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Snow stratigraphy observations in the katabatic wind region of eastern Wilkes Land, Antarctica

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CONTENTS

APPENDIX

FIGURES

TABLES

SNOW STRATIGRAPHY OBSERVATIONS IN THE KATABATIC WIND REGION OF EASTERN WILKES LAND, ANTARCTICA

by

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ABSTRACT

Stratigraphical measurements to a depth of 2-3 m in pits were made along a glaciological traverse route from 68°35'S, 113°19'E to 69°00'S, 130°48'E at approximately 2000 m elevation in Wilkes Land, Eastern Antarctica. Observations of the snow surface and meteorological conditions began on 29 August and continued until 28 December whilst the stratigraphical measurements were made between 28 September and 20 November 1982.

The traverse route lies entirely in the katabatic wind region which encircles the central plateau. The snow surface which develops under the influence of such a constant wind was observed to have some interesting properties.

(1) A very hard crust had developed by September (early spring) and this was covered by a thin (~1 mm) icy glaze. These were observed in conjunction over the length of the traverse and over several years of accumulation as measured in the pits. It is suggested that the glaze is formed by the dissipation of the kinetic energy of drift by friction and the crust by 'sintering' from vapour transport within the snow pack.

(2) Erosional processes are very important in the development of the snow cover. Sastrugi were ubiquitous and reached heights of up to 60 cm, thereby introducing noise levels sometimes equal to or greater than the annual layering observed in the pits. This complicates any inter-site correlation and disrupts the interpretation of annual layering from the stable isotope ratio, $^{18}O / ^{16}O$ ($\delta^{18}O$).

(3) The existence of temperature gradients within the snow surface sufficient for the formation of deep-hoar was inferred from its occurrence at least once in most annual layers at each site.

(4) Summer snow surfaces were considerably softer than those of winter and extensive layers of deep-hoar were observed to develop within them.

1. INTRODUCTION

The Antarctic Plateau provides a unique environment for a study of the densification and recrystallisation of snow as it is high, cold and windy. In most areas above 1000 m little, if any, melting takes place and thus it is possible to study the metamorphism of the snow surface when only the solid and vapour phases of water are present. Furthermore, wind action plays an important role in the development of the snow surface, particularly in the katabatic wind zone which encircles most of the central plateau (Kotlyakov, 1961). This is a belt several hundred kilometres wide beginning at or near the coast, with average wind speeds above 10 ms^{-1} (20 knots) for a distance of at least 300 km inland.

It was in part of this region that an ANARE traverse based from Casey operated in the spring and summer of 1982. The purpose of the traverse was to remeasure and extend a survey line (designated 'GD-line') established in 1980 and extended in 1981. The line consists of 375 line markers spaced every 2 km with an ice-movement survey-marker (via Doppler Satellite Positioning) every 50 km. It proceeds from A028 (68°25'S, 112°12'E) to GD03 (3rd ice-movement marker) at (69°00'S, 115°30'E), thence along 69°S to GD15 at 130°48'E. At the ice-movement markers simple stratigraphical measurements were carried out in pits.

The traverse began on 29 August and continued until 29 December. Over this period it was possible to maintain continuous qualitative observations of the snow surface and meteorological conditions to augment the pit data.

2. EXPERIMENTAL METHOD

At the ice-movement stations (GD01-GD15) pits were dug to a depth of about 2.5 m by bulldozer. They were carefully sited to avoid areas possibly interfered with by the 1980 and 1981 traverses and always crosswind to minimise chemical contamination from the parked tractor trains. When the pit was finished a face was selected and 'finished' by hand spade to give a metre-wide work face.

A tape measure was pinned to the top of the face and dropped to the bottom of the pit so that depths could be easily measured.

The rest of the measuring equipment consisted of: a stainless steel knife to clean the 'face' and search horizontally for changes in layers and/or depths and to chip sample pieces into clean plastic melting bottles; a 0-10 kg Canadian hardness gauge with 2 tips (0.1 cm^2 and 1.0 cm^2) to measure hardness; and a stainless steel 'cookie-cutter' of 100 mL^3 volume to cut samples for weighing with a 0-1 kg spring balance ($\pm$ 0.002 kg).

When the 'face' was ready for measuring a quick search was made for the hard winter layers and their associated glazes using the stake measurments at the site as a guide. This defined the annual layers. The face was then measured by layer for density, hardness and a qualitative description of crystal size and type. A sample of snow equivalent to 50 mL water was taken from what were thought to be the winter and summer layers for measurement of the stable isotope ratio $^{18}O/\ ^{16}O$.

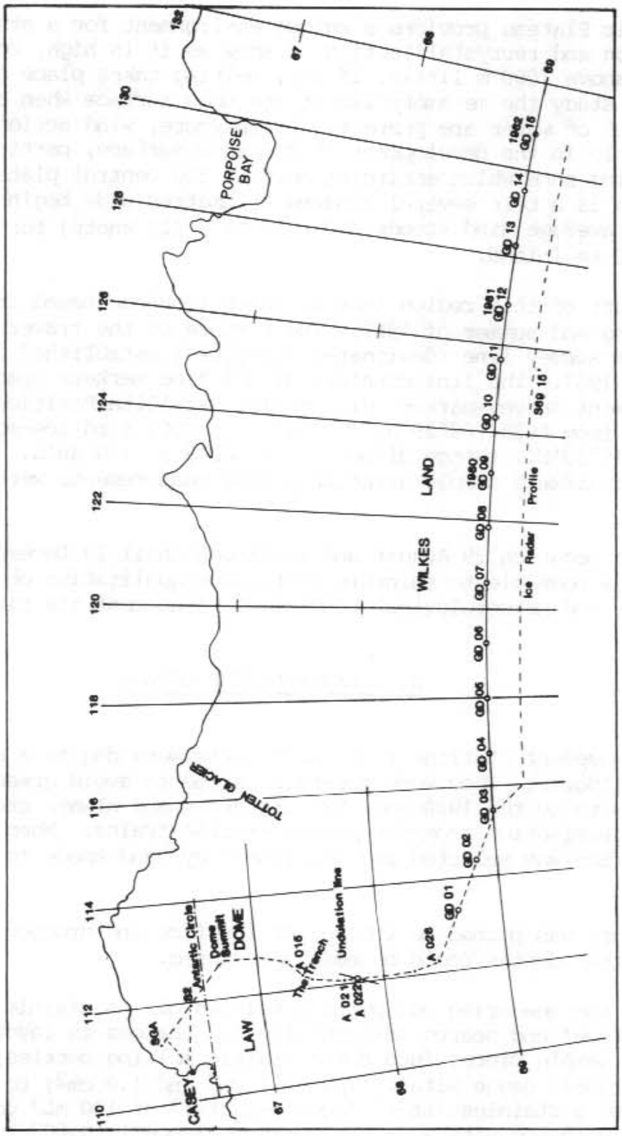


Figure 1. 1982 Casey spring traverse route.

At each site, the working face was at least 1 m wide. However, because of the shape of the pits, (Figure 2) it was often possible to check for horizontal continuity in the upper layers to a distance of several metres.
In this way an estimate of 'noise' levels could be made, so that the stratigraphical profiles were intuitively 'smoothed' before recording.

3. OBSERVATIONS

The following well correlated observations of the snow surface and synoptic conditions were made over the duration of the traverse.

(1) For about 90% of the time along the traverse route the wind was ESE with clear, sunny conditions. Initially the average wind speed was about 25 knots (~13 ms^{-1}) with moderate ground drift and temperatures averaging about -35°C. This changed gradually over the 3 months spent in the area to 15 knots (~8 ms^{-1}) of average wind and -20° average temperature, with occasional days of moderate drift. In the period in which the stratigraphical measurements took place 3 significiant incursions of maritime air ('cyclonic intrusion' (Watanabe, 1978)) took place, turning winds to the NW-NE, raising temperatures to about -15°C and dumping about 20 cm of fresh snow along the traverse route. These events are marked on the stratigraphical diagrams.

(2) On the snow surface a tough, virtually continuous wind glaze of about 1 mm thickness existed above about 1100 m elevation. This persisted until well into summer on those sastrugi left prominent after the 3 storms referred to above.

(3) There was a wind crust under the wind glaze, up to 300 mm thick, of average hardness 7 kg/cm^2 and up to 50 kg/cm^2. This was defined as the 'winter surface'.

(4) Uniformly 'tough' sastrugi existed everywhere along the traverse route; the 'toughness' being independent of the aspect of the formation with respect to the sun. The sastrugi were up to 300 mm high singly and up to 1000 mm in clumps. The latter were probably eroded barchan dunes, and had developed into fantastically convoluted shapes, sometimes undercut. In general, one 'system' or 'clump' of sastrugi could be discerned in every 10 m^2 or so, this changing by a factor of 2 each way depending on location. A 'system' (i.e. an eroded barchan) was often carved into 20-30 individual edges or pockets, which were always aligned ESE-WNW.

(5) As the synoptic conditions moderated the sastrugi edges left prominent after the 3 storms become noticeably smoother.

(6) As the sun's noon elevation increased, friable, thin (<0.5 mm) radiation glazes formed on new snow and the winter wind glaze left on the exposed sastrugi often became indistinguishable from the hard wind crust.

(7) Summer snow surfaces were softer than those formed during the winter.

(8) At lower elevations, around 1200 m, 'sand-snow' or 'deep hoar' developed within the still exposed winter crust (sastrugi tops). For example, at A022 (elevation 1160 m) a layer about 150 mm thick had developed about 50 mm below the wind glaze. Similar formations, although up to only 50 mm thick, were observed in the pits at 2000 m elevation.

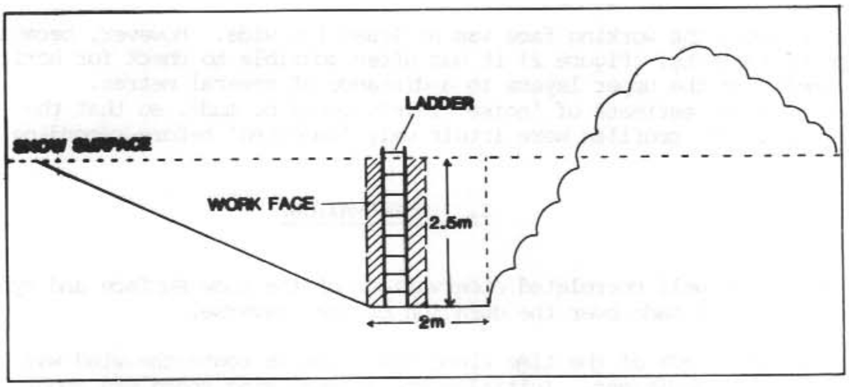


Figure 2. A typical snow pit.

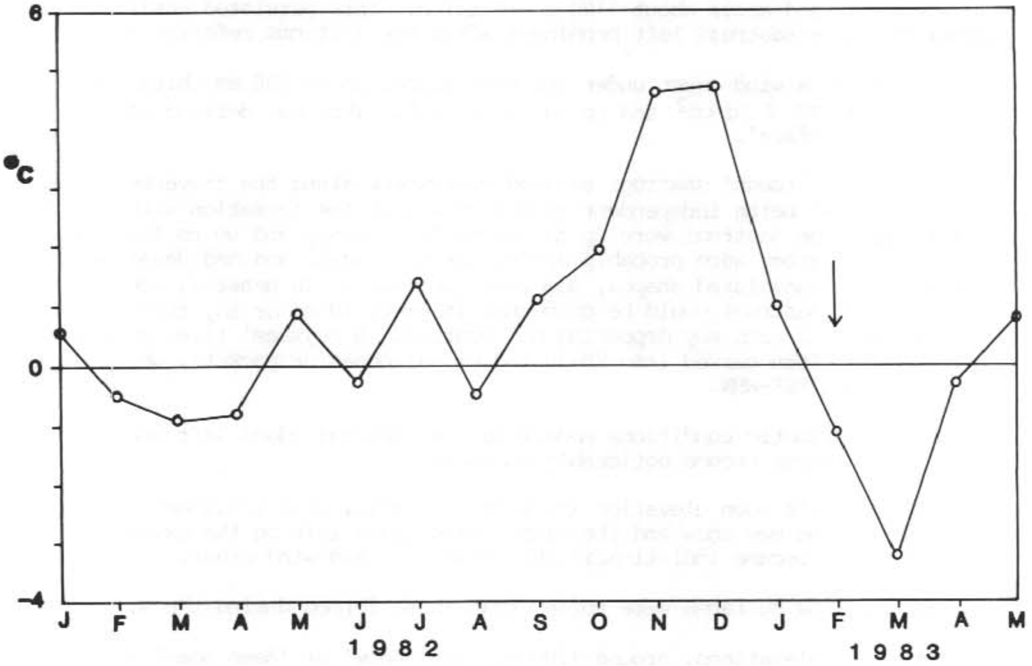


Figure 3. Temperature gradients at autostation 8561 from surface to -100 mm, increasing to -200 mm at arrow.

4. DISCUSSION

Table 1 and Figure 3 are a summary of weather data collected by Automatic Weather Station 8561 (personal communication) in an area with similar climatic characteristics to the GD line. The Automatic Weather Station is at a similar altitude to most of the 'GD stations' in the katabatic wind zone. There are two important features:

(1) Strong winds play an important role in the development of the snow surface; and

(2) Extremes of temperature occur even in mid-winter.

The constant strong wind during the winter and spring (say May-October) is responsible for the development of the wind glaze and its underlying crust. There are probably two mechanisms. Firstly, the frictional heat generated by the drifting snow bouncing and rubbing along the snow surface must be sufficient to cause enough melting to form a tough ice-like layer (Appendix I).

Secondly, pressure and temperature gradients caused by the wind close to the surface facilitate the movement of water vapour in porous snow and cause 'sintering' and densification of the surface layers.

Hence, winter surfaces are consistently harder than those of summer and were used to 'date' the layering observed in the pits.

The summer surface that had developed by mid-December was softer and smoother than the winter surface. The snowfalls accompanying the three storms caused most of the sastrugi hollows to be partially filled and the lighter winds failed to produce any significant new sastrugi. Thus it was possible for a radiation crust to develop on new summer snow between the sastrugi tops. The latter underwent partial evaporation and/or melting causing the radiation crusts to merge into the harder winter surface boundary where the latter protruded. The winter glaze and crust buried by summer snow maintained its integrity.

The extremes of temperature that occur throughout the year, and in particular during the summer months, are responsible for the formation of deep hoar. There are probably two mechanisms. Firstly, solar radiation warms the surface during the summer and produces a vapour pressure (or temperature) gradient to form between the warm surface and the colder layers beneath, thereby causing hoar frost to form in an intermediate layer. Secondly, an autumn or winter storm is likely to deposit snow at a higher temperature than that of the surface on to which it falls. Thus a temperature gradient will exist for a short time (of the order of days) sufficient for the formation of a thin (~10 mm) layer of hoar.

Hence, thick layers of hoar with well developed crystals (~2 mm in size) are probably a summer phenomenon, whilst the thinner layers of finer crystals (~1 mm) are probably exclusively an autumn and winter phenomenon where the temperature gradients are relatively short-lived.

Wind blown snow is also the predominant erosional mechanism in this region of Antarctica. Although there was no evidence from the stake measurements that erosion predominated over accretion on an annual basis, it was obvious that some of the seasonal layers were missing in the pits. It was also obvious

AUTOMATIC WEATHER STATION 8561, 68°39'S, 60°33'E, 1850 m asl

1982	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	YEAR
Mean Temperature (°C)	-16.4	-22.5	-30.5	-36.0	-36.0	-39.6	-36.1	-40.6	-39.1	-31.2	-20.6	-14.1	-30.2
Maximum Temperature (°C)	-6.4	-11.6	-20.3	-24.6	-23.7	-24.6	-22.1	-25.7	-27.6	-21.0	-10.5	-2.4	-2.4
Minimum Temperature (°C)	-26.8	-32.9	-45.2	-43.8	-47.6	-45.6	-48.8	-49.9	-53.4	-41.5	-39.5	-25.4	-49.9
Mean Station Level Pressure (mb)	758.3	779.0	772.9	771.2	773.2	772.3	773.6	767.8	764.6	773.9	783.2	791.1	775.7
Mean Wind Speed (kts)	15.5	20.1	18.0	23.8	24.3	N/A	23.0	22.0	21.1	21.7	N/A	N/A	N/A
Maximum Wind Gust (kts)	41 (SSE)	68 (ESE)	48 (SSE)	55 (SSE)	52 (N/A)	N/A	53 (SE)	51 (N/A)	50 (ESE)	52 (SE)	N/A	N/A	68 (ESE)
Days Strong Wind (22 Kts)	10	17	17	23	24	N/A	26	22	21	19	N/A	N/A	N/A
Days Gale Wind (>34 Kts)	0	3	2	5	9	N/A	7	3	2	1	N/A	N/A	N/A

Table 1. Summary of weather data collected by Automatic Weather Station 8561.

Mark	Acc metres snow	Period 1980 - 81	Acc metres snow	Period 1981
GD001	0.12	13 Oct - 2 May	0.98	2 May - 17 Oct
GD002	0.86	13 Oct - 2 May	0.54	2 May - 17 Oct
GD003	0.69	13 Oct - 2 May	0.36	2 May - 17 Oct
GD004	0.48	13 Oct - 2 May	0.80	2 May - 17 Oct
GD005	0.08	13 Oct - 2 May	1.53	2 May - 17 Oct
GD006	0.46	13 Oct - 2 May	1.02	2 May - 17 Oct
GD007	1.13	13 Oct - 2 May	0.84	2 May - 17 Oct
GD008	0.16	13 Oct - 3 May	1.32	3 May - 17 Oct
GD011	0.61	13 Oct - 3 May	0.72	3 May - 17 Oct
GD012	0.42	13 Oct - 3 May	0.74	3 May - 17 Oct
GD013	0.39	13 Oct - 3 May	1.16	3 May - 17 Oct
GD016	0.37	14 Oct - 3 May	0.99	3 May - 17 Oct
GD019	0.05	14 Oct - 3 May	0.66	3 May - 17 Oct
GD020	-0.07	14 Oct - 3 May	0.78	3 May - 18 Oct
GD022	-0.56	14 Oct - 4 May	1.81	4 May - 18 Oct
GD023	0.35	14 Oct - 4 May	1.15	4 May - 18 Oct
GD024	0.29	14 Oct - 4 May	0.84	4 May - 18 Oct
GD026	0.19	14 Oct - 4 May	0.76	4 May - 18 Oct
GD027	0.42	14 Oct - 4 May	0.90	4 May - 18 Oct
GD028	0.38	14 Oct - 4 May	1.07	4 May - 18 Oct
GD034	0.09	14 Oct - 4 May	0.53	4 May - 18 Oct
GD035	0.21	14 Oct - 4 May	0.57	4 May - 18 Oct

Table 2. Accumulation data GD001 to GD035.

that this phenomenon never extended more than a few tens of metres in all directions from the pit; in other words, the extent of a dune. The pits were always some distance from the accumulation (ice-movement marker) stake and it was often difficult to reconcile the position of the hard glazed layers with the stake measurements. However, the variation was always within the local sastrugi dimensions.

Accumulation measurements were available over the two previous years to GD09 at 4 and 6 km intervals and over the previous year to GD12 at 2 km intervals. The stakes were measured at the same time each year (early October - mid-November) and hence provide a reliable annual accumulation figure. No ablation (erosion) occurred at any of the stakes: the average for the GD line to GD12 for 1982 being 0.82 ± 0.25 m ($\pm 1\sigma$) of snow, ranging from 0.06 to 1.90 m.

The first 70 km of the line (A028-GD035) were traversed in May 1981. A comparison of the stake measurements made then to those in October 1981 (Table 2) show that autumn and winter accumulation predominates over that of spring and summer, in this region. However, no significant precipitation occured in a period of 4 weeks from 23 September to 22 October 1982. With reference to the appendix, a hiatus of this length in spring would be more than adequate for the formation of the observed wind crust and glaze.

Erosion of the snow surface mixes snow of various origins and ages, in an unpredictable fashion. Hence, it is unwise to attach any significance to inter-layer differences in δ^{18}C at each site. However, in correlating layers between sites (i.e. regional) it was sometimes possible to see similarities in the δ^{18}O value sequence. A true measure of δ^{18}O in this region would have to be done by sampling fresh snowfall directly.

Figure 5 is a summary of the stratigraphical observations and Figure 6 is an attempt at inter-site correlation. This is not a unique set of permutations, but self-consistency has been preserved by choosing what appears to be the hard spring surface as the winter-summer interface. A wind-glazed layer was commonly present on this surface, which aided in its identification. There is only one apparent anomaly. At GD09, a very hard, almost icy layer 40 mm thick was found at a depth of 830 mm. This was taken to be a winter surface left bare throughout summer and early autumn, allowing some melting to occur and hoar frost to form in a colder, covering layer when this finally adhered.

The study outlined above was preliminary and additional snow properites, such as temperature and crystal size need to be measured. A similar, improved study is taking place in the same region to the west of A028 this year (1983) and to the south in 1984. As Australian glaciologists gain experience in these studies, some understanding of snow metamorphism in these regions will develop.

Figure 4. Legend for Figures 5 and 6.

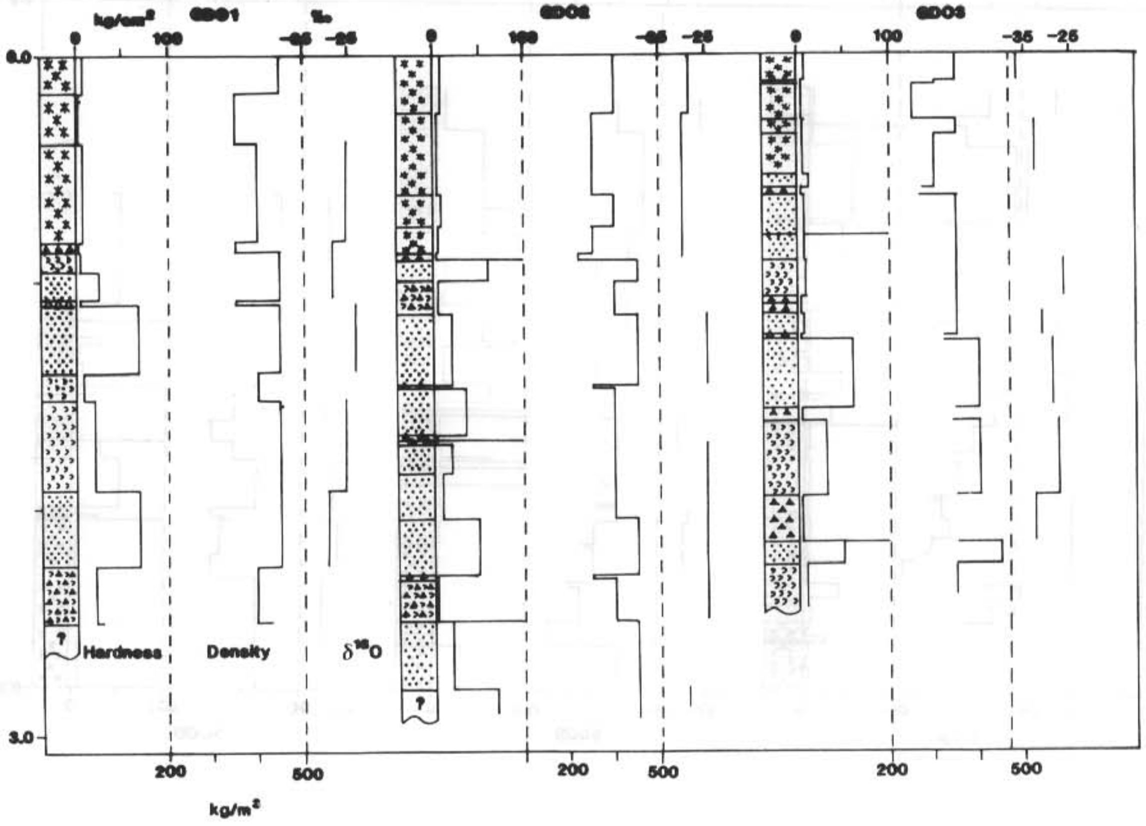
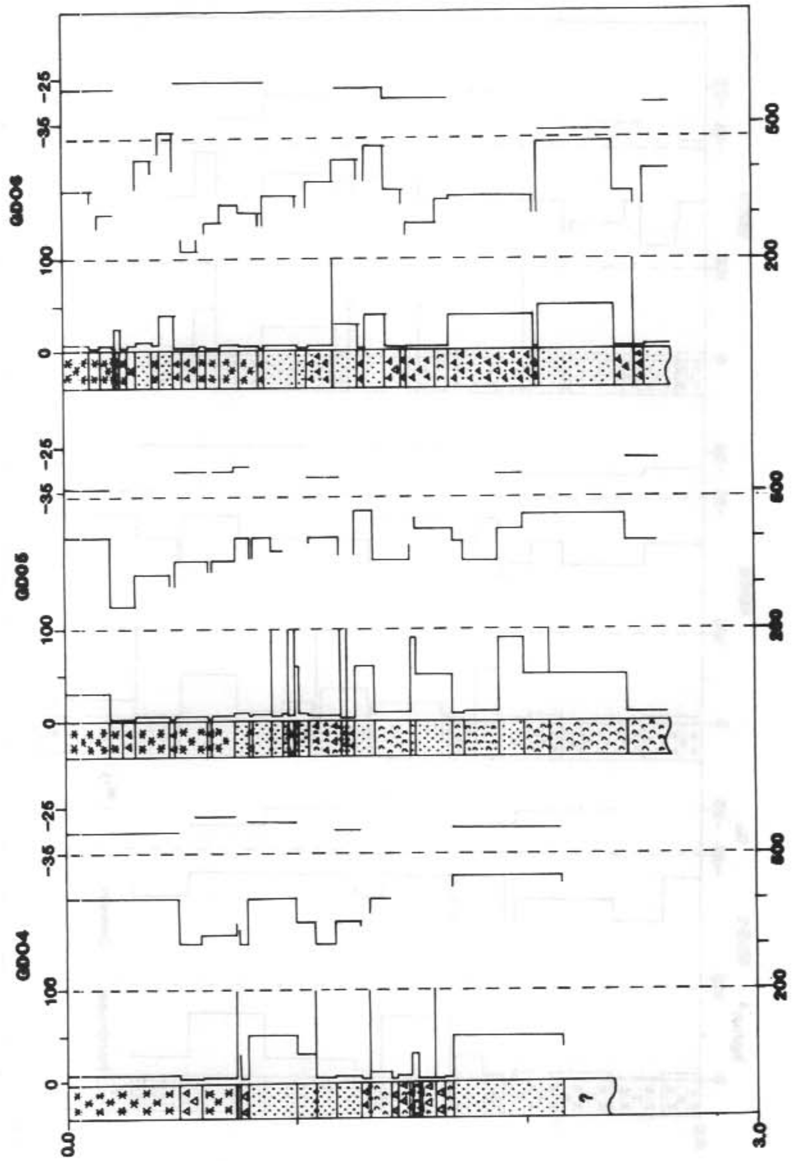
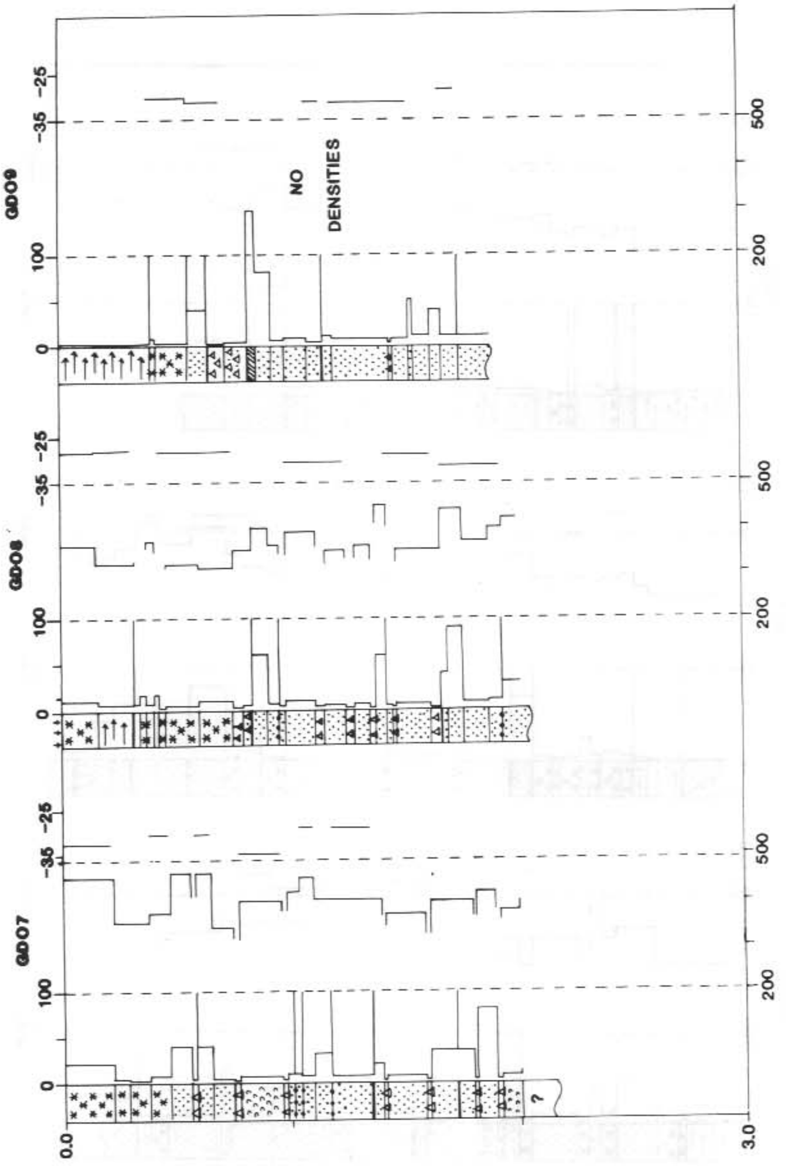


Figure 5. Stratigraphical data.



Stratigraphical data



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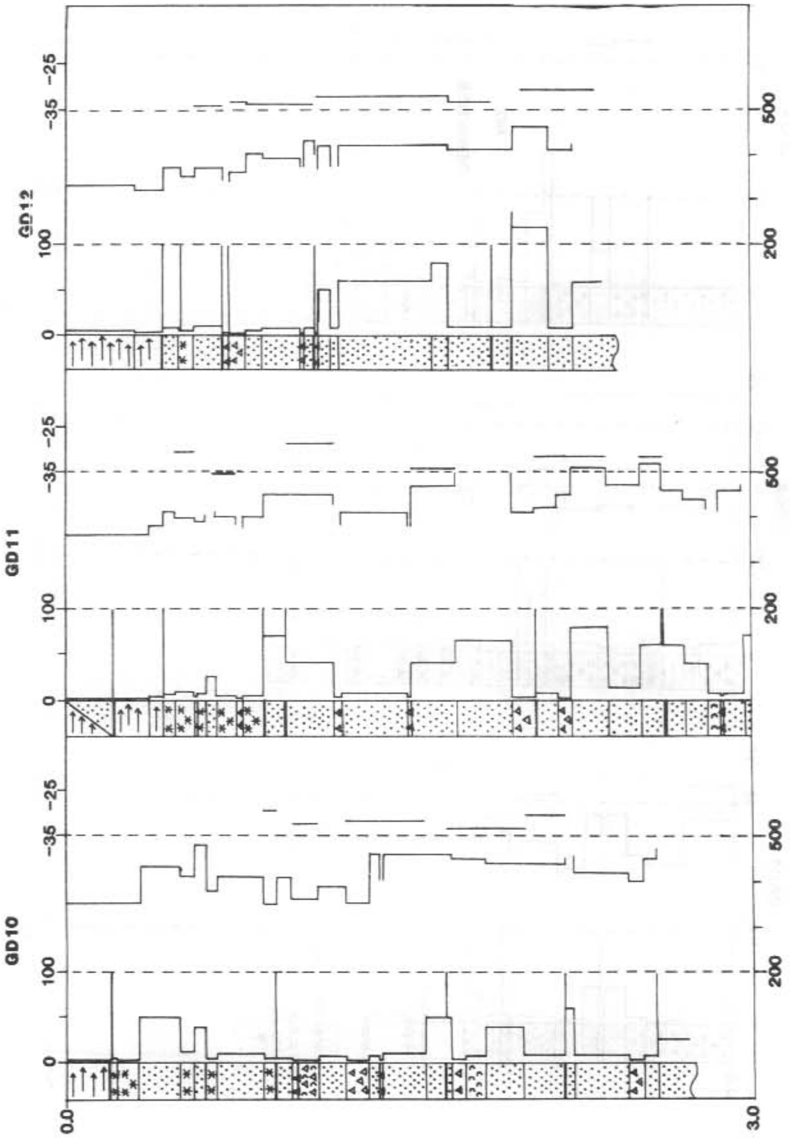

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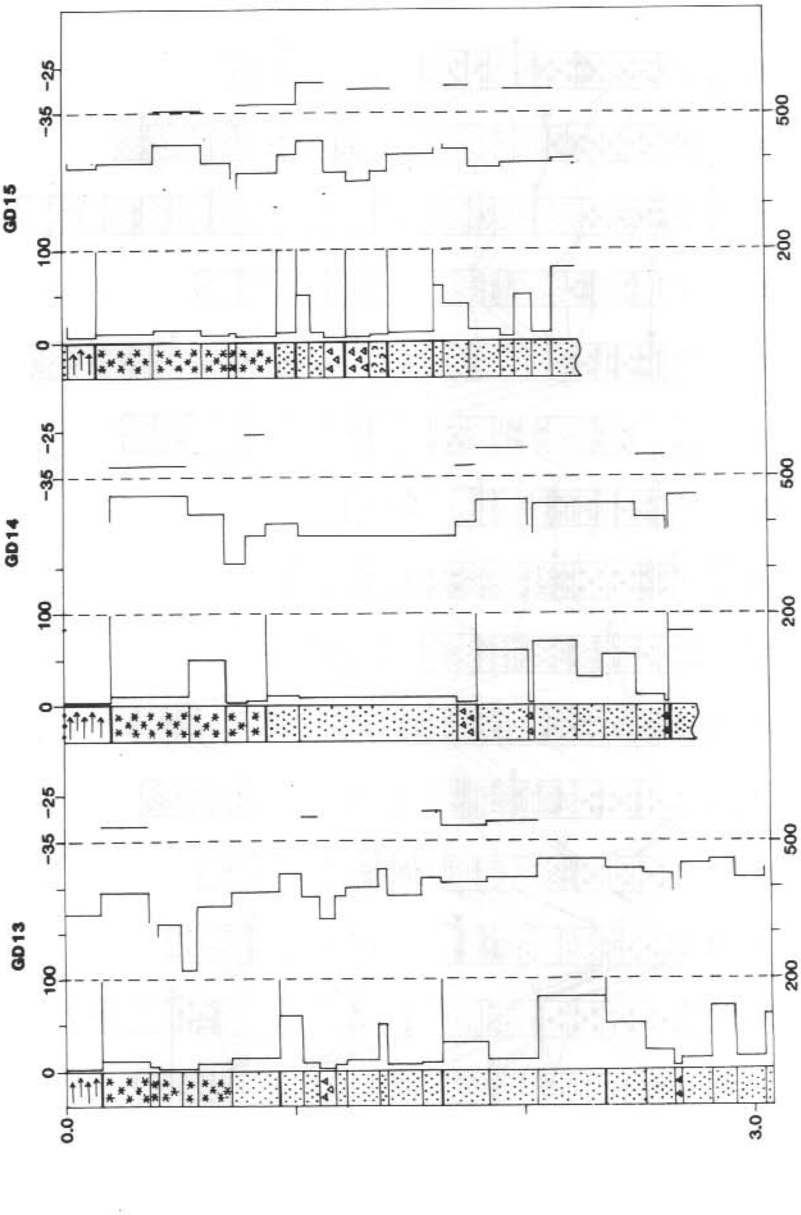

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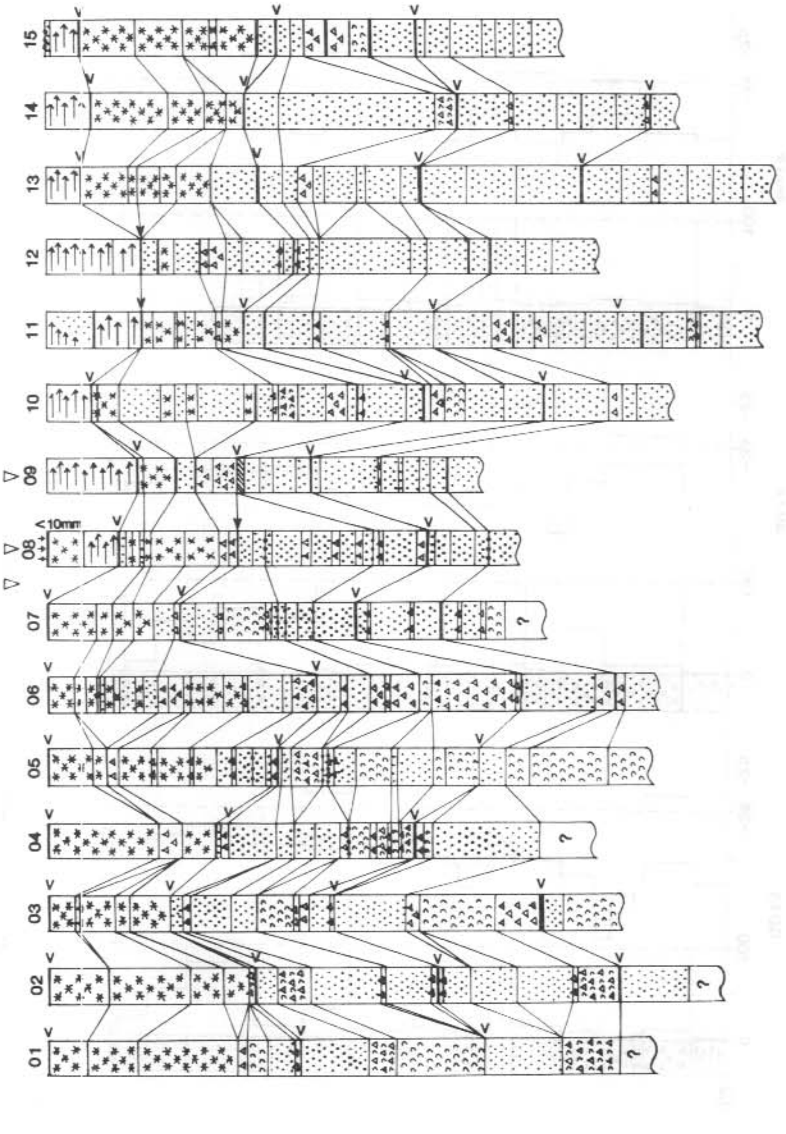

Figure 6. Intersite stratigraphical comparison.

APPENDIX I ESTIMATE OF KINETIC ENERGY LOSS PER UNIT AREA OF SNOW SURFACE FROM DRIFTING SNOW

In the absence of measured wind velocity profiles and drift particle size distributions an order of magnitude estimate has been made of the kinetic energy loss per unit area of snow surface from drifting snow.

At GD01 the pit filled with compacted snow in about 36 hours. Hence an approximate effective ground drift (or saltation) mass flux can be calculated to be 0.08 tonnes hr^{-1} across a linear metre. The average wind speed was about 12 ms^{-1}.

A mean path between impacts of a drift particle has been estimated to be 0.5 m, and it is assumed that all the kinetic energy is lost on impact. Clearly these will vary but not by more than a factor of about 2.

Hence 3.2 Wm^{-2} is transferred.

A millimetre surface layer of ice (worst case) at -40°C needs about 3.9×10^5 J to melt.

If each collision results in localised surface melting then a millimetre layer needs about 34 hours to develop due to wind action alone.

The above mass flux compares favourably with Bagnold's (Bagnold 1941) data for wind-blown sand if particle concentrations alone are considered.

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