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Snow characteristics, distribution and disappearance in a subtropical volcano (Teide, Canary Islands)

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Abstract

An analysis is carried out of the snow characteristics, distribution and disappearance on a subtropical volcano. Teide (28° 16′ N–16° 38′ W), is a stratovolcano with the highest altitude in Spanish territory at 3718 m a.s.l. It is characterized by an arid climate, with only 12.7 days of snow per year and very clear skies during most of the year. The snow cover is rarely continuous even during the cold season. In addition, the particular geothermal conditions of its ground, the layout of the lava flows from the crater, and not only its subtropical latitudinal position, are responsible for its special snow distribution and ablation processes, such as the banded and radial snow pattern, the hollows in the base layer of the snowpack and snow penitents. These features create a unique snow cover within the high mountain environments.

1 Introduction

Snow is the most common element in high mountain environments during the majority of the cold season if not the whole year. However, there are important differences regarding its properties and processes upon the different latitudinal and geographical location. Teide's subtropical location confers special characteristics on its snow, which differs greatly from that observed and described in most of other mountains or cold regions.

While several works have been carried out on the snow cover of sub-tropical and tropical mountains: Himalaya (e.g., Kulkarni et al., 2002; Negi et al., 2009), Atlas (e.g., Schulz and de Jong, 2004), and Andes (e.g., Lejene et al., 2007), there are not so many investigations on tropical and subtropical volcanoes: Nevado del Ruiz (Thouret, 1990), Sajama (Hardy et al., 1998), Ojos del Salado (Gspurning et al., 2006), Cordillera of Ecuador (Wagnon et al., 2009). Previous researches in the Teide Volcano have been focused on the snow penitentes (Martínez de Pisón and Quirantes, 1981a), snow hydrology (Becht, 1991) and sublimation processes (Becht and Trimborn, 1993). Not previous work, to our knowledge, has been done exclusively on the snow distribution and disappearance in subtropical active volcanoes.

The fieldwork has been carried out during the cold seasons of 2002 and 2004. Since then, many images, aerial photographs and documents have been consulted in order to understand better the distribution and disappearance of the snow on Teide.

The aims of this paper are threefold:

1. Describe the snow special characteristics and properties on a high subtropical volcano.

2. Understand the factors and conditions which make the snow distribution in the Teide so distinctive.

3. Explain the disappearance of the snow and the processes involved in the snow penitents' development and ablation.

2 Study area

The Canary Islands are found at 28° North latitude, just 100 km off the African continent (Fig. 1). Tenerife Island, on which Teide is located, is the largest of them. The Canary Islands are a group of volcanic massifs independent of the continental shelf and slope. The Teide is a stratovolcano with two craters which belongs to the Teide-Cañadas volcanic structure (Araña et al., 1989; Martínez de Pisón et al., 2009). It is the highest altitude in Spanish territory with 3718 m a.s.l., and the third highest stratovolcano on a volcanic ocean island. The lithology is very diverse as a result of its composite nature; aa lavas, trachybalsaltic lava flows, accretionary lapilli, black lava flows (Martínez de Pisón, 1986). Teide's last eruption took place in 1798 (Carracedo et al., 2007).

The precipitation takes place mostly in winter, with 43.4 days per year in the Izaña Observatory at an altitude of 2368 m a.s.l. (Bustos and Delgado, 2000) (see furthermore in next section). The mean temperatures here are −3 °C and 5 °C, winter and summer, with extreme values of −9 °C and 14 °C, with an absolute minimum temperature of −16.8 °C (Bustos and Delgado, 2000). At the highest altitudes these records must be much lower.

3 Snow characteristics in the Teide

There are several factors which determine the particular qualities of the snow on this Canary Islands volcano.

(i) First, it is necessary to understand the low precipitation on Teide in terms of the mountain's latitudinal and geographic position. Most precipitation occurs in the winter, not only because of the evident decrease in temperature, but also because at this time the Azores Anticyclone is much more variable in both position and power than in the summer, and the Canary Archipelago is more exposed to the low pressure systems which are the main causes of precipitation. The majority of snows are produced during the invasions of polar air in the cold season; the duration of these invasions is quite variable, with an average of 5 or more days during the winter months. Snowfalls associated with low pressure systems from the more temperate S and SW are very uncommon, as much for their low frequency as for, principally, their moderate temperatures; however, these systems can cause snows in the more elevated zones of Teide during the coldest winter months. The number of days of snow precipitation at the Izaña Observatory, is from 12.7 days per year, concentrated between December and April, and occasionally though less often between November and May (Bustos and Delgado, 2000).

(ii) The high level of incident solar radiation throughout the year due to its altitude, its meridian latitudinal position and the great quantity of clear days (the Izaña Observatory maintains the most extensive registry of mean annual insolation in all of Spain, with 3448.5 hours per year, chiefly due to its location above the cloud layer). Even in winter, the sky remains cloudless relatively often (the mean insolation between November and February represents more than 60% of the theoretical illumination, which causes an important reheating during the day, keeping the temperatures positive (Morales et al.,

TCD
5, 75–93, 2011

1977)). Also, though to a lesser extent, the volcano's high elevation encourages a lack of clouds due to the clearing of the air in the high layers of the troposphere (Bustos and Delgado, 2000).

(iii) The great loss of long wave irradiation, which generates a rapid and sudden nighttime cooling, further accentuated by the dryness of the air (maximum humidity in winter is 55%, compared to only 18% in the summer). The daily temperature variation in winter is very high. Accordingly, nocturnal irradiation will be one of the differentiating factors in understanding the snow of Teide. The great daily temperature variation was compared by Zerolo to that observed in the Alps in the 19th century:

"...when the sun appeared to us in all its splendor, the temperature of the temperate zone immediately became like that of the hot zone. A strange phenomenon, this imposition of the tropical climate on that of the Alps!" (Zerolo, 1878).

In consequence of the sudden cooling at night and the subsequent rise in daytime temperatures, the snowpack undergoes very rapid change, even in the cold season. During the day, this results in a loss of snow by sublimation (due to the high radiation available for the phase change). Sublimation plays the most important role in snow ablation in high and dry environments (Schulz and de Jong, 2004). In some areas such as the mountains of California (at 37° N), about the 65% of the snowpack was estimated to sublimate (Beaty, 1975), while in the Andes at an altitude of 4000 m a.s.l. it could amount 60% (Vuille, 1996). This fact has been confirmed in the Teide as well (Becht, 1991; referenced in Schulz and de Jong, 2004), where evaporation in responsible of most of the snow ablation (Becht and Trimborn, 1993; referenced in Schulz and de Jong, 2004).

Besides, fusion takes place in the snow ablation processes during the cold season. Fusion provokes an increase in the density of the snow and the accumulation of water in the basal zones of the snowpack. According to our observations, nightfall is followed by a significant drop in temperature which is conducive to the freezing of fusion waters and wet snow in the basal zone of the snowpack. This phenomenon is most clearly expressed in tropical mountain ranges, like Peru's Cordillera Blanca or Bolivia's Cordillera

TCD
5, 75–93, 2011

Real, where patterns can be seen in the snow or ice resulting from daytime fusion due to large amounts of radiation and the sudden nighttime freezing. This rapid and constant transformation will be responsible for some very high densities in the snow of the Teide even during the cold season.

3.1 Snowpack properties

Our observations showed that Teide's snow crystals are large with a granular, poorly cohesive appearance, especially on the surface of the snowpack, which remains until the disappearance of that layer. Certain investigations carried out in tropical mountain ranges (Haray et al., 2001) consider this phenomenon a response to water pressure gradients resulting from temperature gradients within the snow pack, which, essentially, cause formation of crystals on the surface of the snow.

According to our observations, the stratification of Teide's snow is very simple or nonexistent, with the snowpack most often being formed by a single snowfall with no differentiation of various layers. The snowpack of the Teide is therefore characterized by a homogenous, granular, porous, and permeable snow, except in the basal zone, where it might remain saturated with water liable to freeze.

4 Snow distribution in the Teide

4.1 The radial distribution of the snow from the crater

The distribution of snow on Teide's peak is, in a certain way, affected by the morphology and path of medieval black lava flows, as well as their distribution from the point of origin: the volcanic crater. These flows, which descend from Teide's crater, originated in an eruption of the 14th century, arrange a more or less compact area of volcanic aa lavas, formed by the juxtaposition, imbrication, and superposition of corrugated lava flows, either interlaced with one another or isolated (Martínez de Pisón and Quirantes

1981b). These are characterized by the transverse presentation of a channel or trough shape, with an internal depression along the axis and two lateral walls of cooled lava of a certain kind. These morphologic traits of the lava flows create an ideal location for the accumulation and maintenance of snow. However, the preservation of snow along the central axis of these lava flows, or in the passages between them, depends not only on the flow morphology but also and more importantly on their orientation and altitude. The black flows radiate from Teide's crater. In the flows oriented E and SE, there is direct and prolonged exposure to sun rays, as a result of which the snow disappears very rapidly. On the contrary, in those flows oriented oppositely, the snows remain much longer due to the protection from sun rays provided by the lateral walls of the lava channels. The result is a radial distribution of snow, with abundant and homogenous covering on the N and NW faces, and an irregular covering on the opposite slope, across which all the flows are at least partially present (Fig. 2).

4.2 The influence of the geothermal activity in the summit of the volcano on the snow cover

The appearance of moderate volcanic activity in Teide also confers some special characteristics upon the spatial distribution of its snow, up to the point at which the geothermal heat released in the volcanic conduit influences snow distribution. The better parts of historical records from the 18th, 19th, and 20th centuries make mention of fumarole activity in the summit areas, as well as chemical and thermal analyses.

It has been estimated that the summit of the Teide releases 144 megawatts of energy each day (López et al., 2003). According to the same source, this freed energy is found to be associated with the transport dynamic of volcanic gases from the deep zones of the volcanic system, found at 234 °C and 32 atmospheres of pressure, up to the surface. This important liberation of energy limits the permanence of snow in the highest areas, where these gaseous emanations are greatest, between 3450 and 3716 m a.s.l., Teide emits about 400 t of high-temperature CO_2 into the atmosphere daily (López et al., 2003). This quantity of gas is equivalent to the emission of 3140 t

TCD
5, 75–93, 2011

of water vapor, if the latter were not to condense before reaching the atmosphere. Despite the absence of spectacular visible hydrothermal discharges, the amount of energy freed by Teide through this process is enormous.

The consequences of these thermal anomalies of the ground in the snow are evident. After a snowfall, the totality of the stratovolcano is covered in snow, which quickly begins to disappear from the base in a regular ascending pattern due to the logical accentuation of the ablation processes at lower altitudes, varying again by orientation. However, snow also disappears irregularly from the peak towards the lower reaches until arriving at a determined altitude, about 3500 m a.s.l., in consequence of the geothermal heat released by the ground (Figs. 2 and 3). Thus, we see a mechanism of snow ablation that is bidirectional in the vertical way and unusual compared to that of high mountains and cold regions, and which is seen only on certain active volcanoes of great height (we find the perfect example in large, active volcanoes topped by glaciers, the ices of which depend so much on volcanic activity that they extend over their slopes (for example on Popocatepetl, in Mexico), but not on the top cone, or which even begin to disappear occasionally during the development of very accentuated volcanic phases, which provokes the much-feared lahars, as in the sad case of Nevado del Ruiz in 1985).

Through direct observation and consultation of images and aerial photographs, it is evident that the permanence of residual snow is at its maximum below about 3500 m a.s.l., falling slightly under this level, as well as above it. Although this phenomenon may appear similar to what occurs on the world's largest mountains, where snow permanence is maximum up to 7500–8000 m a.s.l., above which snow almost disappears, this disappearance is caused by intense winds experienced by mountains like Everest. Meanwhile, the weak persistence of snow in the volcanic summit of Teide could be related to some regular winds which sweep away newly fallen snow (although, logically, with much less prominence than in the previous discussed example of the Himalayas), geothermal factors are the causes of this banded snow pattern.

4.2.1 The influence of the geothermal activity within the snowpack

Examining this in greater detail, we also see a clear influence by the geothermal heat in the ground of the volcanic summit in the snowpack. Because of the spatial irregularity of the thermal anomalies in the base layer of the snowpack, the temperature of this layer is more elevated in some zones than in other adjacent ones, and in which the deposited snow undergoes double ablation in the vertical dimension: a) from its surface, mainly due to solar radiation, as well as other ablation mechanisms, and b) from its base, as a consequence of the heat released by the ground. The result is the appearance of hollows present between the snowpack and the ground, which are frequently detected during winter ascensions to Teide's peak.

5 Disappearance of snow

The duration of snow cover on Teide is short and rarely continuous, only in the areas best protected from the sun and where accumulation is greatest, small and relatively permanent snow patches may form, which are characterized by a hard, icy snow resulting from the metamorphosis previously described.

The high absorption of radiation by Teide's snow, due logically to the great quantity of available energy is further encouraged by the high concentration of particles originating from the dark volcanic lithology which are deposited onto the snow, (this last fact is facilitated by the light weight of these fine materials and the resulting ease of transport by wind – such as pumices, for example –, as well as by the low levels of snow accumulation) (Fig. 4). The abundance of cryoconites on the snow demonstrates not only this phenomenon, but also the significant thermal differences between the ground and the air, due to direct solar radiation. This important energy absorption by the snow encourages faster rates of ablation through sublimation.

In addition, the albedo on granular snow in tropical and subtropical areas has been estimated lower that in the temperate and cold mountains (Lejeune et al., 2007). That contributes to accelerate the ablation of the snowpack due to enhanced absorption of the incoming solar radiation.

5.1 The snow penitents of the Teide

A magnificent example of the importance of solar radiation, its absorption by the snow, the sublimation and disappearance processes is the snow penitents on the Teide. Penitents are common where sublimation is an important mechanism of snow ablation (Schulz and de Jong, 2004). Snow penitents are typical of high subtropical and tropical mountains with arid or very dry conditions with a dew point below zero and high solar radiation (Lliboutry, 1954; Corripio, 2004). The penitents of the Teide were first mentioned by Blumenthal in 1959 (published in 1961), who advanced the oldest hypothesis, formulated by Darwin in 1835, which attributed the genesis of these formations to the direction of the wind compounded with the orientations of melting paths (Martínez de Pisón and Quirantes, 1981a). There would not be detailed studies until 1980s, when Martínez de Pisón and Quirantes separately published articles specifically concerning the snow penitents of the Teide.

Teide's exhibits the optimal conditions for the development of penitentes, but also factors which limit their formation, such as the absence of a thick enough snow pack. The difference in temperature between the air and the ground is what stops the development of the irregular fusion process in vertical areas of snow (Martínez de Pisón and Quirantes, 1981a). The fusion of certain micro-topography of the snow or irregularities in the drifts is due to a strong insolation with a nearly vertical angle of incidence, above the permeable snow, with high evaporation and nocturnal refreezing. Later, these irregularities progressively transform into larger and larger depressions due to the differences between the sublimation on the top and the melting in the lower areas, which surround the snow penitents on the sides and eventually separate them when the substratum remains uncovered. The placement of penitentes follows the path of the sun E-W, so much that when the ground on which they are situated has a slope, the penitentes appear inclined towards it (Lliboutry, 1954). On Teide, the slope is a

TCD
5, 75–93, 2011

fundamental factor, so the snow penitents are arranged ENE-SSE, clearly following the generatrices of the cone (Martínez de Pisón and Quirantes, 1981a).

The snow penitents observed in 2004 on the Teide were much smaller in size than those described in 1981 and photographed in the 1970s (which were up to 2 m.). Their maximum height was 50 cm from the base to the pinnacle (Fig. 4). These snow penitents develop oriented E on a small area of gentle slope at an altitude of approximately 3450 m a.s.l., just below the zone of high geothermal activity. Despite their moderate size, they form a well-defined and homogenous body. The alignments of pinnacles and depressed channels are clearly oriented E-W, tangentially to the sun rays. The pinnacles, in the most inclined areas display an axis oriented in the same direction as the slope, with their sharpest angle disposed toward the lowest downward inclination. The inclination of the pinnacles is thus greater in areas with higher slopes, which agrees with the findings of Martínez de Pisón and Quirantes (1981a), up to the point where, in uninclined areas the penitentes do not incline either, due to the perpendicularity of sun rays. Despite the high level of morphological development seen in these snow penitents, none of the alignments of the pinnacles is pronounced enough to create corridors between them in which the substratum appears uncovered; however, channels have been observed reaching the ground during the advanced stages in the evolution of the penitentes (Martínez de Pisón, personal communication). Occasionally, penitents can appear individually and isolated, with a high level of ablation, without coming to form the continuous alignments of the large bodies. From this observation we establish the following stages in the formation of penitents on Teide:

1. The first phase in which the differential ablation processes split the crests of the pinnacles of snow from the corridors between them.

2. A second phase of plentitude, in which, as a consequence of the increment of a strong insolation with nearly vertical angle of incidence and the presence of dark particles within the corridors, the pinnacles and partitions are isolated down to the lowest layer.

3. A final phase of destruction with rising temperatures, in which the crests of the penitentes are dissociated until they are individualized and eventually disappear.

The frequency and size of the snow penitentes in the Teide is decreasing due to the current global warming. According to some studies (Bustos and Delgado, 2000), there is a thermal increasing of 1.21 °C since 1916. This important factor contributes to the minor extension and duration of the snow cover nowadays in this subtropical volcano.

6 Conclusions

Teide's snowpack is subject to important daily thermal oscillations, even in winter. Its subtropical location affects the distribution, characteristics, and permanence of the snow, principally due to the scarce snow precipitation, high incident solar radiation and high nocturnal irradiation. The result is a simple, thin, irregular, and relatively unimportant snowpack, when the high altitude of the volcano is taken into account. On Teide the snowpack is often being formed from only a single snowfall. The density of the snow is elevated in the Teide, due to the rapid metamorphosis by the high radiation and scarce solid precipitation that occurs. During the cold season, Teide's snow is transformed significantly.

Due to the greater energy requirements of sublimation, this process is common in Teide even during winter. In a similar way as takes place in other subtropical and tropical mountains of the planet.

Teide's subtropical position and evident volcanic character lead to the irregular distribution of its snow, as a function of the geothermal heat freed by the volcano, and of the morphology and disposition of lava flows. The result is a snow cover which disappears bidirectionally in altitude and radially from the crater, and which possesses characteristics such as the appearance of hollows in the base of the snowpack resulting from thermal anomalies within the ground. This constitutes a distinctive and unique high mountain winter landscape.

TCD
5, 75–93, 2011

The melting of the snowpack can occur at any time during the cold period, which generates a highly irregular seasonal snow covering, even in winter. Because of its latitudinal position and altitude, snow morphologies originally associated with processes of ablation may be created, such as snow penitents, similar to those found in subtropical and tropical mountains like the Atlas, Andes or Himalayas.

Finally, the decrease in both extension and duration of the snow cover on Teide due to the current global warming is remarkable.

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TCD

5, 75–93, 2011

Snow in a subtropical volcano

R. Martín Moreno

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TCD
5, 75–93, 2011

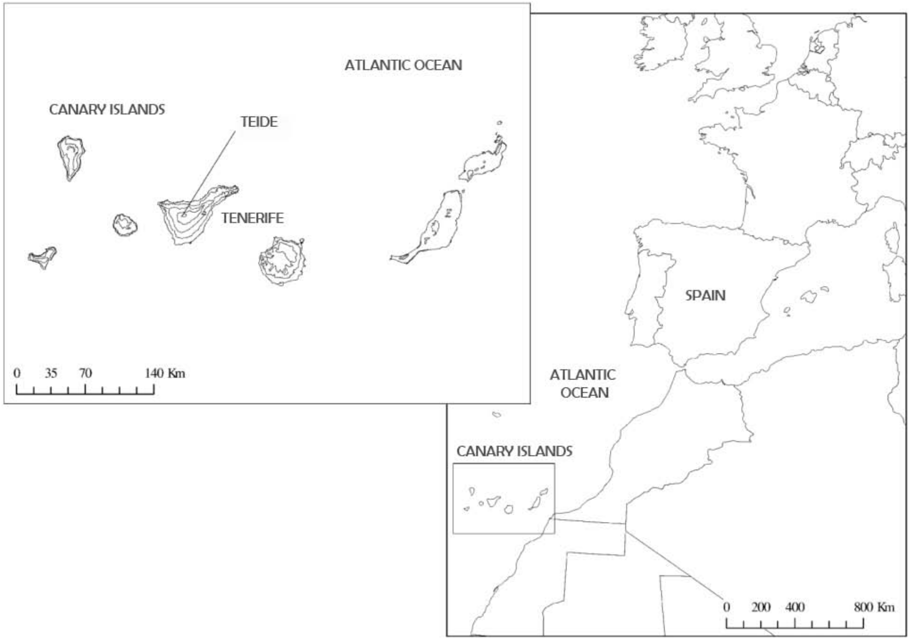

Fig. 1. Location of the Canary Island within the Atlantic context.

TCD
5, 75–93, 2011

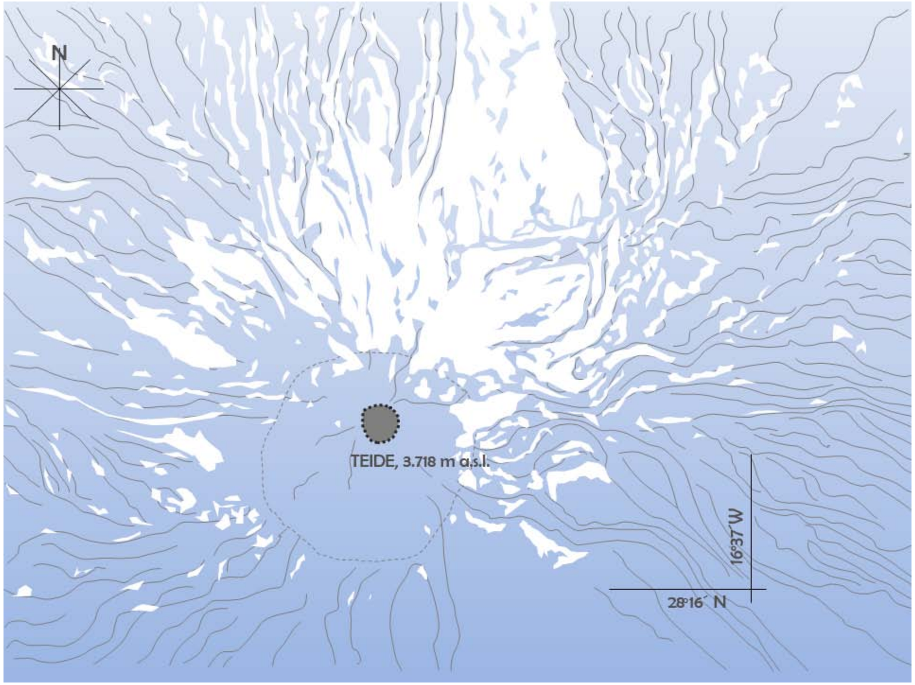

Fig. 2. Snow distribution on the Teide Volcano, lines: lava flows, dotted lines: geothermal activity from the ring to the summit. Note the radial pattern of the snow cover from the crater, and the minimum at the S and SE orientation and up the ring of geothermal activity (3450–3600 m a.s.l). (base layer Google Earth, 1 January 2009).

TCD
5, 75–93, 2011

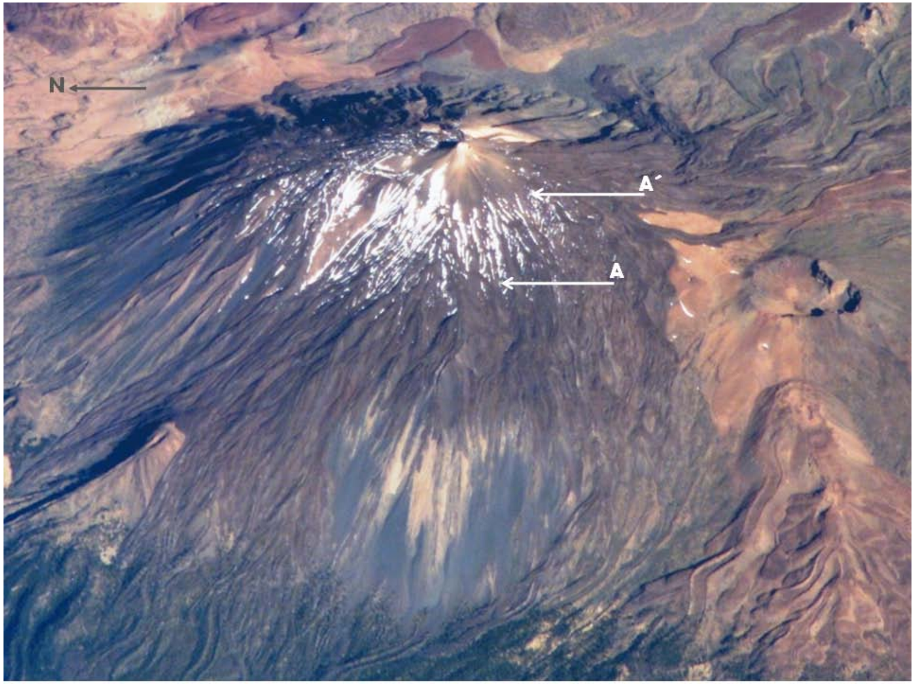

Fig. 3. Banded snow pattern in Teide. The maximum snow cover is found between A and A′, below A the snow disappears due to the logical accentuation of the ablation processes at low altitude, – varying by orientation and the lava flow layout –, and up from A′ in consequence of the geothermal heat released by the summit. Picture by NASA©, May 2006 (ISSO13E23272).

TCD
5, 75–93, 2011

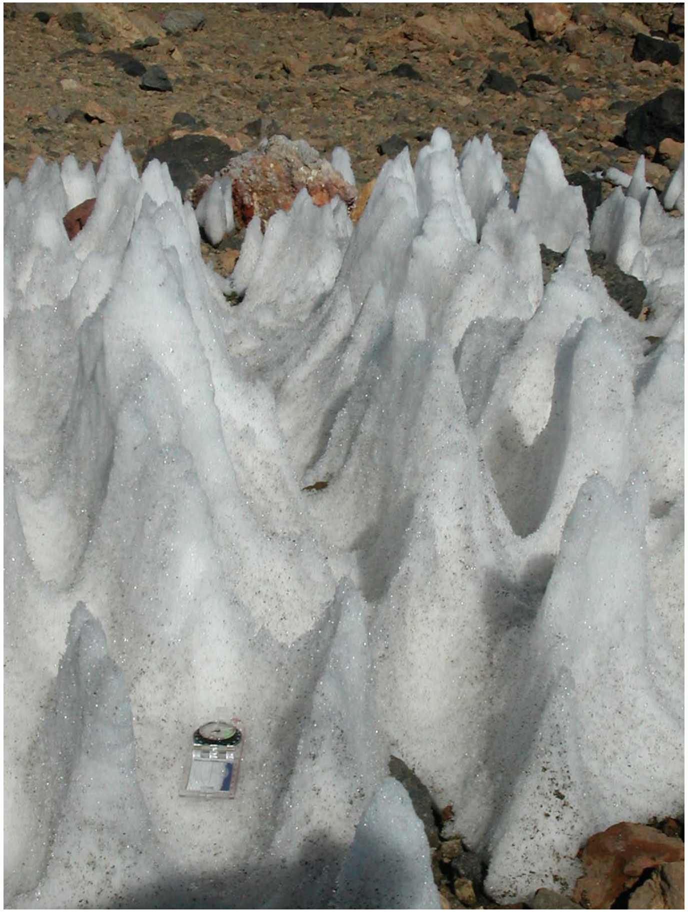

Fig. 4. Teide's snow penitents in 2004. Maximum height is about 50 cm. Notice the granular snow and the volcanic particles on it.

TCD
5, 75–93, 2011

Snow in a subtropical volcano

R. Martín Moreno