**Current thermal state of permafrost and potential impact on the El Niño Southern Oscillation (ENSO) in the Southern Peruvian Andes**

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**1. Abstract**

Tropical, high-mountain permafrost has a unique thermal regime due to its exposure to strong solar radiation and to the rougher surface snow morphology (due to an increased occurrence of penitentes -- that is, snow spikes and ridges ranging from centimeters to meters in height) which reduce convective sensible heat transfer from the surface. Latent heat transfer and higher albedo occurring during the wet season contributes to positive feedback that supports the presence of permafrost. This preliminary study reports on the thermal state of Peruvian permafrost. It evaluates the potential combined impact of the El Niño Southern Oscillation (ENSO), along with the eleven-year solar cycles of Coropuna (15°32′S; 72°39′W; 6,377 m a.s.l.), and the Chachani volcanic complexes (16°11′S; 71°31′W; 6,057m a.s.l.); both mountains are located in the western Central Andes (e.g., west edge of the Altiplano). Temperature monitoring boreholes were established at 5217m on Coropuna and 5331m at Chachani, and electric resistivity was surveyed to better understand permafrost spatial distribution in these locations. This seven-year record of permafrost temperature data encompasses historically extreme El Niño and La Niña events. Our results show that the current lower-altitude permafrost boundary (ca. 5100m) is critically influenced by the balance of wet and dry seasons: permafrost tends to deplete during drought years. Typical permafrost thickness was 10-20 m and contained ice-rich pore spaces. The presence of permafrost and its thermal resistance depends on ice content and on higher albedo, usually due to pyroclastic materials (especially pumice) which are ideal materials for supporting permafrost resilience.

**2. Introduction**

Tropical high mountain permafrost was reported in Mauna Kea, Hawaii (Woodcock 1974, Schorghofer et al., 2017, Yoshikawa et al 2013), Iztaccíhuatl, (Andrés et al. 2011a), Pico de Orizaba, Mexico (Vizoto 2018), Kilimanjaro, Tanzania (Yoshikawa 2013) and the Southern Peruvian Andes (Yoshikawa et al 2013). Typically, the lower boundary of the permafrost is reported to be around 5100m on the polar-facing side slopes (between 15°-23° degrees N and S) and 5750m or higher at the equatorial-facing side slopes, where the mountains between the Tropic of Cancer and the Tropic of Capricorn are located. Mauna Kea was a little exceptional in that a pocket of isolated ice-rich frozen soils was reported at the bottom of the cinder corn, near the summit (ca. 4300m). This was considered a result of the unique microclimate cooling and the presence of ice-rich, bonded permafrost which better resists thawing (Woodcock 1974). In order to understand the thermal state of tropical mountain permafrost, we consider five differential conditions, each quite different from those affecting permafrost in the polar regions: 1. A minimal seasonal temperature variation (minimal active layer) that makes thermal offset unlikely; 2. Maximum daily temperature variation at the surface (sometimes over 40°C difference between day and night); 3. Strong short-wave (solar) radiation; 4. The importance of the wet/dry seasons in the presence of penitentes (the snow spikes and ridges create a strong surface thermal off-set; see Figure 1); and 5. The low atmospheric density affects the surface heat budget. Along with these unique phenomena, we considered how tropical permafrost was affected by climate change on the centennial-millennial scales (e.g., glaciation, inter-glaciation cycles, and the Little Ice Age) (Saito et al. 2016). Since the Little Ice Age or older cold periods, tropical high-mountain permafrost is thought to be due to a critical balance between formation and persistence. This paper discusses all these considerations, including current climatic cycles and conditions such as precipitation impact.

**Study area**

Coropuna and Chachani are two volcanic complexes located in the western part of the Peruvian Andes, on the northern boundary of the Central Volcanic Zone (Stern, 2004). (Figure 2). Nevado Coropuna is a complex of five volcanic summit cones exceeding 6000 m altitude (Mariño et al., 2018). These stratovolcanoes are covered by the most extensive glacial system in the tropics (Kochtitzky et al., 2018; Úbeda et al., 2018). The glacier system surface area in 2010 was S2010=~46 km2; its Equilibrium Line Altitude (ELA) in the same year was ELA2010=5984 m, and the past ELA depression was much greater than at present, almost 1000 m during the late Pleistocene (Úbeda et al., 2018). Almost all of the Coropuna lava flows are completely glaciated or cut by glacial valleys. However, there are also three lava flows (west, northeast, and southeast of the summit areas) which have been eroded only by the latest glacial advances. Those lava flows have been dated by 3He and 36Cl at ~6.0, ~2.0 and ~0.7 ka respectively, supporting evidence of recent volcanic activity at Coropuna (Mariño et al., 2018; Úbeda et al., 2018; Úbeda et al., 2012).

About 140 km southeastward of Nevado Coropuna is Nevado Chachani, immediately northeast of Arequipa city (2560 m in altitude at the airport), whose suburbs are close to large lava flows from this volcanic complex. Taking into account the ELA at Coropuna (Úbeda et al., 2018), the absence of current glaciers in the Chachani is probably due to the altitude of the volcanic structures, which is just on the threshold delimited by the regional ELA (~6000 m). However, it is possible that there were glaciers in these mountains during the Little Ice Age, and the geomorphological evidence suggests that the ice tongues reached at least 4000 m in altitude at the Last Glacial Maximum (Andrés et al., 2011b). Previous publications deduced the extension of the periglacial conditions in the region from the air temperature (Richter, 1981; Troll, 1944, 1959) and from thermometers buried in the ground since 2004 (Andrés et al., 2011b), whose records have also been used in this work.

Both study site topographies are heavily characterized by formed penitentes (Figure 1) during most of the summer months. Penitentes are unique features of tropical high mountains where stronger solar radiation waves and heterogeneous ablation processes form pinnacles. They are considered to contribute to local ground temperature regime. The general direction of these pinnacles is upward, toward maximum solar radiation. Modeling suggests that penitentes enhance conservation of snow cover, and the consequences of penitente loss might be increased ablation over the whole season (Betterton, 2001; Cathles et al., 2014). The increased ablation increases the amount of incoming short wave radiation available to latent heat transfer, and thus the underlying ground stays cooler. Also, the topography produced by multiple tall penitentes can create a micro-climate that develops convective heat circulation, pushing warmer air up during the day and causing colder air to sink at night. This paper focuses on periods of penitente snow cover and ground temperature patterns to understand the thermal state of permafrost areas in the tropical Andes.

**3. Materials and methods**

Permafrost boreholes were drilled at 5217m in Nevado Coropuna (3m deep) and at 5331m in Nevado Chachani (4.2m deep) respectively, and permafrost temperatures have been monitored since 2012; later (2014 and 2018 respectively) electric resistivity tomography was performed to understand special distribution of the permafrost in these areas. A comparison of annual mean ground temperature (30cm below ground) versus each elevation point was used to determine the lapse rate and the lower boundary of the permafrost. Due to the lower air density, sensitive heat flux is minimal at this elevation. As a result, air temperature and ground surface temperature differ significantly, typically by 5-10°C. For accuracy in understanding the location of the permafrost boundary, we measured, in hourly intervals year-round, temperatures 30cm below the ground surface, collecting data since 2008 at both Coropuna and Chachani.

DC resistivity sounding was conducted, along with two-dimensional resistivity profiling (IRIS instruments; Syscal pro R1 24-48 channel) for this investigation using the Wenner electrode configuration. The tomography line was mapped to cross the borehole sites using ground control points. The electrical resistivity of soil depends on the soil type, temperature, water content, porosity, and salinity. In general, the resistivity (ohm-m) values of frozen soil are 10-1000 times greater than that of unfrozen soils (Harada and Yoshikawa 1996). DC resistivity sounding uses four electrodes for measurement. A current (I) is delivered and received between the outer electrodes, and the resulting potential difference (V) is measured between the inner electrodes. For this array on the ground surface, an apparent resistivity a (ohm-m) is calculated from:

a= 2a V/I (1)

where ‘a’ is the distance separating the electrodes. Inversion analyses were performed with changing values of resistivity and layer thickness by using the linear filter method (Das and Verma, 1980) for a one-dimensional investigation. For acquisition of two-dimensional apparent resistivity data, we used multi-channel, equally spaced electrodes with a standard spacing of five meters. Each measurement was repeated up to 16 times, depending on the variance of the results. Two-dimensional model interpretation was performed using the software package RES2DINV (Geotomo software), which performs smoothing and constrained inversion using finite-difference forward modeling and quasi-Newton techniques (Loke and Barker, 1994). Surface geology for the Coropuna site was lava, boulder, and less fine materials. The site was so dry that the contacting electrodes needed extra saltwater for operation.

Stable isotope samples were obtained during drilling operations at Chachani and Coropuna. The permafrost layers showed 20-40% ice content by volume, along with more pore space and permeable materials. Ice-bonded permafrost ice seems "injected" into the pore spaces rather than formed through segregation processes. At the same time, various water samples were obtained from local sources, such as precipitation, snow and penitente formations, glacier ice, and spring water. The stable isotope samples were analyzed at the Alaska Stable Isotope Facility, Water and Environmental Research Center, University of Alaska Fairbanks, using the Pyrolysis Elemental Analysis-Isotope Ratio Mass Spectrometry (pyrolysis-EA-IRMS) DeltaV system.

In this method, a sample is pyrolyzed into H2 and CO gases then separated chromatographically. These gases are then transferred to the IRMS, where the isotopes are measured. δ2Hv-smow and δ18Ov-smow values are reported in reference to international isotope standards. The typical quality control scheme involves analyzing laboratory working standards every seven replicate samples. Each sequence batch is calibrated to NIST standards to confirm quality assurance. NIST Standards are analyzed in replicate throughout the sequence.

The degree of the sublimation was evaluated by calculating a deuterium excess *d* (*d*-excess) parameter (a reference on the method is needed):

*d*-excess = 2H -818O (2)

National weather station data was obtained from the Chichas (15°32′51”S; 72°55′05”W; m a.s.l.) and Yanaquihua (15°46′29”S; 72°52′34”W; m a.s.l) stations (Figure 2); the record ranged from 1964 to present. Daily precipitation and temperature data are available for the entire 54-year period.

**4. Results**

**4.1. Ground temperature lapse rate**

Temperatures at a ground depth of 30cm show no daily fluctuations and are more reflective of permafrost conditions. Figure 3 shows annual mean ground temperature versus elevation for each mountain’s slope aspects. In general, the ground temperature regime shows a linear relationship with altitude. This simple trend line was used to predict the location of the permafrost lower boundary. Measurements began at 4000m or higher to avoid the local temperature inversion layer.

The elevation where the temperature curve crossed 0° C was about 5100m on the south-facing slopes for both mountains that indicated around 5100m to the lower permafrost boundary. However, the 0°C crossing elevation was much higher on north-facing slopes; data suggests that here permafrost would appear at 5750m or higher.

**4.2. Borehole temperature profile**

Maximum, minimum, and average borehole-temperature profiles are shown in Figure 4. While the data still describe a trumpet curve, the characteristics of the tropical ground temperature profile is unique and unlike those found in polar regions. In tropical areas, the annual temperature variation is minimal, but daily temperature fluctuations are quite large. At both study sites, at 1m depth, the annual temperature amplitude is 0.2°C (Coropuna) and 2.0°C (Chachani). The daily (day and night) temperature amplitude is over 40°C during the dry season. However, this daily temperature fluctuation penetrates the ground surface only to a depth of 5 to 15cm, and this layer undergoes frequent freeze-thaw cycles. The ground surface is marked with a pattern of stripes and formed needle ice, indicating this daily freeze/thaw activity.

At the Coropuna borehole site, at 1-3 meters' depth, the permafrost temperature was already at the thawing point (e.g. zero curtain). This indicated that this borehole was established close to the lower boundary of the permafrost zone. As the tropical region demonstrates less seasonality and little or no organic layer over the permafrost, no active layer thermal offset was observed.

**4.3. Resistivity tomography**

Permafrost thickness was shown to be around 10m at the Coropuna borehole site (Figure 5a), and the active layer was over 1 meter thick. At the Chachani borehole site, the permafrost thickness was shown to be around 15m (Figure 5b). Frozen ground at this site was covered with ice-rich pumice and the active layer was 10-30cm.

DC resistivity profiling results were quite favorable (Figure 5a for Coropuna and 5b for Chachani), revealing the presence of an ice-rich pumice layer. An ice resistivity of 7500ohm•m was obtained, which is a reasonable value. Resistivity studies permit better investigation of the detailed subsurface structure, especially distinguishing the frozen layer and the lower boundary of the permafrost. The permafrost distribution and thickness showed a relatively good correlation with the surface albedo and slope aspect. At Chachani, permafrost was observable in the white pumice/tuff layer.

**4.4. Albedo & snow**

Figure 6 shows an explanation of the one-meter depth ground-temperature regime observed in 2013 with different slope aspect and different albedos. All sites are spaced no more than 20m apart horizontally, and the data show the borehole site at its warmest conditions. The south-facing slope next to the borehole site (southeast-facing ridge) is much colder (average temperature -1.5°C) and is snow-covered two months earlier than the borehole site. Higher winter ground-temperature spikes such as those recorded during early September indicate that bigger penitentes developed on the south-facing slope site. Higher albedo (50%) at a site with the same slope aspect as that of the borehole site resulted in slightly colder temperatures than those recorded at the borehole site all year around (average temperature -1°C). This also indicated the importance of the surface albedo (e.g. incoming shortwave flux) for the thermal state of the permafrost ground temperature.

**4.5. Stable isotopes from permafrost**

Figure 7a shows results of the oxygen and hydrogen stable isotope analysis. Most of the local water sources (snow, glacier ice, cold and hot spring waters) aligned with the local meteoric waterline (which has a 7.5 slope). However, both oxygen and hydrogen stable isotope results from permafrost ice indicated heavier isotopes than those found in current precipitation and in values off those of the local meteoric line. This indicates that the water from the ice-rich permafrost core is possibly remained as water after long time, undergoing evaporation/sublimation processes (Figure 7b). These results suggest percolation of snow meltwater that originated from the long-enduring penitentes as well as from well-aerated snow. Consider also that the estimated original snow isotope-concentration of oxygen reaches to -13 parts per mil (ref), which could be a much heavier isotope than that found in today’s snow precipitation. The heavier isotopes found in the permafrost might therefore suggest more active atmospheric circulation, or a closer original source of water.

Figure 7c shows the relationship between *d-excess* versus deuterium. The *d*-*excess* is strongly affected as evaporation or sublimation takes place. When humidity is low, the vapor is strongly depleted, and the deuterium excess *(d)* reaches or exceeds 10. All local water sources (snow, precipitation, groundwater) showed some relationship to higher evaporation or sublimation processes (e.g. *d-excess* exceeds 10). However, the permafrost ice samples were all below 10, which points to snow meltwater as a more likely origin.

**5.0 Discussion**

**5.1 Penitente effect**

The general direction of these penitente pinnacles is upward, toward maximum solar radiation, resulting in a very rough surface. Simple heat budget components appear in Figure 8. Penitente topography may increase or maintain higher albedo, and therefore more latent heat, causing continued heat loss from the soil surface, which may develop more moisture, which in turn contributes to ice-rich soils.

For penitente-based topography, any snow cover remaining more than several weeks could form penitentes at this latitude and altitude. In summary, snow cover (or we might specify "penitente cover") has a huge impact on maintaining conditions favorable to permafrost conservation. Without this highly irregular snow surface, the result is dramatically warming ground (see Figure 8) and degrading permafrost.

Snowfall typically occurs in early summer months in the Chachani and Coropuna study areas. Typically, snow precipitation events result in penitente-rich snow cover that lasts for the rest of the following summer months. The timing of the precipitation and summer season (the higher angle of the solar radiation) found in the Peruvian Andes is well-suited for protecting, or even forming, new permafrost, where, under ideal conditions, the ground stays cool and permafrost remains. Also, most of the penitente-rich snow cover remains until the following winter, maintaining ground surface (at the transition between the bottom of the snow cover and the ground) temperature near the thawing point (0°C) throughout the summer months. In winter, ground surface temperatures can drop to below freezing. Penitente cover does not insulate the ground like other types of snow cover do, but it does block solar radiation and promote cooling of bare ground. Figures 9a and 9b show, for 2012-2014, ground temperatures to be stably cold (or at 0°C); however, the site had little to no snow cover in 2016 (the beginning of a La Niña event), and during that period ground temperature significantly fluctuated and average ground temperature increased. This data indicates that during the low-snow conditions characterizing the El Niño to La Niña period, significant ground warming occurred.

Tropical high-altitude ground surface forms a unique heat-budget structure compared with other areas that contain permafrost, especially those within the polar regions. Firstly, seasonal temperature variation is minimal (e.g. typically 2-5°C) instead of the 80°C typical of Interior Alaska or Eastern Siberia. Under tropical high-altitude conditions, the active layer thickness is minimal (a few cm to 20cm); with little to no thermal offset in the thin active layer, and there is no buffer zone provided by an organic layer or vegetation cover. The ground thermal conditions are found in terms of the surface energy balance (Williams and Smith, 1989):

Q\*=Qh+Qle+Qg (3)

Ground surface total heat flux Q\* is composed of Qh (sensible heat flux), Qle (latent heat flux) and Qg (heat conduction to the ground). The components of the surface energy balance at tropical high altitudes (ca. >5000m a.s.l.) are shown in Figure 8. Atmospheric air density is already less than 50% of that found at sea level (0m a.s.l.), making sensible heat flux (Qh) significantly minimal. The daytime total for incoming energy Q\* is positive in relation to that transferred away from the surface by evaporation and sublimation (Qle), unless the ground surface is wet, which allows some convection of the sensible heat (Qh) and more conduction into the ground (Qg).

In contrast, at night Q\* is negative due to the lack of incoming short wave (solar wave) radiation; however, some long wave (thermal) radiation is received from the low density atmosphere, but more long wave energy is emitted from the ground surface to the atmosphere. In practical terms, Qg is minimal in the annual energy balance. That is the main reason permafrost in these areas does not change drastically in this short period.

As noted earlier, variable Qh also tends to be very small at higher altitudes; thus Qle (wet or dry indicates snow cover or not) is a very important parameter at this study elevation. The presence or absence of snow cover is a major factor in ground cooling, and, again as we noted earlier, snow creates a unique morphology at this latitude and elevation, forming the snow spikes and ridges known as penitentes. If the ground surface is dry, Qle and Qh are both minimal at this altitude. The following equation expresses this relationship:

Q\*=Sdown (1- albedo) –Lup =Qg (+Qle+Qh) (4)

**5.2 El Niño - La Niña events (ENSO)**

*El Niño/La Niña events are well-discussed weather patterns that affect regions all over the world (e.g. https://www.climate.gov/enso). These events also affect the Peruvian Andes, often extremely reducing the frequency and amount of precipitation (*Sagredo and Lowell, 2012*). Figure 10 shows recent El Niño and La Niña events and precipitation occurrences based on data from a local meteorological station near Coropuna collected from 1963 to 2018.* While this paper does not examine the cycles or actual patterns of low-precipitation events directly related to ENSO, some patterns seem to appear, and these leave an open question for climate researchers.

In the last +50 years, extremely low precipitation has been observed at the end of an El Niño year and the beginning of a La Niña year. At the study site altitude, such years are characterized by sparse and infrequent precipitation throughout the summer and winter seasons. Most precipitation events that do fall occur during the spring as snow, which remains for the entire summer. However, the majority of the preceding year (such as June through February 2015-16) was characterized by low snow cover that exposed the ground surface to stronger summer solar radiation. This phenomenon results in drastic changes in the surface heat budget.

This project’s seven years of permafrost temperature records (2008-2017) caught evidence of a clear relationship between permafrost in this area and historically extreme El Niño to La Niña events. Figure 9a shows four years of ground temperatures collected from the Coropuna borehole site. For a “normal” year (for instance, 2012-2013), annual ground temperatures at a 50cm depth hovered at -0.02°C, but in a year characterized by extremely low snowfall (e.g. 2015-2016), recorded annual ground temperatures at a 50cm depth were much warmer (0.48°C). An increase in the ground’s conductive heat results in degrading permafrost.

**6.0 Conclusion**

This paper reports on observations of the thermal state of the permafrost found in the tropical Peruvian Andes. Permafrost distribution was in critical balance based on slope aspect, snow cover periods, surface albedo, the ground material’s field capacity, and elevation. The tropical high elevation creates a unique heat balance characterized by minimal sensible heat flux and higher levels of incoming short-wave radiation. Ice-rich permafrost is currently present and stable under these conditions. In addition, the existing ice-rich permafrost is highly thermally resistant, requiring a lot of latent heat input before thawing occurs. However, a climate characterized by less snow cover could result in degraded permafrost. Currently, the main driving force behind extremely low snow years in this region seems to be El Niño/La Nina events. A change in the frequency or significance of these events will affect the future presence of permafrost in these mountains. The lower limit of the permafrost boundary elevations is close to the Snow Equilibrium Line Altitude (ELA) elevations, often marked by the presence of glaciers. Permafrost is absent at the bottom of most of the "wet" or temperate glaciers found in Peru (Herreros et al., 2009). Most of the higher mountains in northern Peru, Ecuador, and the Colombian Andes are usually covered by glaciers or ice caps, (e.g. the ELA is lower than the permafrost lower limits found near the equator. In the arid zone (15°-27° South) regions ranging from southern Peru to Atacama, ELA rises dramatically around latitude 14° S, where the Altiplano starts and splits the east and west parts of the mountains. The western Cordillera (or mountain chain) receives lower and less frequent precipitation than the eastern mountains. Simply, because the Altiplano blocks storm events from the Amazon basin, the western mountains are even drier. As the result, in the western part of the Altiplano, the permafrost lower boundary limit is below the ELA at this latitude (Yoshikawa et al., 2013). Permafrost is only present at the lower elevations of ELA (Figure 11), and permafrost evidence at higher elevations is limited, except in the presence of rock glaciers or sporadic permafrost caused by a localized micro-climate, such as on Mauna Kea, Hawaii. It is possible that retreating glaciers may cause areas of permafrost to expand. Glaciers are strongly related to precipitation, while permafrost at this latitude is affected by precipitation and solar radiation as well as temperature. The permafrost boundary (except in the presence of a rock glacier or other local sporadic distributions) is more closely related to the local solar energy balance. ELA and the lower permafrost boundary cross around latitude 13°S at the Western Cordillera; south of this crossing point, permafrost starts appearing at higher latitudes.

Permafrost distribution is controlled not only by ELA, but also by the surface heat budget, and possibly by past glaciation (e.g. relict permafrost); it is also strongly affected by the amount of thermal heat flow in a region. Geothermal regimes are usually weak (20°C/km) in Northern Alaskan permafrost regions (Lachenbruch et al., 1982). However, all of the tropical mountains where permafrost is present are characterized by dormant or active volcanoes. Some of these volcanoes, such as Kilimanjaro and Coropuna, are predominantly active, but others are fumarole, or they discharge hot springs among the mountains. Volcanoes where active or higher geothermal heat flow conditions occur often reach very high ground temperatures, even above the 5500m a.s.l. elevations, where air temperatures tend to be colder than -5°C. For example, very warm near-surface ground temperatures were observed at Misti (Guagua Putina, 5822m), next to Chachani (Andrés et al., 2011c); temperatures exceeded 10°C at 1m below ground, and no permafrost was present; the same can be found on most of the Kilimanjaro summit (15°C at 1m below ground, 5895m a.s.l.) (Yoshikawa, 2013). In considering the state of the world's permafrost areas, we must also consider the geothermal state of these volcanoes.

**Acknowledgements**

This research was funded by CRYOPERU project (<http://cryoperu.pe>), grants CIENCIACTIVA 144-2015 (Peruvian science council); INGEMMET-GA51 (Instituto Geológico Minero y Metalúrgico, Peruvian geological survey) and MOUNTAIN WARMING (CGL2015-65813-R, Spanish Ministry of Economy and Competitiveness). The research has been also made possible thanks to the cooperation of Autoridad Nacional del Agua (Peruvian water management service), High Mountain Physical Geography research group (Complutense University of Madrid, Spain), NGO Guías de Espeleología y Montaña (Speleology and Mountain Guides) and Canal de Isabel II (public water supplying institution to Madrid, Spain). Our sincere thanks and gratitude Tim Howe and other INGEMMET and UAF WERC staff members and students for help with laboratory analyses and field support, and Sandra Boatwright and reviews who provided insightful comments and suggestions that improved this manuscript.

**Figures Captions**

Figure 1. Snow penitentes developed at the Coropuna permafrost-monitoring site.

Figure 2 study area: Southern Peruvian Andes, western part of Altiplano; ice-capped Coropuna (15°32′S; 72°39′W; 6377 m a.s.l.) is a dormant volcano, and ice-free Chachani is part of a volcanic complex (16°11′S; 71°31′W; 6,057m a.s.l.). There are active volcanoes such as Misti (also known as Guagua Putina, 5822m), Sabancaya (5976m), and Ubinas (5672m) nearby, but no permafrost was reported on the slopes of these active volcanoes due to the higher geothermal rate (ref).

Figure 3. Lapse rate for a ground depth of 30cm and air temperatures on Coropuna’s south- and north-facing slopes and Chachani’s south-facing slope.

Figure 4. Annual mean, maximum, and minimum borehole temperature profiles (e.g. trumpet curve) for both the Chachani and Coropuna permafrost-monitoring sites.

Figure 5a. Resistivity tomography results from the Coropuna permafrost site.

Figure 5b. Resistivity tomography results from Chachani permafrost site

Figure 6. Temperature patterns recorded at a ground depth of 1m in 2013, at various sites on Chachani's south, south-east facing slopes. The south-facing site was 10m from the borehole site. A higher albedo site (50% albedo) was located 25m from the borehole at the same slope aspect, and the borehole drill site itself showed 30% albedo.

Figure 7a. Oxygen and hydrogen stable isotope plots for local water, precipitation events, and permafrost core.

Figure 7b. Oxygen and hydrogen stable isotope profiles from 4.2m of core drilling at the Chachani permafrost-monitoring site.

Figure 7c. Hydrogen stable-isotope versus *d*-excess value for local water, precipitation, and permafrost core.

Figure 8. Components of the surface energy balance at tropical high altitude; the presence or absence of snow cover is highly significant for albedo and latent heat flux. Snow cover affects ground heat conduction, for instance, influencing the depth of the active layer. Sdown: incoming Solar (short) radiation; Ldown: incoming longwave (thermal) radiation; Lup: emitted longwave (thermal) radiation; Q\*: total heat flux; Qh: sensible heat flux; Qle: latent heat flux; Qg: heat conduction to the ground.

Figure 9a. Four years of ground temperature data from the Coropuna permafrost-monitoring site.

Figure9b. Four years of ground temperature data from the Chachani permafrost-monitoring site; data for Summer 2012 was lost due to instrument failure.

Figure 10. Precipitation pattern data from Chichas and Yanaquigua meteorological stations, ranging from 1963 to 2018 near Coropuna. At the top, ENSO and solar cycle patterns are shown for reference. The orange box shows El Niño events and the red box indicates the most severe El Niño events (1982-83, 1997-98, and 2014-16).

Figure 11. Latitude versus equilibrium line altitude (ELA, black-dashed line) and permafrost distribution lower boundary (re-dashed line) profiles of the Peruvian Andes.

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