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RELATIONSHIP BETWEEN GEOTHERMAL GROUND ANOMALIES AND THE ABSENCE OF GLACIAL OR PERIGLACIAL FEATURES ON EL MISTI VOLCANO (SOUTHERN PERU)

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I. INTRODUCTION

El Misti (16°170 S, 71°240 W, 5822 m) is considered to be one of the most potentially destructive volcanoes in America. Its crater is 18 km from the centre of Arequipa (2335 m.a.s.l.), a city which has grown considerably since 1940 as a result of migration from rural areas. The return period for the eruptions of El Misti during the last five thousand years has been established as between 500 and 1500 years (Thouret et al. 2001) and the last eruption occurred between 1440 and 1447. Some fumarolic activity can currently be observed in the crater.

The aim of this paper is to determine the relationship between the absence of cold geomorphologic processes and the influence of geothermal heat in the superficial ground layers on El Misti, since on this volcano no current or inherited glacial or periglacial forms are observed, while on the Chachani volcano (6057 m.a.s.l.) 16.5 km NW of El Misti, which is not currently active, glacial landforms from the Little Ice Age (LIA) and large active rock glaciers have been found (Palacios et al. 2009).

II. METHODOLOGY

To determine whether there are permanently frozen soils and freeze/thaw processes occur, an analysis was carried out of the thermal data logged by thermometers installed on the north slope of the volcano (at 4726, 5455 and 5740 m.a.s.l.) with an air sensor at +100 cm, and three ground probes at depths of –10, –30 and –60 cm. All the sampling stations were sited on horizontal surfaces in trachytic ash accumulations on lava of similar lithology. The thermal air series obtained from the nearest meteorological station (Arequipa SPQU – Servicio Nacional de Meteorología e Hidrología del Perú*)* in Arequipa city airport at 2508 m.a.s.l. were also used.

The valid data series were selected and processed to calculate the most significant statistics and then a two-fold analysis was carried out. First, the behaviour of the mean annual ground temperature (MAGT) with depth was studied at each station. Trend curve equations were obtained for ground temperature against depth from the mean annual temperatures, the mean temperatures of the coldest month and of the hottest month. The three trend curves tend to meet at a point on the graph where the annual range is 0ºC. Secondly, the altitudinal gradient was calculated of the mean annual air temperatures (MAAT) observed at our stations and at the Arequipa SPQU station. The equation for the regression curve showing the relationship between temperature and altitude was applied to the Digital Elevation Model (DEM) from the Instituto Geográfico Nacional (IGN), Peru (1:100,000) (1996), using ArcGis Raster Calculator tool. The –2ºC +3ºC isotherms, which according to French (2007) correspond respectively to the lower limit of predominant frost action and the lower limit of the presence of frost action, were located on the MAAT spatial distribution model obtained.

III. RESULTS

1. Thermal gradient with depth

The annual series statistics calculated for the temperatures obtained at **MISTI 1** station (4726 m.a.s.l.) show that the minimum air temperatures have little influence on the thermal behaviour inside the ground, since although the air sensor records negative values, the probe at –60 cm below ground level did not record any temperature lower than 6.8ºC. Not even the probe installed on the surface (-10 cm) recorded negative temperatures. In addition, the MAGT increase slightly with depth by 0.08ºC per each 10 cm. Therefore, if a uniform trend is supposed for the values, negative temperatures will not be reached inside the ground, so the thermal conditions at this point mean it would not be included in a periglacial environment.

At **MISTI 2** station (5455 m.a.s.l.) the MAAT are always lower than the MAGT. And so on 75.1% days per year the air temperature oscillates around 0ºC, while at –5 cm this falls to 37.8% days per year and below this depth no negative temperatures are found. Therefore only the ground surface (-5 cm) is susceptible to freeze/thaw processes with low frost intensity (the absolute minimum was –2.8ºC). Then, as the depth increases, the MAGT rises by 0.18ºC per 10 cm and supposing the trend is linear, appropriate conditions would not exist for the development of periglacial processes or permafrost.

The two annual series extracted from the values recorded by the sensors installed inside the ground at the **MISTI 3** station (5740 m.a.s.l.) again show that the temperature increases with depth. The MAGT increase by 3.3ºC per 10 cm (Sep2004/Aug2005) and by 2.5ºC per 10 cm (Sep2006/Aug2006), which is very different from the trends observed at the lower stations.

With effect from 2007, a sensor began to operate on a new site called MISTI 4, at the same height as MISTI 3 station, but far away from fumaroles. Only one annual air series has been obtained which shows a negative mean annual temperature and mean monthly temperatures lower than at MISTI 3, although the maximum temperatures are similar to those logged at the original site.

2. MAAT and MAGT distribution models generated from vertical thermal gradients

The MAAT vertical thermal gradient was obtained from the mean temperatures calculated from the values recorded by the probes at MISTI 1, 2 and 4 stations, and the MAAT from the Arequipa SPQU station, obtained in the same period (Sep2007/Aug08). The MAAT from the MISTI 3 was discarded since they deviated from the trend where temperature falls with altitude, due to the influence of the fumaroles. The general gradient shows that temperature falls with altitude by 0.50ºC/100 m, although variations are observed in the different sections: between Arequipa SPQU and MISTI 1 the temperature falls 0.30ºC/100 m, while between this station and MISTI 2 it falls by 0.72ºC/100 m and from here to the highest station it falls by 1.66ºC/100 m.

The MAAT distribution model was generated from the equation of the line of best fit between MAAT and altitude, since the values estimated in this way are more approximate to the values observed at the sampling stations. In this model the –2ºC isotherm is located at 5731m as the lower limit of frost processes, and the +3ºC isotherm at 5.249 m, as the lower limit of the periglacial morphoclimate.

Supposing that the MAGT behaves in a similar way to the MAAT in relation to variation in altitude, the vertical thermal gradients were calculated for the MAGT obtained at –10 and at –30 cm, at MISTI 1, 2 and 3 stations (Sep2004/Aug05). In the first case, it was observed that although on the whole the MAGT fell with altitude (0.41ºC/100 m), between the first two stations the MAGT fell by 0.66ºC/100 m, while between the second and third stations it increased (0.33ºC/100 m). As there was no linear trend, a second degree polynomial was adjusted to give an equation to generate a distribution model. According to the distribution model, MAGT below freezing point would not be found at –10 cm in the area under consideration. The estimated values for points located outside the area of the three sampling stations are not logical either. E.g. for the Arequipa SPQU station (2508 m), with an observed MAAT of 14.75 ºC for the same annual period, the estimated MAGT is 93º at –10 cm.

In the second case, the MAGT vertical temperature gradient at –30 cm was obtained, which showed a temperature increase with altitude between the MISTI 2 and 3 stations. In this case, due to the few sampling points and the already mentioned thermal anomaly at MISTI 3, the model again gave unrealistic estimates outside the area including the observation points.

This means that the distortion of the temperatures inside the ground on the upper cone of El Misti makes it impossible to generate valid temperature distribution models from the vertical gradients observed.

IV. DISCUSSION AND CONCLUSIONS

The results obtained in this paper show that on the north face of El Misti volcano a series of peculiarities occur in the thermal behaviour, of both the air and the ground, due to the influence of geothermal heat. This means that the requisite thermal conditions are not found for the development of periglacial processes or permafrost formation.

The data captured by the air sensors indicated that the MAAT falls with altitude between the first two stations (MISTI 1 with a MAAT of 7.1ºC and MISTI 2 with MAAT of

1.7/2.0/1.8ºC, depending on the year). However, the highest station (MISTI 3) deviates from the trend with a MAAT of 3.0ºC. The number of days with freeze/thaw cycles also increases between the first two stations (22 days at MISTI 1 and up to 350 days at MISTI 2) and falls at MISTI 3 (252 days) with an increase in the minimum daily temperatures. When the position of the MISTI 3 station was changed to the MISTI 4 position, at the same altitude, it was noticed that the trend observed between the two lowest stations was maintained with height . So, on the MAAT distribution model the +3ºC isotherm was located at 5249 m, as the lower limit of the periglacial environment and the –2ºC isotherm at 5731 m, as the lower limit of the frost process domain. According to French (2007), at levels higher than 5249 m the required thermal conditions are found for the development of periglacial processes. In the particular case of El Misti, an undefined area around the site of the MISTI 3 station would have to be excluded. In spite of this, during the field surveys carried out in the late winter and early austral spring, periglacial forms were not encountered on the study site.

The probes installed inside the ground provided information on the thermal behaviour of the ground surface. At MISTI 1 station no negative values were recorded and the MAGT increase with depth. At 5455 m, at MISTI 2, the top 5cm of the ground are affected by daily temperature oscillations around 0ºC, although these are fewer and less intense than in the air. This observation seems to agree with those of authors for other mountains in middle and high latitudes (Smith y Riseborough, 2002), where the vegetation or snow cover acts as thermal insulation. In the case under consideration here, there is no vegetation cover and the thin snow cover for a few days means chilling of the top soil layer. As the depth increases the MAGT continues to increase and negative values are no longer recorded. Finally, MISTI 3 shows a rapid increase of the MAGT with depth and although negative temperatures are still recorded at –10 cm, the MAGT was 8.0ºC. This behaviour indicates the enormous influence of the geothermal heat, which prevents the ground freezing and even raises the air temperature.

Attempts were made to generate temperature distribution maps below ground surface with the MAGT data, but due to the anomalies observed no clear pattern was found to develop the models.

On the other hand, the results obtained here were compared with those published by Troll (1959) and taken as reference data for tropical mountain thermal behaviour (French, 2007). Troll describes 337 daily freeze/thaw cycles over the year for the Mont Blanc station (4760 m) and for the Summit station (5850 m) finds 2 daily freeze/thaw cycles and 323 days with temperatures always below 0º per year. However, this present paper offers different results at similar altitudes: at MISTI 1 (4726 m) only 22 daily freeze/thaw cycles are logged with the rest of the year free of frost; at MISTI 3 (5740 m) there are 252 days per year when the temperature oscillates around 0º and the rest show positive values; at MISTI 4 (5740 m) 45 frost days and 321 daily freeze/thaw cycles were logged. The differences can be explained by the dates when the data was obtained, since Troll used annual series recorded between 1893 and 1895, while the data used in this present paper refer to the years between 2004 and 2008.

Another recent unpublished study by *Grupo Investigación de Geografía Física de Alta Montaña* (Andrés, 2009), offers thermal data collected in the nearby Chachani volcanic complex. According to this data, at an altitude of 5331 m on the Chachani negative MAAT is recorded (–1.9ºC) and the MAGT at –30 cm is also negative (–2.7ºC) (2007/08). On El Misti, in contrast, at 5455 m the MAAT is positive (1.8ºC) and at –30 cm the MAGT is exceptionally high (7.7ºC), for the same period. In this case, there seems to be a clear influence of geothermal heat on the upper cone of El Misti, which prevents the development of the thermal conditions needed for periglacial processes. This may explain why although the number of days with temperatures below 0ºC and with air freeze/thaw cycles would seem to indicate the possible existence of periglacial activity or even the presence of permafrost (MISTI 2 and 4), in the case of El Misti, the geothermal flow completely prevents the development of these on the upper cone.

These results therefore lead to the conclusion that the ground temperature does not fit an altitudinal distribution climatic model on the whole north slope of El Misti. The influence of geothermal heat affects the whole upper cone of the volcano and distorts the temperature distribution.