacier #1 at an elevation of 3872 m above sea level are presented in Figure 7. During that period, the mean air temperature was -6.5℃ and 252 mm of precipitation were recorded.

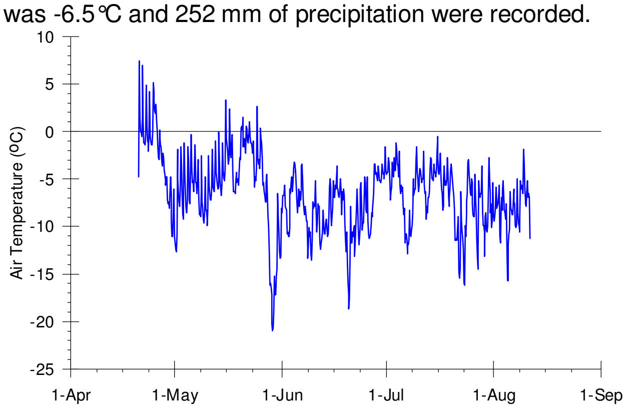

Figure 7. Air temperatures recorded on rock glacier #1 (20. April – 15. August, 2008).

2.3 Ground Temperature Data

Some active layer ground temperature data are available for rock glacier #1. Figure 11 shows temperature profiles based on measurements at three depths from April to August 2008. The depth of the active layer is estimated at about 2.5 m. No summer measurements are available yet to confirm this estimate.

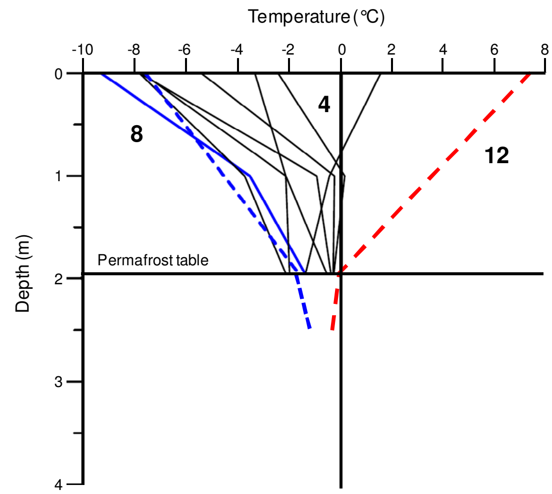

Figure 11. 2008 Rock glacier #1 ground temperature measurements. The dashed lines indicate an approximation of the estimated temperature range in the active layer.

2.4 Test pits

Three test pits were excavated in and around rock glacier #2 (Figure 2). Test pit 1 is located just at the front, Test pit 2 in the centre and Test pit 3 is located above the beginning of the rock glacier. This rock glacier has been subjected to human activity in the past. The geophysical lines crossed at these locations and could therefore be used for calibration. Because all test pits were excavated on a road, the original surface was already disturbed and the measured depth of the permafrost table does not correspond with the original depth. The actual depth was estimated based on the road cut at the location of the test pit.

Figure 8 to Figure 10 show various samples. High ice contents (>50%) were recorded for all test pits. It was noted that the soil in the lower part of the rock glacier (Test pits 1 & 2) is coarser (gravel and cobbles) than the soil found in Test pit 3. Test pit 3 samples even contained clay size material, which results in a high content of unfrozen water at temperatures of just below 0℃. The sample shown in Figure 10 was very soft and could be broken easily, compared to the other samples where the frozen soil was very hard and difficult to excavate. Further, materials found in the frozen layers from Test pit 1 and 2 seem to be poorly graded in contrast to the well graded material found in Test pit 3. Based on an estimated void ratio of 0.3, the volumetric ice content of the sample shown in Figure 10 is about 65%.

Water accumulated on top of the permafrost table in Test pit 2 (Figure 9), which is an indicator of water flow on top of the permafrost, i.e. on the permafrost table. Even though solar radiation was intense at that time of the year the water observed was thought to not originate from ground ice thaw. It was further noted that only the very top (5 to 10 cm) of the active layer was dry with most of the ground being moist. This indicates the capacity of the active layer as a temporal aquiclude. The high moisture content further acts as a thermal insulator because of the latent heat effect (e.g. Andersland and Ladanyi, 2004). This prevents the active layer from penetrating deep into the ground, hence protecting the frozen ground / permafrost. An overview of the three test pits is given in Table 1.

Table 1. Rock glacier #2 test pit overview.

Test Pit	Active Layer	Comment
1	~3-4 m	Massive ice and ice-rich gravel – cobbles, poorly graded material in the permafrost and active layer, i.e. no fines.
2	~3-4 m	Massive ice and ice-rich sand – cobbles, poorly graded in the frozen part, but ~well graded in the active layer. More fines than in Test pit 1. Water accumulation on top of permafrost table.
3	~3 m	Ice-rich ground, clay to gravel size particles, well graded. No massive ice was found. Volumetric ice content: ~65%.

Figure 8. Samples from Test pit 1. Note the air bubbles and sandy - silty inclusions of the interstitial ice (top). The tape measure is in cm.

Figure 9. Sample from Test pit 2 (top). Also note the water flow on top of permafrost table (arrow).

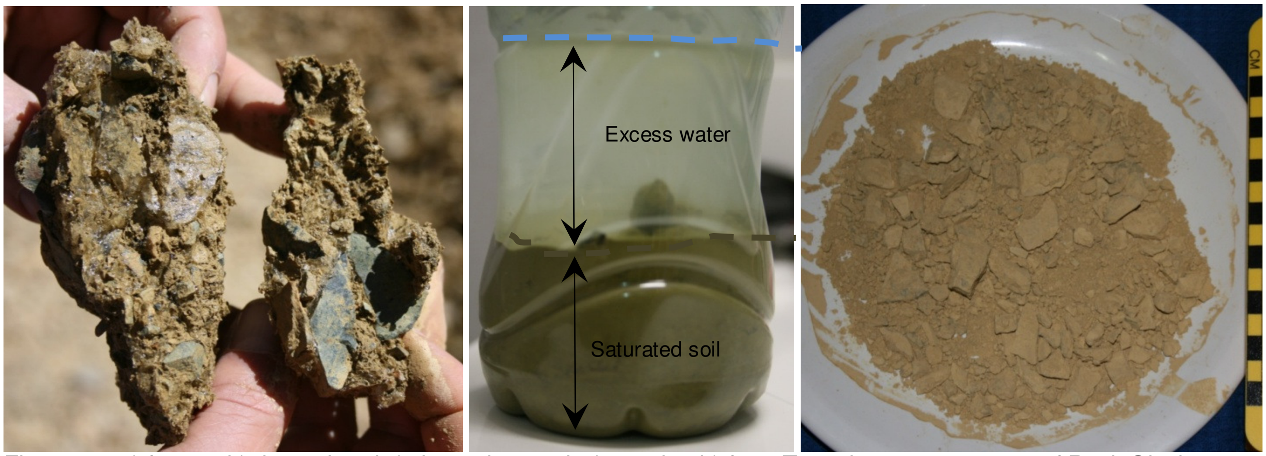

Figure 10. a) frozen, b) thawed and c) dry grab sample (~3m depth) from Test pit 2 at upper zone of Rock Glacier #2.

2.5 Near-Surface Geophysics

Five seismic refraction tomography lines (in total: 1,390 linear meters of P-wave refraction seismic tomography survey) and 50 vertical electrical soundings (VES) were carried out in three investigation zones. To carry out the seismic tomography surveys, a 24-bit Delta Sigma digital data acquisition system by SUMMIT (DMT GmbH Product) was used. The 2-channel receivers (Remote Unit/RU) are linked with the central recording station (Standard PC or Laptop) via a simple two-conductor line wire (PCM-cable) anywhere along the transmission cable. Every 250 m a special amplifier unit (RP) is added. Each channel consists of an automatically controlled Pre-amplifier, an analog High-Cut Filter, an A/D-Converter and a high performance 24-Bit Delta Sigma Processor. This circuit allows high speed data conversion, digital signal filtering and has a dynamic range of more than 130 dB. Further details are provided in Table 2.

Table 2. Refraction seismic recording geometry.

Geophone spacing	10 m
Source spacing	20 m
Geophone type	8 Hz Geospace (single)
Spread layout	16-20 active Channels
Seismic source	10 kg Sledgehammer
Recording length	256 ms
Sample rate	0.5 ms
Gain factor	Automatic gain control

To carry out the resistivity surveys the digital data acquisition system OHMEGA (Allied Associates Geophysical Limited Product) was used.

Rock glacier #1 was covered with three seismic tomography profiles. Further one VES-Cross-section was carried out using 14 soundings. Rock Glacier #2 was covered with two seismic profiles. Nine VES were carried out directly on each of these seismic lines. Two additional VES-Cross-sections were carried out in this zone with 12 and 3 soundings, respectively.

The results of the seismic tomography and VES carried out on rock glacier #2 are presented in Figure 12. 50 Iterations were used. It also has to be noted that the presented section only shows the eastern half of the whole profile.

The geophysical survey clearly indicates a 2 to 3 m thick layer consisting of well graded cobbles, gravels and sand with some fines. This layer was interpreted as the active layer and corresponds well with the test pit observations. The eastern most part shows an increase in this layer thickness which is corresponds with the side boundary of the rock glacier. The VES show a high resistivity layer (94 – 113 kOhmm) below the active layer with a thickness of about 10 m. This layer is underlain by a thin (1-2 m) thick high resistivity zone (>1 MOhmm). The P-wave velocity, *Vp*, of the refraction survey profile indicates a layer with velocities between 2,000 and 4,000 m/s, which is typical for frozen sediments (Kneisel et al., 2008). The upper part of this potentially frozen layer shows seismic velocities that indicate ice-rich soil conditions, probably gravels and sands, whereas the slightly higher velocities in the lower part of the permafrost layer indicate massive ice and/or rock material. Drillhole P-016, which is located 20 m from the survey line, indicates a bedrock depth of 11 m, which is used as a reference to calibrate the seismic velocity profile. In this cross section, the rock glacier is therefore estimated to be approximately 10 to 15 m thick, including the active layer (2 – 3 m).

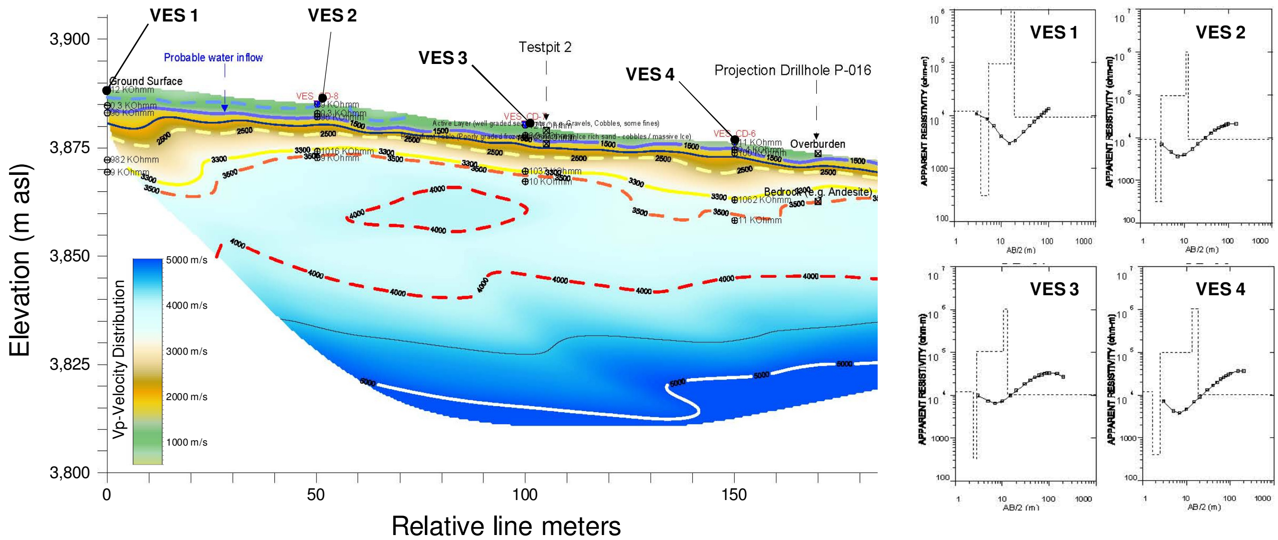

Figure 12. Surface refraction tomography and VES results. Survey carried out in the centre of rock glacier #2, perpendicular to the flow line. The figure only shows the east half of the survey. Drillhole P-016 is located 20 m from the survey line.

3 DISCUSSION

Interpretations of aerial photographs and satellite images, visual inspections, test pits, shallow boreholes with some ground temperature measurements and surface geophysical investigations on two rock glaciers located in the El Pachón Project development area, provide valuable information on the internal characteristics. However, only deep geotechnical boreholes and detailed borehole investigations, including core extraction or in-hole geophysical investigation would allow for a detailed, unambiguous analysis. Even though there are uncertainties in these results, it can be assumed with great certainty that the analysed rock glaciers are active, i.e. down-slope permafrost creep of up to some decimetres per year may occur. This conclusion can be made based on the ice-rich conditions found in the test pits in combination with the geophysical sections and frontal characteristics. The frontal slopes are at the angle of repose with over-steepened tops (Figure 13).

Figure 13. Rock glacier #1 front.

The seismic refraction profiles and VES presented in Figure 12 indicate that rock glacier #2, for example, is about 10 – 15 m thick, consists of a 2 – 4 m thick active layer and the upper part of the permafrost body is likely slightly less ice-rich than the lower part. Latter might even consist of massive ice. Active layer thicknesses in the order of 2 to 4 meters are typical for coarser rock glacier surfaces (Trombotto et al., 1999; Arenson et al. 2002; Trombotto and Borzotta, 2009). A low resistivity layer at the bottom of the rock glacier may be an indicator of a porous layer consisting of blocky material without pore ice. Such a high permeable layer was also found at the base of rock glacier Corvatsch in the Swiss Alps (Vonder Mühll et al., 2003). Temperature measurements confirmed seasonal temperature variations in this layer that are likely caused by water or air flow. Similar conditions may exist at other rock glaciers in the Pachón Valley region. It has to be noted that such a layer may form an ideal ground water flow zone. Water that can be seen at the rock glacier front might, therefore, be attributed to ground water flow from higher altitudes that passes through that layer below the permafrost base and is not related to any permafrost thaw / degradation. The source of this water may therefore be significantly different from what is often observed at the front of glaciers, where the water origins from direct glacier ice melt.

Most rock glaciers in the area are located on south facing slopes. Because these slopes are better protected from incoming solar radiation the permafrost boundary is lower than on the slopes with different aspects. The elevations of the rock glacier fronts in the area varied typically between 3750 m ASL and 3850 m ASL, which is thought to be the lower elevation boundary where permafrost is possible. Larger rock glaciers may subsist at lower elevations because of their significant amount of ground ice compared to smaller ones.

Extrapolating details from one rock glacier to all the rock glaciers in the area is not recommended because every rock glacier is unique in terms of its micro-climate conditions, thermal regime, source zone, geomorphology, topography, or geological setting. However, in general, it can be assumed that ice-rich conditions prevail for south facing rock glaciers above 3800 m ASL. This would indicate that most rock glaciers in the area are active. Even though this is thought to be realistic, only long-term deformation monitoring will offer a definite answer, in particular information on creep rates.

4 CONCLUSION

Studies on the internal structure of rock glaciers in the dry Andes are scarce, but needed for mine development projects. The complexity, uniqueness and heterogeneity of rock glaciers make it even more difficult to judge their status, including potential ice content, compared to glaciers. In order to better understand some rock glaciers in the El Pachón Valley, Argentina, near surface geophysical investigations were carried out on two rock glaciers in combinations with test pits. Overall, the internal structure of the rock glaciers investigated show active layer thicknesses of 2 to 4 meters and total rock glacier thicknesses of up to 25 m. The upper layers of the permafrost body may be slightly less ice-rich than the lower layers, but generally ice-rich conditions are expected. It is further likely that a porous, unfrozen zone exists in-between the bedrock and the permafrost base.

Even though it is not possible to conclusively say whether the investigated rock glaciers are active or not without deformation measurements, it is likely that they are. The increased ice content closer to the permafrost base also would suggest that the majority of deformation occur at these depths.

The active layers are found to be good aquicludes. Despite the dry air conditions, moisture can accumulate in the layer just above the permafrost table. In addition with the potentially highly permeable layer at the permafrost base it can be concluded that water run-off that may be observed at the front of a rock glacier is likely related to annual snow melt cycles rather than any permafrost thaw, i.e. degradation.

However, based on these initial findings, additional studies, including long-term monitoring is required in order to better understand characteristics and dynamics of the rock glaciers investigated and obtain quantitative information on any ground ice thaw. Although it is not recommended to simply extrapolate the information from these two rock glaciers to the whole area, the study provided valuable information on rock glaciers in the dry Andes that should be used to further future studies.

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