## Surface Structures in Snow

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### Abstract

Observations on small- and large-scale snow surface structures were made during oversnow traverse operations in West Antarctica from 1958 to 1960, and during the winter of 1959 at Byrd Station. The strucutres are illustrated and described; their formation is discussed in relation to the shape and size of the individual crystals, the surface temperature, wind, and the interaction of these parameters. Snow surface structures are classified genetically into two major groups: Depositional and Erosional. Depositional structures include drift forms and fosses deposited around obstructions, current ripple marks, and barchanoids (barchan-like snow features). The erosional structures include several forms of sastrugi, irregular patterns, pits, footprints (human and canine), and other forms.

The study reveals that footprints, impressions of boots, and other structures have a better potential of being preserved than do the original smooth and soft surfaces. This depends largely on the micrometeorological parameters which provide subsequent consolidation and densification of the covering snow particles.

By understanding the physical characteristics and the mechanisms involved in the formation of these surface structures, their interaction with their environmental parameters, and comparing them with corresponding factors affecting other sedimentary deposits, it will be possible to reconstruct certain ecologic conditions prevalent at the time of deposition.

### I. Introduction

One of the least pursued aspects of the geological sciences is that dealing with the different structures and forms encountered on snow surfaces.

Whether it falls in the realm of physics by virtue of the mechanics of movement, or is ascribed to geomorphology by virtue of its physical form, or to stratigraphy and sedimentation due to the sedimentary structures resulting from deposition and erosion, the subject is by no means trivial. The observing eye of the scientist cannot condone the diversity and the fascinating stages of birth, growth, movement, and disappearance of these forms. Interest is further augmented by the intriguing, yet simple, mechanisms of deposition and erosion responsible for their creation.

Attempts have been successfully made by a few early scientists at explaining the mechanics of blown snow, and presenting the analogies to similar behavior in sand. The inaccessiblity of polar regions to scientific reseach of this kind, and the severe climatic conditions in deserts and on ice caps, which present the two extremities of the temperature gradient, might have been the reason for the scarcity of relevant literature. Nowadays, these regions are not as inaccessible as they used to be; and the writer has had the opportunity of being in the Arabian Desert for over two years, and intermit-

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tently in Antarctica since the International Geophysical Year.

During the first 16 months spent in Antarctica, there was ample time for the study of snow forms and patterns, and their behavior, as compared to patterns and the behavior of sand. The work presented here is the result of these observations, and is concerned primarily with snow surface structures and occasional comparisons and contrasts with sand.

## II. Field Work

The field work was conducted during the transition from the IGY to the United States Antarctic Research Progam, from November 1958 to February 1960.

At the end of 1958 the writer joined the last IGY traverse (Horlick Mountains Traverse) from Byrd Station at latitude 80°S and longitude 120°W. The first USARP traverse (about 700 km) was conducted during February-March 1959 to the Executive Committee Range in Marie Byrd Land, followed by a long (2 000 km) traverse from Byrd Station, through a major part of West Antarctica from November 1959 to February 1960. Observations were made *en route* during these three traverses.

Further experiments were conducted at and around Byrd Station during the winter months. The station husky presented full cooperation in the experiments on casts and molds of footprints despite temperatures as low as −55°C. The temperature on the traverses ranged between −38 and −2°C, and down to −63°C at the station during the latter part of winter. The average air temperature at the station was −18°C; wind speeds averaged 15.2 knots gusting to 49 knots.

Photography was done by the writer with conventional 35 mm cameras on color and black-and-white films. In some instances only one camera (with color film) could be carried; thus most of the photographs are reproductions from color transparencies. The toy penguin used for scale is 15 cm high. Figure 24 was contributed by Mr. Luis Aldaz.

## III. Depositional Structures

### *Drift forms*

Snow drifts assume many shapes which are deposited in essentially the same manner. Drifts on the lee side of obstructions (Fig. 1) form a main ridge, highest near the obstruction, which serves as an apex to a triangular facet facing the obstruction. The flow of air stream is easily discernible from the overall shape of the drift along its longer axis. The area of least wind disturbance is relatively void of any accumulation, and the distance of the drift from the obstruction is directly proportional to the average wind speed.

During a blizzard the blowing snow is usually confined to the lower layers of the atmosphere, mostly within 2 or 3 m above the snow surface. It is similar to sand during a sand storm where the coarse grains are driven near the surface, and the finer grains are suspended higher in the air stream. The finer snow grains behave as dust particles and, no matter how tightly closed a place is, they seem to find their way easily to the interior, driven through the smallest openings and accumulating in the form of large fluffy drifts (Fig. 2).

Small snow particles present a minimum of resistence, conforming with the flow

**Fig. 1.** A typical drift formed on the lee side of an obstruction

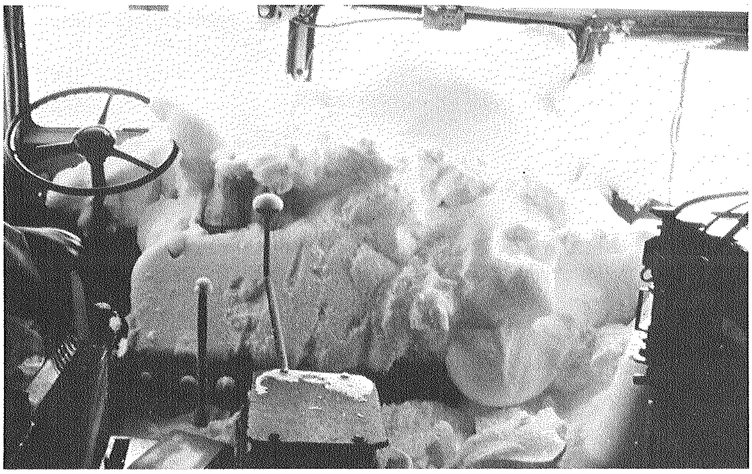

**Fig. 2.** Very fine-grained snow driven like dust particles into the closed cab of a Sno-Cat

lines of the wind, and diverting around obstructions in the course of the stream. The size of the moving grains, and the shape of the crystals would therefore vary inversely with the lift. The smaller and thinner the grains the higher is the wind component relative to their weight.

The larger crystals act rather differently; their orientation along the flow lines of the air stream is relatively low, and they tend to collide with each other, and with an obstacle. Collision among crystals decreases their velocity and upon colliding with an obstacle they rebound and settle at a short distance from the obstruction. Figure 3 shows a snow fosse formed around a mountain by high-speed winds. A fosse-drift is usually asymmetrical with a high-angle axis pointing toward the obstruction. Unlike sand drifts, where sand slip-faces (observed by the writer in the Arabian Desert) do not stand steeper than the critical angle —the angle of repose (Bagnold, 1941, p. 190)— the outer

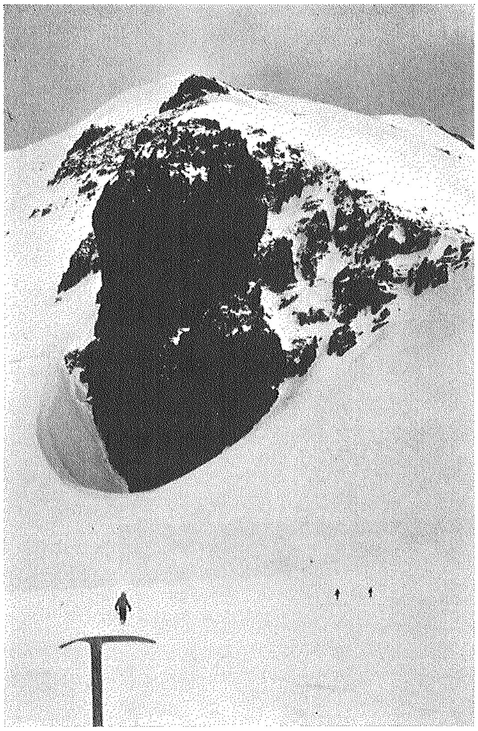

**Fig. 3.** A typical snow fosse formed around a rock outcrop by high-speed winds

**Fig. 4.** Current ripple marks with a zigzag border on the lee side

slope of the snow drift around a fosse is gradually inclined, while the inner slope is very steep and generally assumes a concave curvature with cornices hanging over the edge. The crest in Fig. 3 attains a height of about 50 m. The shape, height, and areal extent of the fosse-drift are dependent on many factors including wind speed, shape of the obstacle relative to the wind direction, and the texture of the snow.

Again the size and shape of the crystals play a major role in the sorting of the deposit. As would be expected, the larger crystals are deposited in the immediate vicinity of the obstruction. An abrupt decrease in grain size and angularity is observed on the outer slope directly below the crest of the drift. Thence the grain size decreases in proportion to the distance from the apex. This form is rather stable and, after induration, assumes a permanent position, with occasional variation in shape and volume. The main features of such forms, however, remain preserved well enough to be of appreciable significance. The behavior of snow in such cases is quite analogous to that of sand, and the fosse-drift is essentially a "snow dune" with a slight difference in the grading of grain size—the sand grains of a dune being finest at the crest, almost homogeneous, except for a small percentage of coarser grains at the bottom.

*Current ripple marks*

Ripple marks in the snow belong almost exclusively to the current-type structures in sedimentary classification. They develop in the same way as sand ripples, and are invariably formed on the lee side of barchan-like forms or rounded sastrugi of large dimensions. The windward zigzag border of the ripples in Fig. 4 outlines the crest of the snow form, and its protruding termini consequently point upwind. Fresh ripples of soft, dry snow eventually become hardened, and may be buried under a layer of coarse granular snow. In the absence of further wind action the original ripples are preserved, and their contours are thickened by the new layer. Figure 5 shows ripples coated with

**Fig. 5.** Well-developed current ripple marks coated with coarse crystals of snow

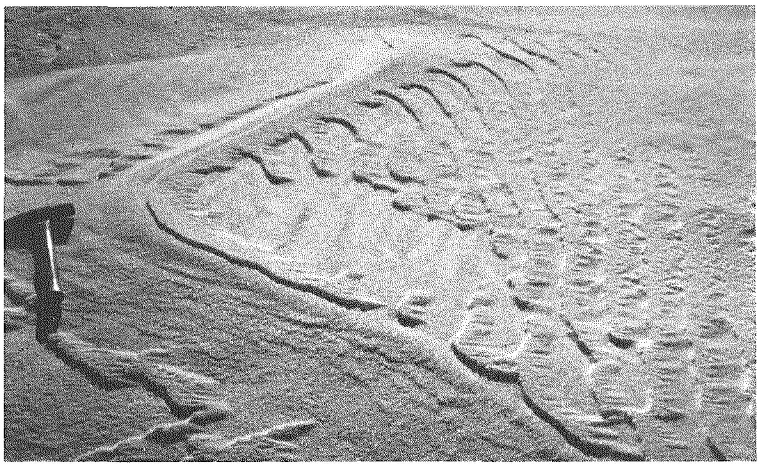

**Fig. 6.** Transverse angular ribs developed in ripple troughs. Note original ripples underlying the layer of course snow

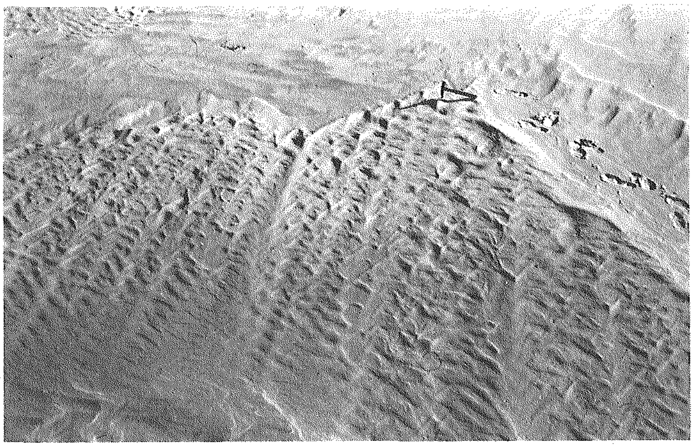

**Fig. 7.** Columns of Y-shaped ripples, interlacing and aligned along axes parallel to wind direction

coarse snow crystals accumulated during a gentle fall from a sky made hazy with a cover of cirrostratus clouds. When these crystals are subjected to wind erosion, the resulting pattern (Fig. 6) assumes the shape of transverse, angular ribs developing in the troughs of the ripples. A careful look into the photograph will show the original ripples underlying the partially-eroded layer of coarse snow. All ripple marks are steeply inclined when narrow (Fig. 4) and gently inclined when broad (Fig. 5), decreasing in size away from the crest.

Whereas most of the common snow ripple marks display close similarity to those of sand, in shape and mode of formation, a peculiar pattern of snow ripples (Fig. 7) was not seen in any of the sand patterns observed by the writer in the desert. This pattern is composed of long columns of interlacing, Y-shaped ripples. The columns are aligned along axes parallel to the wind direction. Each ripple faces the wind—the fork of the Y toward the wind, and the tail to leeward. The whole pattern, however, occurs in the same region with the conventional type of ripples.

*Barchanoids*

Barchanoids are snow forms similar to sand barchans in their mode of occurrence and mechanics of movement, but whereas sand barchans assume a rather consistent pattern throughout a certain area, barchanoids differ and vary widely in shape and overall pattern.

In spite of the fact that snow can form lee-faces*, concave and overhanging due to the cohesive force of the individual crystals, as shown in the walls and cornices of deep fosses, and that slip-faces of sand dunes and barchans cannot attain a slope steeper than the angle of repose, yet barchanoids observed during this study were found to have lee-faces not steeper than the angle of repose for sand. In fact, almost invariably, barchanoids were not higher than 1 m at the crest, with lee-faces not steeper than 30°. The general shape of barchanoids is more triangular than crescentic. The angle between

* The term "lee-face" is introduced here as the snow equivalent of a sand slip-face, due to the absence of slippage in snow.

**Fig. 8.** Barchanoid forms similar to sand barchans

the horns varies from obtuse to acute, and the apex (pointing upwind) mostly acute. Occurrence is rarely in singles (Fig. 8), but comonly in double- and compound-barchanoids extending for scores of meters at a time. Acute-angle barchanoids lack the mirror-image profile which exists in a typical sand barchan along a median plane. The symmetry of the barchanoid depends on the direction of the wind. Obtuse-angle barchanoids result from a steady wind stream in a given direction; these contrast markedly with the acute-angle barchanoids effected by variable winds. Figure 9 illustrates the origin of this type of barchanoid, beginning with a transverse snow ridge, and acquiring an additional ridge smaller in size and longitudinal to the wind direction. This is illustrated by the erosional ridges on the subsequent horn, which are in line with the prevailing wind. Such barchanoids occur individually and in isolated groups of separate individuals, rarely compacted or compounded.

The advance of barchanoids on hard, glazed snow surfaces is faster than on soft,

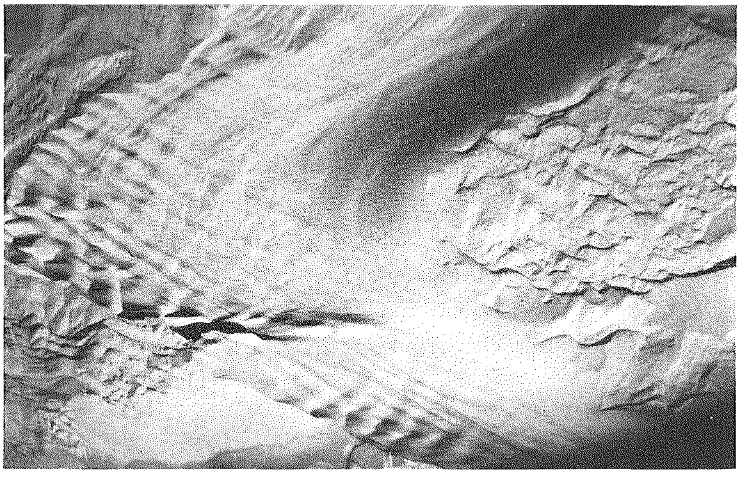

**Fig. 9.** Acute-angle barchanoid showing transverse erosional ridges on a secondary horn (downside half of the picture)

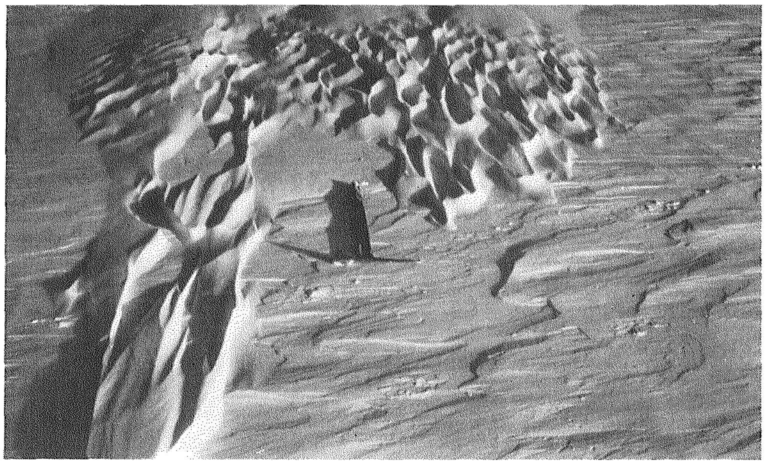

**Fig. 10.** Barchanoid movement effected by snow erosion at the tail and deposition on the lee face

rough snow. The process involves simultaneous erosion and deposition at the windward and leeward ends of the barchanoid, respectively. Figure 10 illustrates this process whereby the wind erodes the snow at the windward end, creating young, easily-carvable sastrugi, and depositing the eroded snow on the lee side. This observation was made at $-50°C$ when the snow surface was fully glazed, and the blowing snow advanced freely (about 2 m/hr) in the shape of tailed barchanoids. Analogy can be made here between barchanoids and barchans in the characteristic that both forms shift constantly and change position with the wind.

## IV. Erosional Structures

Erosional structures in the snow are very diverse and the result of numerous factors governing the process of erosion. They include sastrugi, irregular patterns, pits, and footprints.

*Sastrugi*

Most conspicuous of all erosional forms are the sastrugi (singular sastrug, from the Russian *Zastrug*). Sastrugi have been discussed amply by numerous writers, and attempt is made here to describe only their mechanism of formation or their physical properties. They generally occur in elongate forms, undercut at the head in varying degrees and having stratified bodies, the result of differential wind carving. In undulating, open terrain, and in the vicinity of mountain slopes, a wind-swept snow surface exhibits rough, hard sastrugi up to 2 m in height and 6 m in length. An area with potential development of sastugi is carved initially in a way giving a "Grand Canyon" effect (Fig. 11). Glazing of the topmost layer creates a resistant stratum which eventually protudes while the underlying layers are being eroded away. The resultant overhanging slab is eventually overcome by its own weight and either breaks off or bends down to touch the lower snow level. The shapes of such undercut and bent sastrugi are quite numerous; Figs. 12–16 illustrate a few stages, following the initial carving, then the bending and

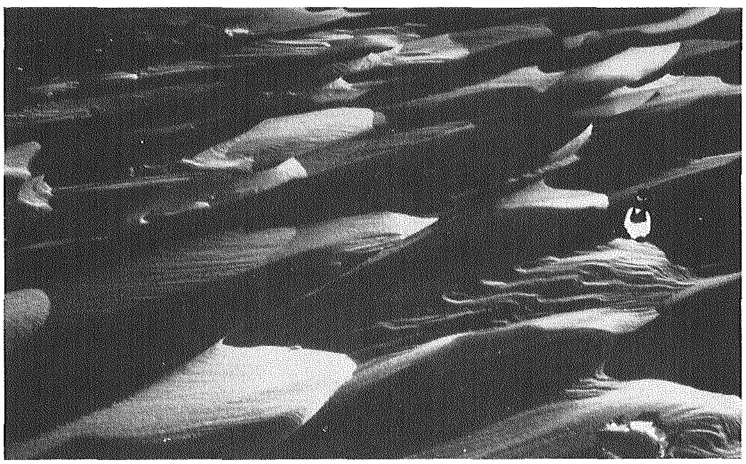

**Fig. 11.** Sastrugi in the initial stage of development

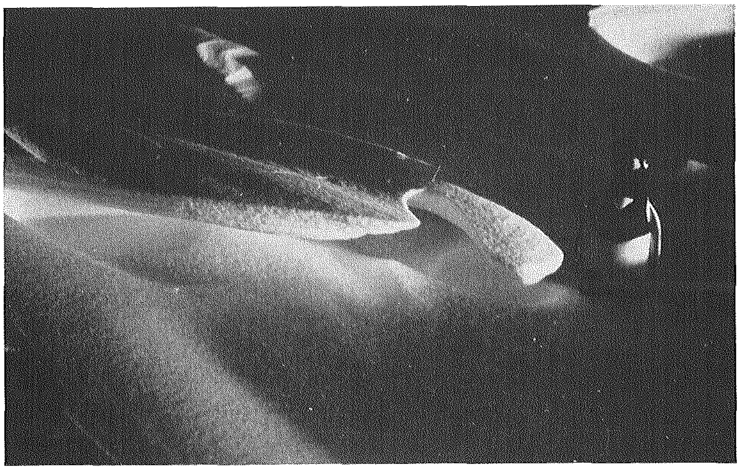

**Fig. 12.** Second stage following the initial carving of a sastrug

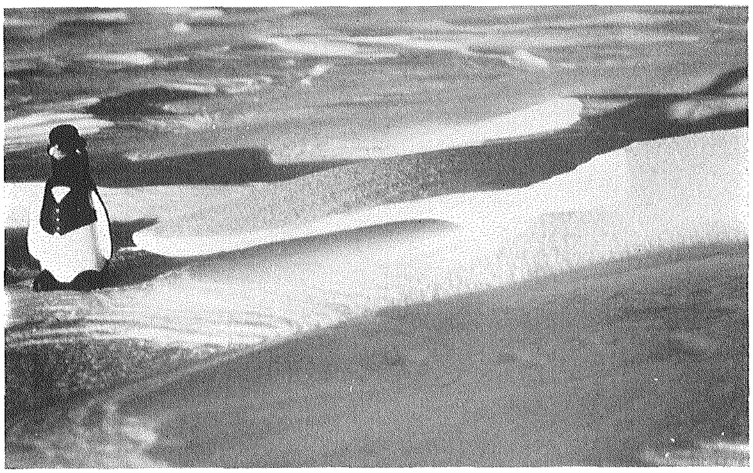

**Fig. 13.** The third or fouth stage when sastrugi are undercut but remain strong enough to retain their shape

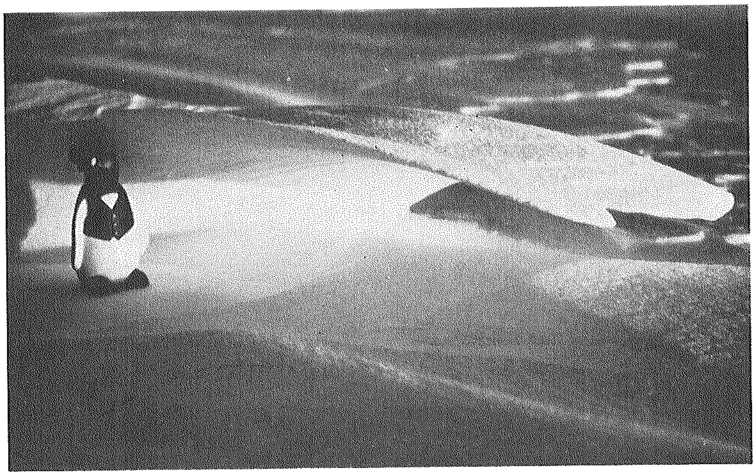

**Fig. 14.** A mature sastrug in the bending stage

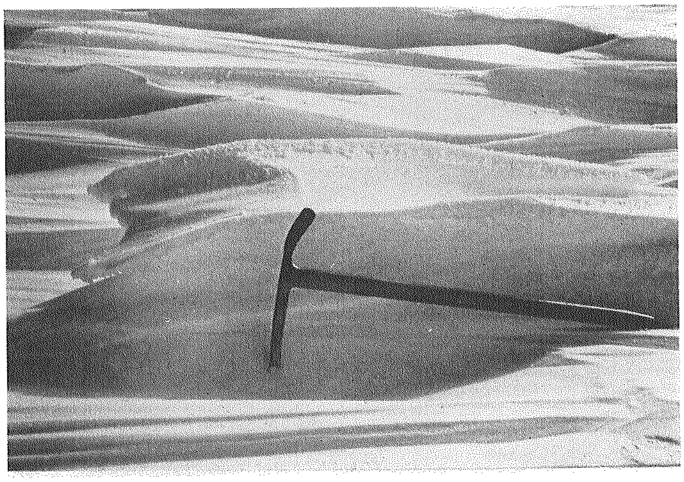

**Fig. 15.** Irregularly carved sastrug being cut through its center

**Fig. 16.** Final remains of an old-age sastrug completely bent and touching the original surface

eventual disappearance of the sastrug. It is worth mentioning also that some forms evolve where the head becomes so thin and relatively short, that the wind bends it upward and backward.

At about −35°C the snow particles are dry, loose, and friable. A mild wind, not strong enough to scour an already-formed obstruction, will deposit snow particles around a sastrug in the form of a fosse, and by the same principle. Further lowering of the temperature hardens the surface, and higher wind speed with scouring ability will carve the original sastrug on the surface rather than undermine the head. The result is sharp grooving (Fig. 17) similar to converging glacial grooves on rock surfaces. Continued deposition eventually results in the burial and preservation of such snow forms; these 'fossil' forms are usually observable in subsurface stratigraphic studies conducted in glaciological snow pits (Fig. 18).

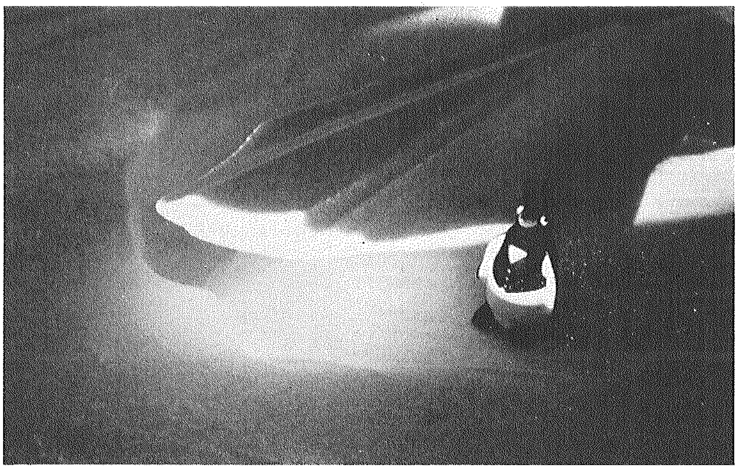

**Fig. 17.** Sastrug showing sharp grooving by high winds

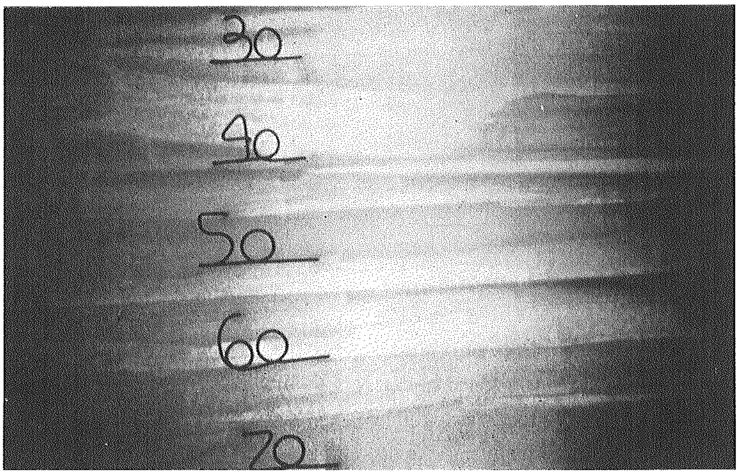


**Fig. 18.** Fossil surface structure observed in stratified snow. Numbers indicate 10 cm intervals

At temperatures below $-40°C$ the snow surface becomes so glazed that the slightest wind-drifted snow assumes several forms of sastrugi that are short-lived and disappear within a few hours. The *lanceolate* sastrug (Fig. 19) is a typical example of this form; it is usually streamlined, narrow, and not exceeding $1\frac{1}{2}$ m in length. It occurs individually or in groups, upwind on the erosional side of a barchanoid.

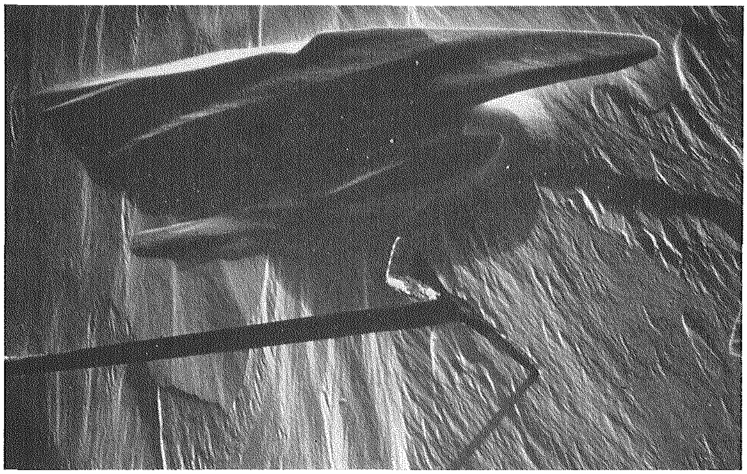

**Fig. 19.** Typical lanceolate sastrug formed of soft snow over a glazed surface

Another example of unstable sastrugi is the *trowel-shaped* form which occurs in series and forms a scalloped border at the crest of a transverse wave (Fig. 20). The individual forms are usually elongate and connected by prominent narrow ridges with a concave depression between every two ridges. They point to the wind and are probably similar to forms described by Cornish (1914, p. 138, Fig. 11). They occur mostly in freshly-blown snow on relatively smooth surfaces.

**Fig. 20.** Trowel-shaped sastrugi showing a scalloped border pointing to the wind

*Irregular patterns*

Soft, crystalline snow behaves in two different ways in forming irregular patterns on hard surfaces. One pattern (Fig. 21) results from rounded, irregular forms, joined together with tails on the lee side, and sharp sides inclined to windward. The main factor controling the formation of these forms is the shape of the individual crystals. The snow is usually dry, loose, and prismatic. The prisms assume a certain orientaion

**Fig. 21.** Rounded, irregular forms of loose, dry, prismatic snow

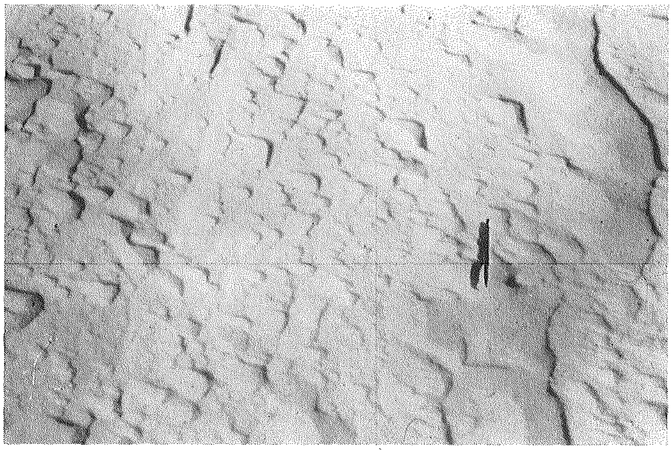

**Fig. 22.** Forms of negative relief formed opposite to those in Fig. 21

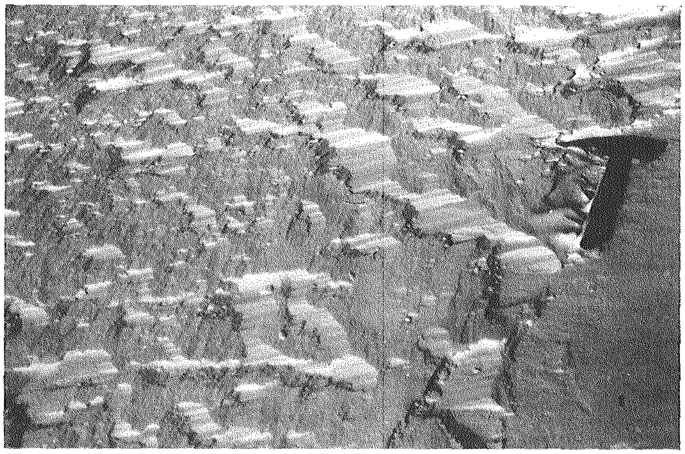

**Fig. 23.** Cleavage pattern of erosion in hard prismatic snow

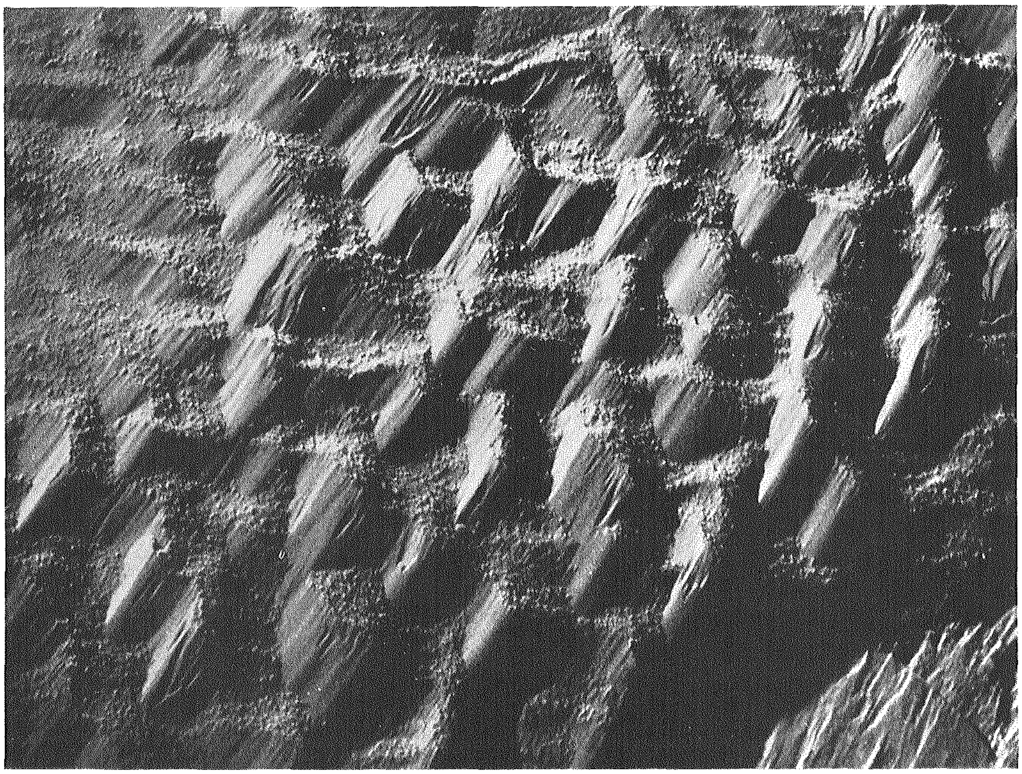

**Fig. 24.** Cleavage pattern with large angular ridges

relative to the wind direction, and are eroded accordingly. The second pattern (Fig. 22) is the direct opposite of the first. It is pitted rather than protruding. No explanation can be found as to the difference in form, for all the factors involved in the formation of the first apply equally to the second; they also occur side by side.

When prismatic snow is hardened the cleavage pattern (Fig. 23) of erosion results. The eroded surfaces display straight lines at right angles to each other, the longer cleavage longitudinal with the wind direction, and the shorter transverse. In the same type of hard snow a similar pattern (Fig. 24) occurs where the cleavage pattern has taken the shape of large angular ridges, serrated and pointing to the direction of the wind.

*Pits*

In all the instances cited above, the surface structures result from the erosion of snow with varying degrees of compaction, thus giving the wind a grip and a place from where to start its action. However, on flat, smooth, glazed snow, the forms resulting from wind erosion (Figs. 25 and 26) are similar, but opposite to barchans, and on a much smaller scale. The snow crystals bombarding the slick surfaces, in turbulent wind at temperatures below $-45°C$, encounter no obstruction which would result in prompt deposition, but collide with the surface with an impact which results in dents and pits. The successive collisions eventually succeed in prying loose a few snow particles from the hard surface. Once the glazed surface is etched, impact of this bombardment becomes greater with depth due to the softer character of the underlying strata,

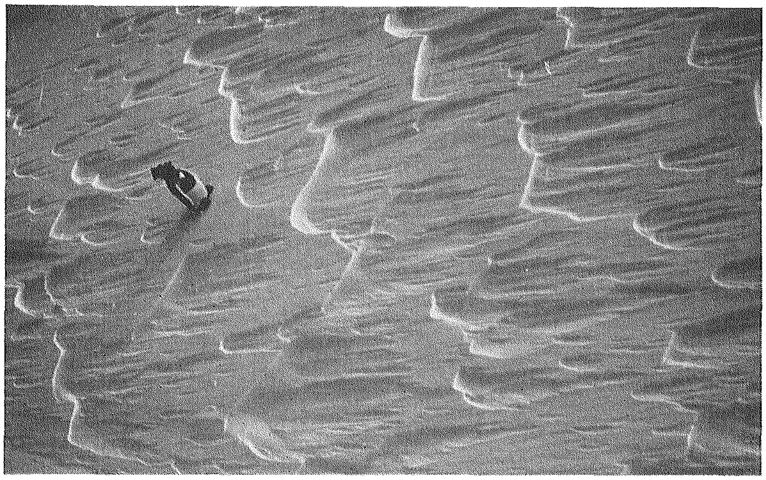

**Fig. 25.** Pitted patterns eroded on flat, smooth, glazed surfaces

**Fig. 26.** Crescent-shaped pits similar to barchanoids but on a much smaller scale

and the pits assume a crescentic shape similar to that of barchans, but facing the wind.

*Footprints*

At −55°C the writer, accompanied by a husky, carried out the interesting experiment of producing footprints in the snow and observing the result of wind erosion on the disturbed surfaces.

The resulting structures were of two distinct types: one a depression (mold), the other a protrusion (cast). Obviously, the main agent involved in their creation is wind. Next comes the condition of the snow at the time of footprinting. Wind-blown snow stays loose and soft until the temperature drops low enough to cement the individual crystals and compact the deposits. When soft snow is stepped on, the area under the foot is compacted by the weight of the body. Differential erosion will then dispose of the rest of the surrounding snow, leaving the compacted footprint protruding high

**Fig. 27.** Human footprints preserved by compaction of soft snow and subsequent differential erosion

**Fig. 28.** Canine footprints on compacted soft snow eroded to form casts

**Fig. 29.** Canine footprints on hard snow eroded to form molds

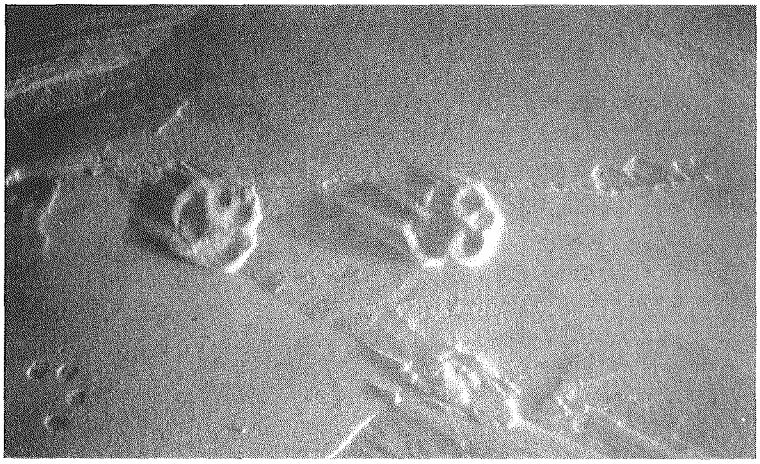

**Fig. 30.** Casts and molds of footprints in soft and hard snow, respectively, occuring side by side

above the original level (Figs. 27 and 28)*.

On the other hand, hard snow (already compacted and well cemented crystals) resists wind action, except where the snow has been disturbed. A step on this snow leaves a depression which becomes susceptible to erosion, allowing the wind to get a grip on the otherwise-resistant snow. The scouring effect of the wind results in a clear mold (Fig. 29) with conspicuous grooves showing the direction of the wind. When stepping is done on patches of hard snow adjacent to recently-blown snow, casts and molds occur side by side (Fig. 30).

* The same mechanism left a Sno-Cat perched on four pillars of snow, each supporting a pontoon 50 cm above the eroded surface.

## V. Conclusion

The significance of these observations lies in the light they shed on the characteristics of snow, and the analogies that could be drawn and applied to other sediments. Footprins, impressions of boots, and other structures have better potential of being preserved than does the original smooth and soft surfaces. In paleontological terms we might say that these structures possess a fossilization potential slightly higher than the surface surrounding them. This, of course, depends on the speed with which these structures become buried, and the micro-meteorological parameters which provide subsequent consolidation and densification of the covering snow particles.

The preservation potential of these structures is essentially the difference in compaction between the stucture and the surface. This difference creates a time-lag factor of resistance to alteration in shape, which provides the feature with longer-lasting durability and, hence, a chance to await the prevalence of conditions favorable to preservation.

By understanding the physical characteristics and the mechanisms involved in the formation of these surface features, their interaction with their environmental parameters, and comparing them with corresponding factors affecting other sedimentary deposits, it will be possible to reconstruct certain ecologic conditions prevalent at the time of deposition.

## References

1) BAGNOLD, R. A. 1941 The Physics of Blown Sand and Desert Dunes, Methuen Co., London, 265 pp.

2) CORNISH, V. 1914 Waves of Sand and Snow and the Eddies which Make Them, T. Fisher Unwin, London, 383 pp.