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Preliminary study on the shape of snow penitents at Piloto Glacier, the central Andes

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Abstract

Jagged pinnacles of snow called snow penitents are seen from spring to summer on the surface of Piloto Glacier (4,100 – 4,900 m a.s.l.) in the central Andes, South America. In December 1995, snow penitents consisted of large-grained granular snow, which covered the glacier ice or moraines. Heights of most penitents ranged from about 0.3 m to 1.5 m, and the faces of them directed toward the north. The northern faces were almost vertical and slopes of the southern faces ranged from 60 to 85 degrees. Strong solar radiation and sublimation of snow should play important roles to the formation of penitents.

1. Introduction

Nieve penitente (snow penitent) is "a jagged pinnacle or spike of snow or firn, up to several meters in height, resulting from differential ablation under conditions of strong insolation, especially in high altitude — low latitude environments ; an advanced stage of sun cup development (Bates and Jackson, 1980)". There are two kinds of penitents, namely snow penitents formed on snow and ice penitents formed on glacier ice. Lliboutry (1954) firstly made rigorous description about features of snow/ice penitents and climatic environments of their formations, namely "Penitents are spikes of old compact winter snow or of glacier ice, roughly ranged in an east-west direction, which in the Andes of Santiago, in summer, cover all the snow fields and glaciers between 4,000 and 5,200 m."

Since the early 20th century, snow or ice penitents have been reported from various high mountain regions (*e.g.* in Himalayas : Workman, 1914). According to Lliboutry (1964), snow/ice penitents were observed at high altitudes around 5,000 m a.s.l. in the northern Iran, Hindu Kush, Pamir, Khumbu and Makalu (Himalayas), Mt. Kilimanjaro (Kenya), Mt. Popocatepetl (Mexico), and Mt. Chimborazo (Ecuador). Roch (1954) described ice penitents of heights of up to 30 m at altitudes between 4,500 m and 5,300 m of Khumbu Glacier. Shi and Ji (1982) made detailed surveys on distribution and shape of ice penitents at the northern slope of Mount Xixia Bangma, China. Each of the ice penitents showed the shape of a cone of 2 to 5.5 m in height in the upper reach of the ablation area (5,800 m a.s.l.) and of an isolated tower of 15 to 30 m in height near the glacier snout (5,600 m). A time necessary for this development was roughly estimated as about 150 years (Shi and Ji, 1982).

On the other hand, snow penitents develop and decay within one ablation season. Ice penitents normally grow from ice blocks of collapsed seracs or from debris of icefalls or ice avalanches (Roch, 1954 ; Shi and Ji, 1982), whereas snow penitents may grow from honeycombed snow, sun spikes, or micropenitents (Lliboutry, 1954). Therefore, snow and ice penitents are regarded as different in species, though the climatic conditions favorable to their formations may be identical.

The shape of snow penitents was described as "the crests of penitents take the form of east-west blades, bending to the sun (that is to the north)—— the form which allows the most outgoing radiation and sublimation, and the least insolation, for a given cross-section (Lliboutry, 1954)". Amstutz (1958) suggested, as a cause of penitents formation, an importance of concentration of heat at the bottom of furrows due to reflection of insolation at side walls of penitents.

Although there are numerous reports or documents on snow and ice penitents as mentioned above, very few quantitative, statistical data have been published as to shape, alignment and distribution of snow penitents. Collections of such basic data are necessary for further studies to clarify the detailed mechanism of formation of snow/ice penitents. This report presents results of a preliminary field research on shapes of snow penitents developed at Piloto Glacier, the central Andes, in December 1995.

2. Piloto Glacier and its mass balance

Piloto Glacier is located at 32°36′ S and 70°09′ W on the eastern flank of the border between Argentina and Chile in the central Andes (Fig. 1). The glacier, which consists of two ice tongues of Piloto Oeste and Piloto Este (Fig. 2), covers an area of 1.4 km² between 4,100 m and 4,900 m a.s.l. on the southwestern slope in the Cajõn del Rubio, that is a headwater region of Las Cuevas River, a tributary of the Mendoza River. Piloto Glacier, being about 12 km northwest of Co. Aconcagua (6,959 m), is a glacier with the easiest access in the Mendoza Province : one can reach the glacier terminus after walking for 25 km from Las Cuevas along Las Cuevas River.

Extensive mass-balance studies of Piloto Glacier were carried out by drilling into winter snow and using ablation stakes from 1979 to 1994 with a few missing years (Leiva and Cabrera, 1996). Annual accumulations at various points ranged from 0.2 m to 2.6 m in water equivalent (w.e.) and annual ablations ranged from 0.6 m to 2.1 m in w.e. (Leiva *et al.*, 1986). Year-to-year variations in mass balance were significantly large compared with the amounts of annual accumulation or ablation ; namely, annual net balances averaged over the whole area of Piloto Este Glacier were largely positive from +1.0 m to +1.5 m (w.e.) in 1979 (the balance year of 1979/80) and 1982 ; largely negative from −0.6 m to −1.0 m in 1980, 1981, 1985, 1988, 1989 and 1990 ; and almost equilibrium in 1983, 1984, 1986, 1987 and 1993 (Leiva and Cabrera, 1996).

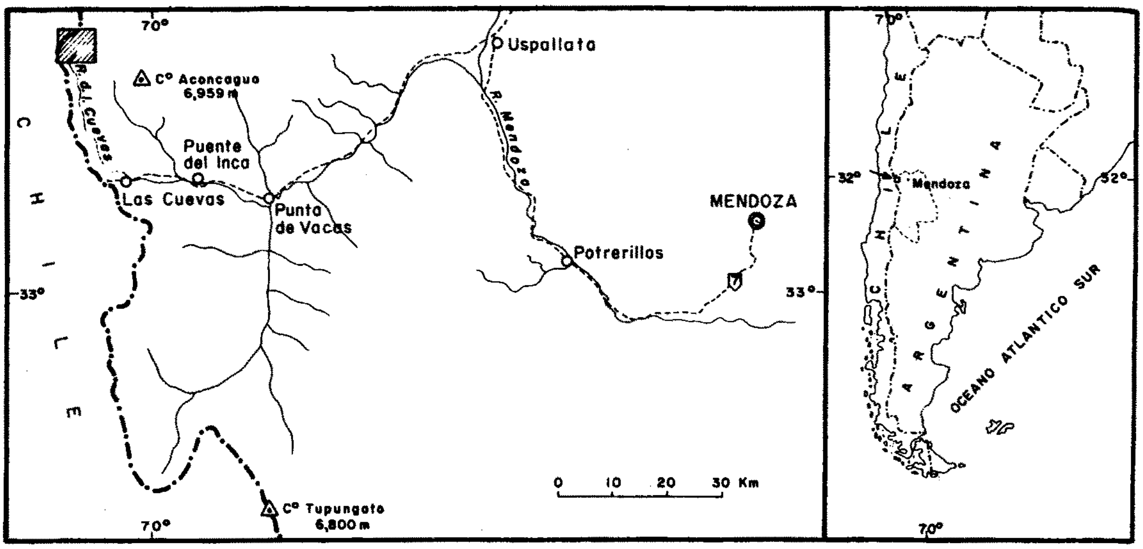

Fig. 1. Map showing the location of the Cajõn del Rubio, where Piloto Glacier exists, at the head of Las Cuevas River in the central Andes, Argentina.

Fig. 2. Piloto Glacier seen northwest from the snowpatch (4,050 m a.s.l.) near the glacier terminus (18 December 1995). The glacier is split into two parts : the left one with a nunatak at the center is called Piloto Oeste and the right one of rather smooth slope is called Piloto Este. Elevations of the upper boundary and the terminus of the glaciers are about 4,900 m and 4,100 m a.s.l., respectively.

3. Distribution and shape of snow penitents

In ablation seasons of normal years, snow penitents cover almost the whole surface of accumulation and ablation areas of Piloto Glacier. It causes great difficulty in ablation measurements. Snow penitents start to form in spring on the surface of seasonal snow, and develop to become maximum in height in the early or mid-summer, then they diminish in size and disappear by the end of ablation season. However, during the summer of 1979/80, frequent storms and accumulation of graupel caused the summer ablation to be minimum, so that snow penitents have not been developed largely (Leiva *et al.*, 1986).

Surveys on distribution and shape of snow penitents were made at Piloto Glacier from 18 to 20 December 1995. The whole surface of the ablation area and the lower part of accumulation area were covered with snow penitents (Figs. 3 and 4). Snow penitents were also formed on lateral and terminal moraines (Fig. 5), on ice-cored moraines and on snowpatches around the glacier terminus (Fig. 6). Heights of most penitents ranged from 0.3 m to 1.5 m (Figs. 4, 5 and 6). The penitents consisted of wet large-grained granular snow.

Each penitent shows the form of a sharp ridge which is aligned in almost the same direction. Orientations of penitents (*i.e.* direction perpendicular to the northern face of penitent) were examined at 22 sites in the ablation area from 4,100 to 4,250 m a.s.l. and in the snowpatches (4,000−4,100 m a.s.l.). A histogram of directions of the faces, at every 10-degrees, is shown in Fig. 7. At 16 sites, the orientations were within 10 degrees from the (true) north. No penitents existed whose orientations deviated more than 25 degrees from the north. It was also noticed that these orientations are not strongly affected by those of the snow surface or the surrounding terrain.

Fig. 3. Ablation area of the eastern part of Piloto Glacier (Piloto Este) covered with snow penitents (20 December 1995).

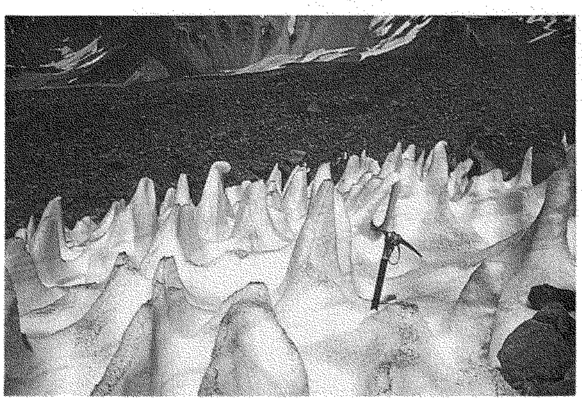

Fig. 4. Snow penitents near the terminus of Piloto Glacier (19 December 1995). Length of the pickel above the snow is about 0.4 m.

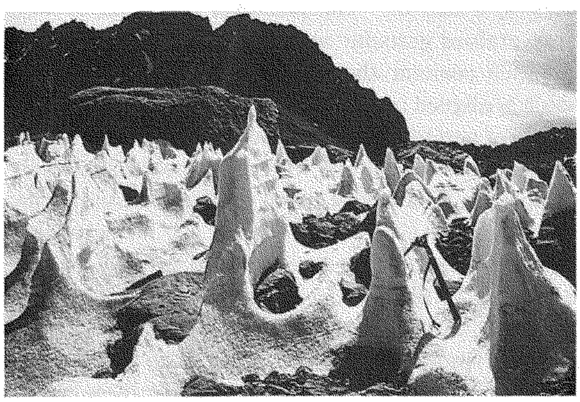

Fig. 5. Snow penitents developed on moraines near the terminus of Piloto Glacier (18 December 1995).

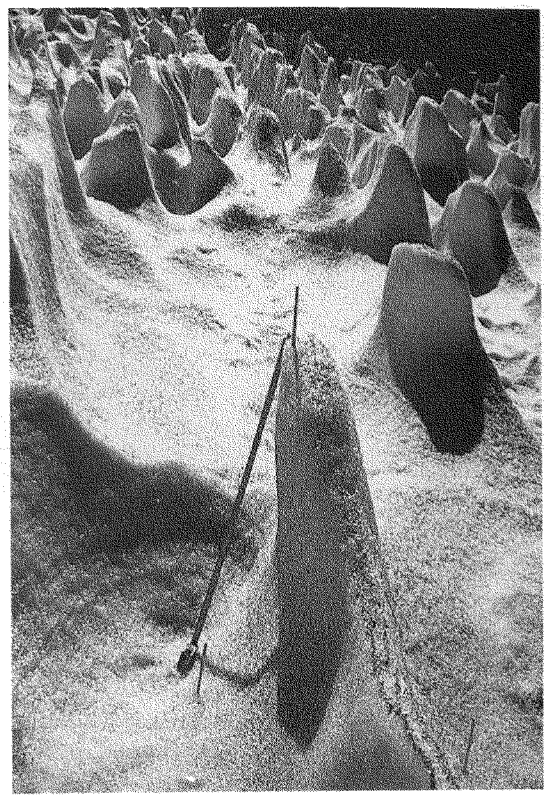

Fig. 6. Snow penitents, with ablation sticks at the top and the bottom, on the snowpatch (4,050 m a.s.l.) near the terminus of Piloto Glacier (20 December 1995).

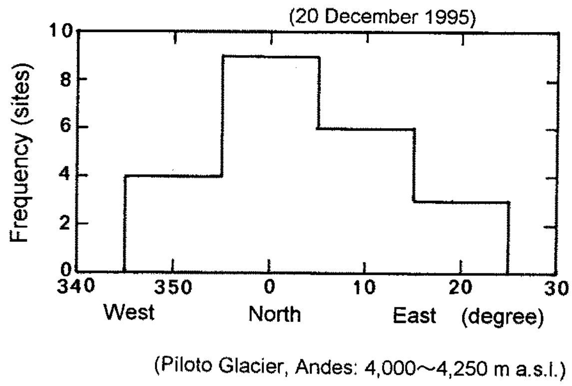

Fig. 7. Frequencies of orientations of penitent faces measured at 22 sites in the ablation area of Piloto Glacier and in snowpatches. Each of data represents a mean in an area of about 10 m×10 m.

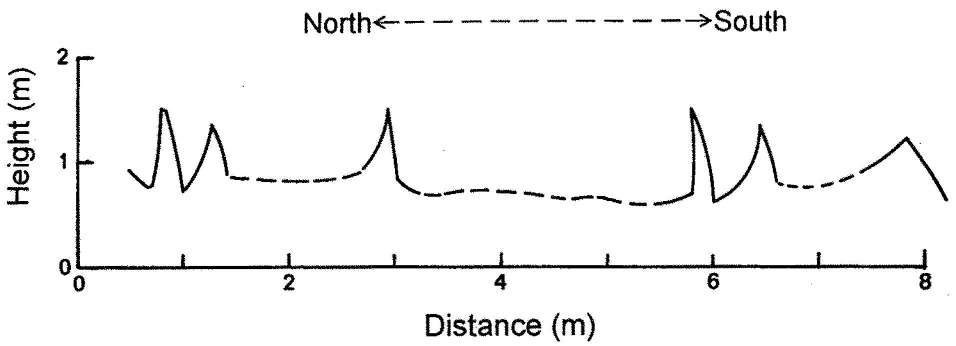

Fig. 8. A north-south surface profile of snow penitents (Fig. 6) on the snowpatch near the terminus of Piloto Glacier (19 December 1995).

An example of surface profile of penitents field is shown in Fig. 8, which was obtained with a handy clinometer and a tape measure along an 8 m long longitudinal line from north to south on a snowpatch near the glacier terminus. The profile with relatively flat surface between penitents around distances of 2 m and 4−5 m is not a standard shape, but the surface usually represents a sharply undulating pattern like a saw teeth as seen at distances of 1 m and 6 m.

A schematic illustration of the north-south cross profile of snow penitent is shown in Fig. 9, which was drawn on the basis of averages of surface slopes of 11 penitents near the glacier terminus. The surface slope of the southern face ranged from about 60 to 85 degrees. It is clearly recognized that the slope of the northern face is steeper with a negative angle (overhung) and almost coincides with the solar angle at noon on the summer solstice (21 December). Features seen in Figs. 7, 8 and 9 strongly suggest an important role of solar radiation to the growth of penitents.

To measure ablation rates on the surface of penitents, thin bamboo sticks of 20 cm long were driven into snow at various parts such as the top and walls of penitents (Fig. 6). Only one-day measurement was made from 19 to 20 December 1995. Ablation rates averaged for four sites were 88 mm/day at the top, 89 mm/day on the northern face and 80 mm/day on the southern face. Over the penitents field near the glacier terminus, air temperature was 12.5 °C and 5.5 °C, and relative humidity was 88 % and 80 % at noon on 19 and 20 December, respectively. Due to high air temperature in this period, sensible heat, in addition to shortwave radiation, should have accelerated ablation rate. Consequently, no large differences were observed among the parts of penitents.

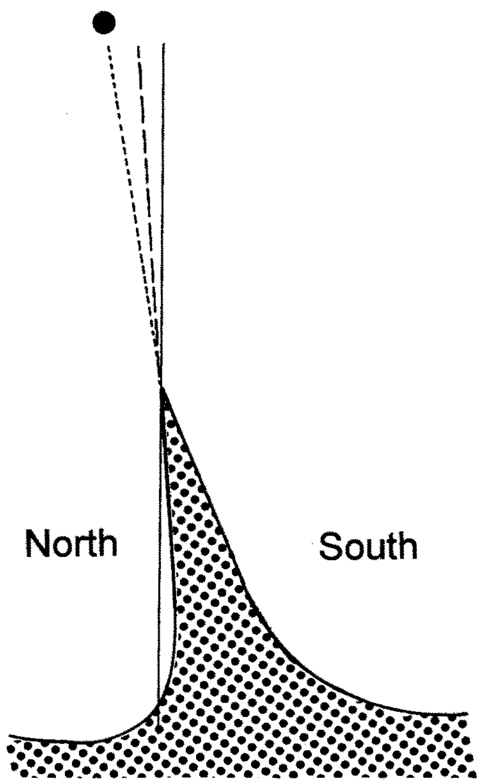

Fig. 9. A schematic north-south cross section of snow penitent (a mean of 11 penitents) near the terminus of Piloto Glacier (19 December 1995). A solid straight line indicates the vertical, a broken line indicates the surface slope of the northern face, and a dotted line with ● indicates a direction to the sun at noon (12 : 00 LT) on the summer solstice (21 December 1995).

4. Concluding remarks

Lliboutry (1954) suggested such climatic conditions which give rise to penitents as, 1) dew point definitely below 0 °C, that is a very dry condition, 2) strong insolation, and 3) air temperature never strongly positive. Then he proposed the following hypothesis ; namely "The sublimation of the snow or ice allows the crests to maintain their temperature below 0 °C, while in the spaces or passages between the penitents, where radiation is concentrated and removal of water vapour not so easy, melting takes place".

All the field data obtained through the present preliminary research are consistent with and support Lliboutry's hypothesis. Namely, the shape of penitents is in favor of such an inhomogenious ablation pattern as enhanced melting at the bottoms due to absorbed shortwave radiation and ceased melting at the top due to cooling by sublimation and outgoing longwave radiation. Climatic conditions which accelerate this process should be high solar angle, low air density and low vapor pressure.

However, there remain lots of interesting and curious problems unsolved. We would like to know, in particular, embryos of snow penitents, parameters to determine the spacing and alignment of penitents, the manner of multi-reflection of shortwave radiation between penitents, and mechanisms to maintain their own peculiar shape of penitents. In order to make clear these detailed processes and mechanisms, it is necessary to carry out micrometeorological (*i.e.* small -scale heat balance) studies from the beginning of an ablation season to mid-summer.

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References

1. Amstutz, G. C. (1958) : On the formation of snow penitentes. J. Glaciol., **3**(24), 304−311.
2. Bates, R. L. and Jackson, J. A. (1980) : Glossary of Geology. Second Edition. American Geological Institute, Virginia, 751pp.
3. Leiva, J. C., Cabrera, G. and Lenzano, L. E. (1986) : Glacier mass balances in the Cajōn del Rubio, Andes Centrales, Argentinos. Cold Regions Sci. Tech., **13**, 83−90.
4. Leiva, J. C., and Cabrera, G. (1996) : Glacier mass balance analysis and reconstruction in the Cajōn del Rubio, Mendoza, Argentina. Zeitschrift für Gletscherkunde und Glazialgeologie, Bd. **32**, 101−107.
5. Lliboutry, L. (1954) : The origin of penitents. J. Glaciol., **2**(15), 331−338.
6. Lliboutry, L. (1964) : Origine des pēnitents. Traitē de Glaciologie. Tome **I**, Masson et Cie, Paris, 375−376.
7. Roch, A. (1954) : The glaciers, snow and avalanches of Mount Everest. J. Glaciol., **2**(16), 428−430.
8. Shi, Y. and Ji, Z. (1982) : Ice pyramids and other related ablation forms on the northern slope of Mount Xixia Bangma. Monograph on Mount Xixia Bangma Scientific Expedition, 1964. Science Publication Co., China, 74-91 (in Chinese language).
9. Workman, W. H. (1914) : Nieve penitente and allied formations in Himalaya, or surface-forms of nēvē and ice created or modelled by melting. Zeitschrift für Gletscherkunde, Bd. **8**, 289−330.