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INTERNAL STRUCTURE OF SANDY GLACIER, SOUTHERN VICTORIA LAND, ANTARCTICA

By WAKEFIELD DORT, Jr.
(Department of Geology, University of Kansas, Lawrence, Kansas, U.S.A.)

ABSTRACT. This narrow, 600 m. long cirque glacier is apparently composed throughout of alternating layers of ice and sand that strike parallel to the edge of the glacier and dip into the glacier at an angle of 82°. The thickness of the sand layers averages 10 cm., and that of the ice layers 20 cm. The sand layers are generally composed of thin parallel laminations but micro-cross-bedding is present locally. The layers have been broken into angular blocks 0·5 to 3·0 m. long, separated by ice columns connecting adjacent ice layers. The ice layers show thinner zones of contrasting bubble content which bend into the columns separating the sand blocks.

The sand was probably blown into this cirque from the floor of Wright Valley 6 km. south-west and 1,100 m. below. Each pair of sand and ice layers may record accumulation during one year. The steeply dipping yet otherwise undeformed layers clearly prove that rotational movement has taken place. The breaking of the sand layers into blocks is the result of plastic extension within the glacier.

RÉSUMÉ. *Structure interne de Sandy Glacier, Victoria Land du sud, Antarctique.* Cet étroit glacier de cirque, long de 600 mètres, est apparement composé entièrement de couches alternées de glace et de sable parallèles au bord du glacier et d'un pendage de 82°. L'épaisseur des couches de sable est en moyenne de 10 cm, celle des couches de glace de 20 cm. Les couches de sable sont généralement composées de lames minces et parallèles, mais la stratification micro-entrecroisée est présente localement. Les couches ont été cassées en blocs angulaires de 0,5 à 3 m de long, separées par des colonnes de glace joignant les couches adjacentes de glace. Les couches de glace montrent des zones plus minces avec contenu de bulles differentes qui se courbent dans les colonnes separant les couches de sable.

Probablement, le sable a été soufflé dans ce cirque de la Wright Valley, 6 km au sud-ouest et à 1 100 m en dessous. Il est possible que chaque paire de couches de sable et de glace est l'enregistrement de l'accumulation annuelle. Les couches à fort pendage toutefois non deformées montrent bien qu'un mouvement de rotation a en lieu. La cassure des couches de sable en bloc est la conséquence d'une extension plastique dans le glacier.

ZUSAMMENFASSUNG. *Die innere Struktur des Sandy Glacier, Süd-Viktoria-Land, Antarktika.* Dieser schmale, 600 m lange Kargletscher besteht anscheinend durch und durch aus wechselnden Schichten von Eis und Sand, die parallel zum Gletscherrand streichen und in den Gletscher unter einem Winkel von 82° einfallen. Die Mächtigkeit der Sandschichten beträgt durchschnittlich 10 cm, die der Eisschichten 20 cm. Die Sandschichten setzen sich im allgemeinen aus dünnen, parallel angeordneten Lamellen zusammen, stellenweise ist jedoch kleindimensionale Schrägschichtung vorhanden. Die Schichten sind in kantige Blöcke von 0,5 m bis 3 m Länge zerbrochen, getrennt durch Eissäulen, die benachbarte Eisschichten verbinden. Die Eisschichten enthalten dünnere Zonen verschiedenen Blasengehalts, welche zu den Säulen, die die Sandblöcke trennen, hingebogen sind.

Es ist anzunehmen, dass der Sand aus dem Talboden des Wright Valley, das 6 km südwestlich und 1100 m tiefer gelegen ist, in dieses Kar hineingeweht worden ist. Jeweils eine Sand- und Eisschicht zusammengenommen könnte die Akkumulation eines Jahres darstellen. Die steil einfallenden, sonst jedoch ungestörten Schichten zeigen deutlich, dass eine Rotationsbewegung stattgefunden hat. Plastische Ausdehnung innerhalb des Gletschers hat den Bruch der Sandschichten in Blöcke verursacht.

THE rugged mountainous land bounding the western shore of the Ross Sea in eastern Antarctica comprises several distinct alpine ranges separated by deep broad valleys. Several of these valleys are at present "dry" or ice-free. Lying between Wright and Victoria Dry Valleys is the east–west-trending Olympus Range (Fig. 1), interrupted near its center by a major transverse valley known as Bull Pass. The eastern part of the Olympus Range has been dissected by the development of cirques and glaciated valleys tributary to the main drainageways of Wright and Victoria Valleys. One of the smallest of these tributaries is located at the intersection of Bull Pass with Wright Valley, where a small cirque faces south-south-west, nestling at the base of Mount Orestes (Fig. 2).

The elevation of the outer part of the gently sloping floor of this cirque is approximately 1,200 m. On the eastern and western ends of the head wall are peaks rising to 1,780 and 1,620 m., respectively. Between these high points the divide has been partially breached and lowered to an elevation of about 1,500 m. by headward growth of this small cirque and a larger one at the head of Orestes Valley (Calkin, 1964) on the opposite side of the divide.

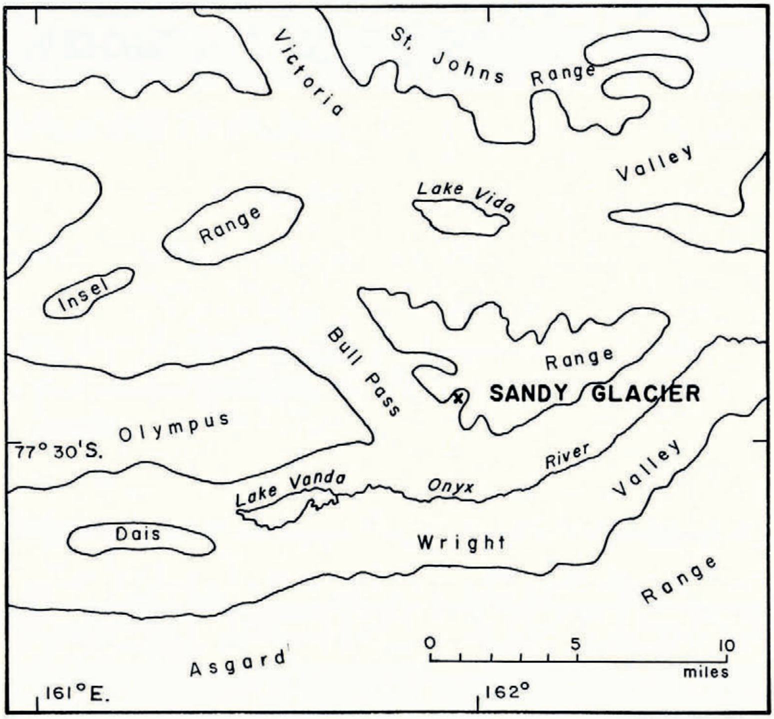

Fig. 1. Location of Sandy Glacier. The shore of McMurdo Sound is 16 miles (26 km.) east of this map area. McMurdo station is 65 miles (105 km.) east-south-east

The eastern side wall also has been lowered and beveled, in this instance by temporary high-level confluent flow between this cirque and an adjacent one.

The floor and western wall of the cirque are eroded in a complex mixture of granitic, gneissic and porphyritic dike rocks comprising the Basement Complex of presumed Precambrian age. Above a major regional unconformity, Ferrar Dolerite and small areas of Beacon Sandstone are exposed in the head wall and eastern side wall.

On the floor of this cirque is an irregularly elongate ridge of sand that extends outwards approximately 600 m. from the base of the head wall and along the western side wall. This ridge is smoothly streamlined and gently sloping. Its longitudinal axis is inclined down-valley at a nearly constant angle of 10°; inclination of its side slopes is about 6°. A broad, shallow melt-water drainage channel furrows the ridge from near the base of the head wall to the south-eastern edge of the sand area, beyond which is a rough bouldery moraine that forms a subdued jumble of irregular hillocks and hollows.

Initial Observations

When this area was first visited on 13 December 1965, the permafrost table was at a depth of 3–8 cm. in the sand. The loose active layer had been wind-blown into irregularly discontinuous, asymmetrical sand waves with a crestal separation of 30–60 cm. Superimposed on these miniature dunes were ripples with a wave-length of about 5 cm. The asymmetry of these waves and ripples indicated that a prevailing sand-moving wind had been blowing from the south-west, parallel to the long axis of the sand ridge. It was therefore thought at first that this ridge was a longitudinal dune resting on the rock floor of an ice-free cirque.

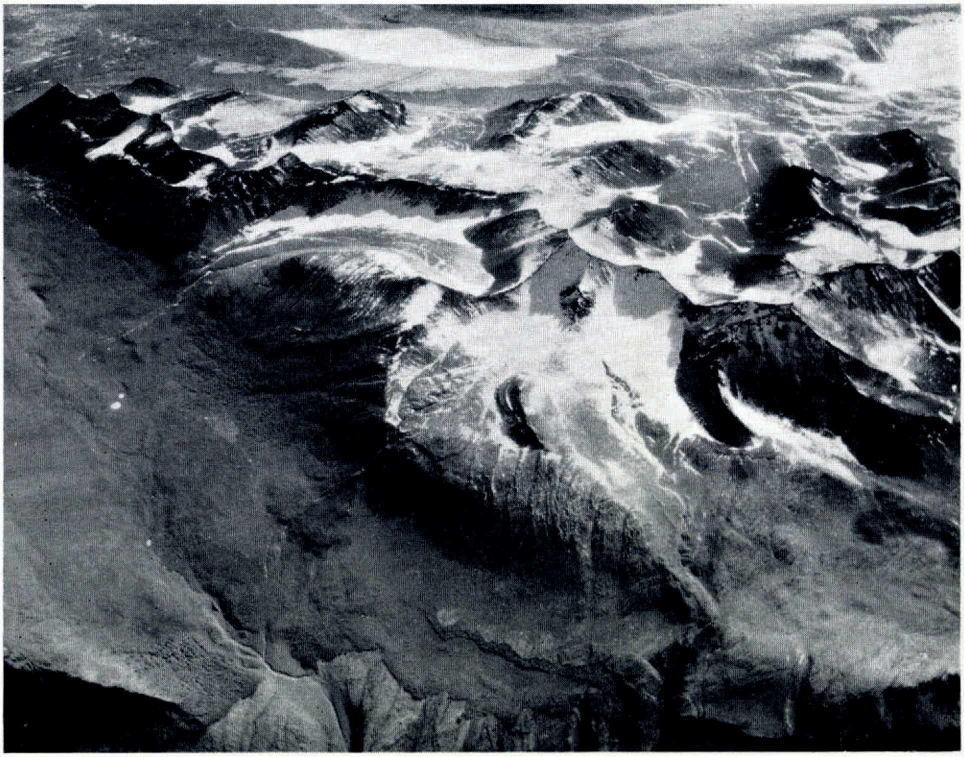

Fig. 2. Aerial view northward from directly above Wright Valley. Sandy Glacier lies on the floor of the cirque in the exact center of the photograph. Bull Pass extends along the left-hand margin and Victoria Valley at the top

However, several exposures of glacier ice, totaling perhaps 1,000 m.^{2} in area, were found around the lower end and along part of the eastern side of the ridge. On this basis, it was decided that the entire sand-covered ridge is actually the last remnant of the glacier that originally occupied this cirque. Because of the presence of so much sand, this ice mass has been formally named Sandy Glacier. It is located at lat. 77° 29′ S., long. 161° 57′ E.

The most unusual aspect of this glacier is that it is composed of alternating layers of ice and sand (Fig. 3). These layers strike parallel to the margins of the sand ridge and dip into the slope at angles of approximately 82°. The outcrop width of the sand layers, almost exactly the true thickness because of the high angle of dip and the slope of the ridge surface, ranges generally from about 2 cm. to more than 25 cm., with an observed maximum of 43 cm. The average width was estimated to be about 10 cm.

The outcrop surface of each sand layer was almost flat and part of the general surface of the ridge. Most of the layers showed distinct internal bedding (Fig. 4) that had a strike parallel to the gross stratification and a dip at angles of about 80°, parallel to the ice layers. The individual beds or laminations were very thin, many 1 mm. or less, and they showed as slight contrasts in grain-size (mainly within the medium to fine sand range) or by contrasts in color. In most of the gross layers the laminations were even and conformable throughout the exposure, but at a few places there was slightly undulatory bedding, and some examples of micro-cross-bedding were found. Relief on the undulations or cross-beds was less than 2 cm.

All of the gross sand layers have been broken into numerous blocks 0·5–3·0 m. long, separated by 5–20 cm. of intervening ice. The ends of these blocks had sharply angular to

Fig. 3. Eastern side of the Sandy Glacier tongue showing the outcrop of alternating ice and sand layers exposed in December 1965

very slightly rounded corners. In most instances, despite separation of the blocks, the orientation of the strike was maintained. In some places, however, blocks showed minor skewing and there were a few examples of *en échelon* overlapping of the ends of blocks that were originally part of a single straight layer with readily recognizable internal stratigraphy. Scattered examples were also found of the complete disappearance of a sand layer caused by what appeared to be a small thrust fault extending only between adjacent ice layers. At one spot, a sand layer 12 cm. thick showed extensive fragmentation and skewing for a distance of 4 m. along the strike. Beyond these limits the layer had perfect continuity and conformability.

The ice layers present between the gross sand layers were continuous along the strike within the bounds of each exposure (a maximum length of 20 m.). Where the sand blocks ended, ice formed separations up to 20 cm. wide, thereby providing numerous connections between adjacent ice layers. These layers ranged in width from 2 cm. to as much as 60 cm. The average width was estimated to be about 20 cm., or roughly twice the average width of the sand layers. It was further estimated that the total thickness of the ice layers was two to three times that of the sand layers.

The gross ice layers were themselves divisible into thinner zones based on internal stratigraphy delineated by the size and number of included bubbles. In general, the ice was of medium clarity and had a light grey color. Those layers with a high content of bubbles

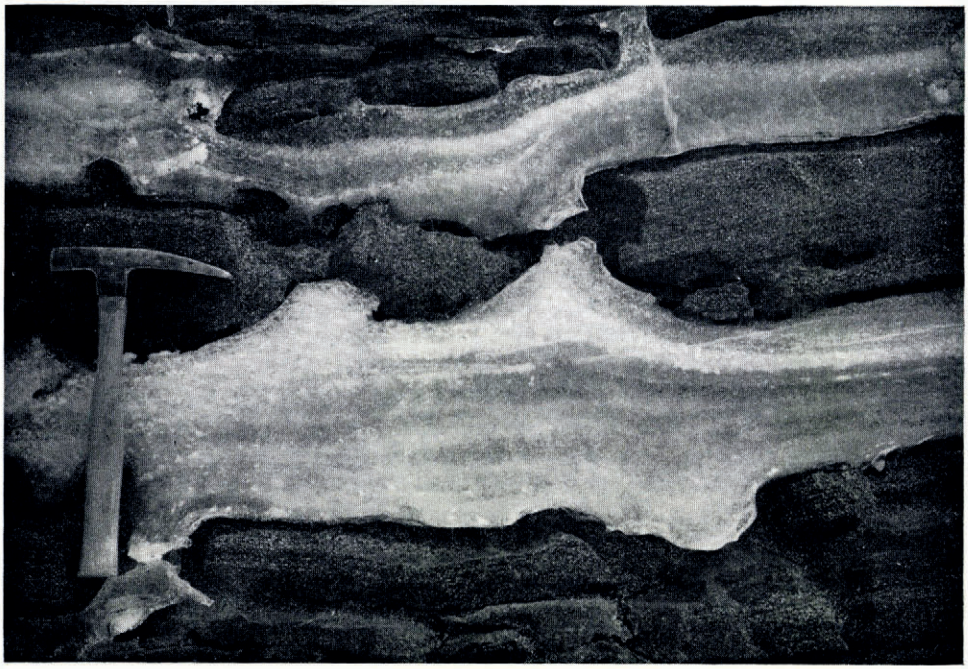

Fig. 4. Layers of thinly laminated sand partly broken into blocks and separated by ice layers

were, of course, nearly white. A few very faint dust bands were present in some of the ice layers. These sub-divisions of a gross ice layer had thicknesses ranging from 2 cm. to the diameter of a single bubble (about 1 mm.). The strike of all of the ice layers and their internal sub-divisions was generally parallel to the margin of the glacier tongue beneath its sand cover, and the dip angled steeply into the sloping ice face.

At closely spaced intervals, adjacent ice layers were connected by the column of ice present between sand blocks. Here the internal layers of bubbly and clear ice bent into the narrow separating column (Fig. 5). On especially long sand blocks the normally straight sand–ice contact was interrupted by one or more small V-shaped projections of ice, suggesting incipient breaking into shorter blocks. Here, also, the minor stratigraphic units within the ice tended to bend and approximately follow the outer edge of the ice layer. These minor deviations in strike appeared to be of equal intensity from both sides of the sand layer, or from the top and the bottom, if it is assumed that these layers were originally horizontal.

A few sand-filled cracks crossed the ice surface at various random orientations. They appeared to be minor tension cracks developed, perhaps, by heating and cooling, and were probably not crevasses related to ice movement. In fact, all indications were that the entire glacier is now motionless. Excavation of a pit 1 m.^{3} in size showed that the conformable sand–ice stratigraphy continued at depth but the sand-filled cracks did not. It was clear that the sand was not present in the cracks originally but it had fallen in as each crack opened, and by its presence had helped melting to enlarge the space further.

At the time of first observation in December 1965, in some areas where the ice surface was not visible because of a complete mantle of sand, the sand surface showed development of discontinuous parallel furrows, cracks and cross-fractures in a rectangular pattern that clearly outlined the block structure present beneath. This pattern was caused by slight melting of the ice under a very thin sand cover and consequent subsidence of that cover. The locations of the sand blocks were marked by small rectangular projections, and the ice layers by the linear furrows. Over much of the ridge, however, the sand mantle was so thick that the base of the unfrozen active layer had not reached the underlying ice. Nevertheless, the presence of bare ice and sand showing the bas-relief block pattern was so widespread it strongly suggested that the entire ridge was underlain by the remnant of a glacier composed completely of this unusual interbedding of ice layers and sand layers.

Later Observations

At the time of the visit to Sandy Glacier, observations were limited to those that could be made during a period of only a few hours while awaiting helicopter evacuation. A return trip to this glacier was made on 31 January 1966 for the express purpose of mapping both the glacier and its stratigraphy, and to obtain additional quantitative data. Unfortunately, it was found that almost the entire surface was sand-covered. In only a very few spots was any ice visible, consisting only of skeletal remnants of partially melted ice layers. However, these limited occurrences did provide a measure of the ablation that had taken place. After the interval of 7 weeks during a prolonged period of sunny, relatively warm Antarctic summer weather, the fragmentary tops of ice layers, which previously had been level with the general sand surface, were projecting 10–15 cm. above the surrounding sand. It could be assumed that at least most of the snout of the glacier had been lowered by this amount. A new 1 $m.^3$ pit was chopped into the sand and ice to confirm that the alternating layers were indeed still present at depth.

In addition to the increase in area of the sand cover, the bas-relief block pattern on the sand surface was more prominent and more widespread than it had been when the locality was first visited. Even though freezing of moist sand to within 2 cm. or less of the surface, caused by generally decreasing air temperatures, inhibited widespread sub-surface investigation, there was clear surface expression of aligned sand blocks separated by furrows overlying the intervening ice layers (Fig. 6). On the basis of this evidence, it was clear that alternating layers of sand and ice are present throughout most if not all of Sandy Glacier. The bas-relief block pattern was present on the snout and along the eastern side for about two-thirds of the distance to the head wall. Especially significant was the clear-cut continuity of layers across the medial swale, demonstrating conclusively that this low area is merely a drainage channel melted into the surface of a single ice tongue. Furthermore, the three-dimensional pattern of the layers crossing this swale showed that the stratigraphy was indeed continuous at depth and that the strata have an almost vertical dip near the glacier margin.

Source of the Sand

The suite of rock fragments and minerals present in the sand that both covers and occurs within Sandy Glacier indicates that a major proportion came from the assemblage of igneous and metamorphic rock types comprising the basement complex. Although basement rocks do crop out along the western side of the short valley extending from the Sandy Glacier cirque to Bull Pass, there is no evidence to indicate that all or even most of the sand was derived from this local source. Indeed, there appears to be far too much sand present to have come from such a restricted area, especially when this occurrence is compared with the general scarcity of sand in nearby cirques eroded in the same group of rocks. Sand must have been transported into the Sandy Glacier cirque.

The absence of extensive outcrops of basement rocks along the side walls and cirque head wall topographically above the glacier rules out importation by ice or gravity. Furthermore, neither of these agents is competent to produce the well-formed thin laminations characteristic of the sand layers. Either water or wind could deposit laminated sand showing

Fig. 5. Clearly zoned ice layers beside and protruding into separations between sand blocks

Fig. 6. Eastern side of the Sandy Glacier tongue showing bas-relief pattern of sand cover in January 1966

slight sorting of grains by both size and mineral specific gravity, and either agent could cause development of the observed micro-cross-bedding. But in the frigid Antarctic environment it would seem to be unreasonable to suggest the repeated presence of running water in quantities sufficient to distribute sand gently and evenly in thin laminations over the area of a cirque floor, especially since that area is neither level nor smooth. It therefore appears that the sand in Sandy Glacier must have been brought in by wind.

The short Sandy Glacier valley opens toward the south-south-west, where its discordant mouth overlooks the southerly end of the broad valley of Bull Pass. This in turn discordantly overlooks the major east–west lowland of Wright Valley (Fig. 1). 4 miles (6·4 km.) west is Lake Vanda. Between the mouth of Bull Pass and this lake the shallow Onyx River follows a winding course during the warmest weeks of summer, carrying toward the lake a load of sand derived from the igneous and metamorphic basement rocks exposed along the sides and floor of Wright Valley. When water ceases to flow, as it does at intervals of colder weather ranging from a few hours to many days, as well as throughout the long Antarctic winter, the upper surface of the sand is dry and loose. It is then caught up by strong winds blowing alternately up and down Wright Valley and accumulates in irregular sheets and dunes on the broad valley floor.

The prevailing wind in southern Victoria Land is from the south-west, thus blowing across Wright Valley at an oblique angle. On many days winds of 20–30 kt. (10·2–15·5 m./sec.), or even higher velocities, blow down tributary valleys on the southern side of Wright Valley. Under such conditions, sand on the floor of Wright Valley may be picked up and carried up the northern side slope. The mouth of Bull Pass is located at the point where the orientation of the axis of Wright Valley changes from east-north-east to due east. Winds blowing from the south-west therefore tend to have a strong component funneling into the broad mouth of Bull Pass. With the establishment of this powerful up-slope air stream, there is a tendency for it to continue in a north-easterly direction and so up Sandy Glacier valley rather than following Bull Pass toward the north-west. Melt water has eroded a narrow ravine into the southern end of the floor of Bull Pass and the slope descending from there to the floor of Wright Valley. Where the path of winds rising from the floor of Wright Valley towards Sandy Glacier crosses this drainageway, the ravine is blocked by a large dune (Fig. 2).

The stream of sand-laden air moves along the length of Sandy Glacier valley. It is, however, following a course orientated slightly to the north-east of the valley axis. This means that there is a relative lee area in the north-north-western corner of the valley head. Here Sandy Glacier lies with its cover and content of sand that seems to have come from the floor of Wright Valley just east of Lake Vanda, a distance of about 6 km. and a lift of about 1,100 m.

It is not known whether this up-slope sand transport is continuing at the present time, or whether it occurred during a somewhat different climatic regime in the recent past. A smoothly continuous snow cover on the valley-side slope might to some extent facilitate movement of sand derived from a snow-free valley floor. However, the relatively smooth surfaces formed by a combination of solifluction spreading of loose debris and glacial scouring of bedrock should offer little impedance to sand movement by strong winds.

That some sand is now being affected by the south-westerly winds in Sandy Glacier valley is demonstrated by the presence of small lee shadow dunes on the north-eastern sides of large boulders, and by the orientation and asymmetry of sand waves and ripples on Sandy Glacier itself. Furthermore, sand is now being blown onto the head of this glacier in quantities sufficient to form layers as much as 15 cm. thick in snow on top of the ice near the cirque head wall (Fig. 7). However, this sand could now be supplied from the lower end of the glacier where some is being released from the internal strata by ablation lowering of the surface. If sand in large quantities was being carried up from Wright Valley now, the presence of larger lee shadow dunes or even complete burial of obstructions and perhaps the entire glacier would be expected. It is therefore believed that the sand layers of Sandy Glacier were formed under climatic conditions slightly different from those of the present.

Implications of the Stratigraphy

It is accepted that glacial ice forms by recrystallization of snow. Rock material present within a glacier may have been included with the original snow that ultimately was converted to ice, may have been introduced into the interior of the glacier by way of crevasses open to the surface, or may have been raised up from the bottom along internal shear planes. Crevasse fillings cannot produce well-defined conformable layers of fine-grained debris distributed throughout a glacier. Debris rising on shear planes cannot account for multiple interbeddings of thin layers of sand and ice. Neither origin will permit extensive formation of laminations and micro-cross-bedding within well-sorted debris layers. It appears that only deposition of beds of sand alternating with snow in the zone of accumulation can account for development of stratigraphy such as is present in Sandy Glacier.

The widespread demonstrations of the presence of interbedded sand and ice around the snout and along the eastern side suggest that this stratigraphy is present within most if not all of Sandy Glacier. This in turn indicates that during the entire period of accumulation of the snow from which this glacier was ultimately formed there were frequent episodes of sand accumulation on the surface of the snow or *névé* in the cirque. The agent of deposition must have been wind, both because it is unlikely that water in quantities sufficient to move all that sand has been present within the cirque and because had such water been present it would have strongly modified the structure of the snow layers.

The small range in grain-size of the sand (1·0–0·125 mm. with more than 50 per cent occurring in the 0·5–0·25 mm. range) must be a consequence of a fairly stable balance between the strength of the sand-moving winds and the size distribution of weathering products made available for transport. If it is correct that the main source of the sand was alluvium deposited by the Onyx River on the floor of Wright Valley, then primary sorting by running water had already taken place.

The density of newly fallen snow averages 0·1 g./cm.^{3} and may be less. The density of glacier ice ranges from 0·8 to 0·9 g./cm.^{3}, providing clear indication of very considerable compaction accomplished during the transformation. Certainly the compaction of sand under pressures present in the lower part of a small cirque glacier would be very much less. Indeed, the preservation of minor laminations and micro-cross-bedding demonstrates that there was very little settling of the sand in Sandy Glacier.

What may have been a valid sample of conditions of accumulation throughout the formation of Sandy Glacier was provided during the period of observation. When seen in mid-December, the upper part of the glacier still retained an unbroken cover of fresh snow of unknown depth. By the end of January ablation had removed much of this snow. The disappearance had been irregular, however, so that numerous miniature mesas of unmelted snow stood as much as 1 m. above the general sand and ice surface that constituted the base of the melting. The faces of the upstanding remnants showed an intricate stratigraphy consisting of many layers of slightly compacted snow and interbedded ice plus a few layers of sand (Fig. 7). It could readily be accepted that upon transformation into glacier ice, the thinnest of the snow layers might be represented by a single layer of bubbly ice, and the thicker layers by narrow bubble zones. The ice layers already intervening between the snow layers, probably the result of minor episodes of melting, would form zones of relatively clear ice in the glacier. The sand layers would remain essentially unchanged.

The relationship of the observed snow, ice and sand stratigraphy to seasonal weather variations was not clear. There appeared to be no detectable difference in the snow layers revealed from the top to the bottom of a single exposure. It therefore seemed likely that the

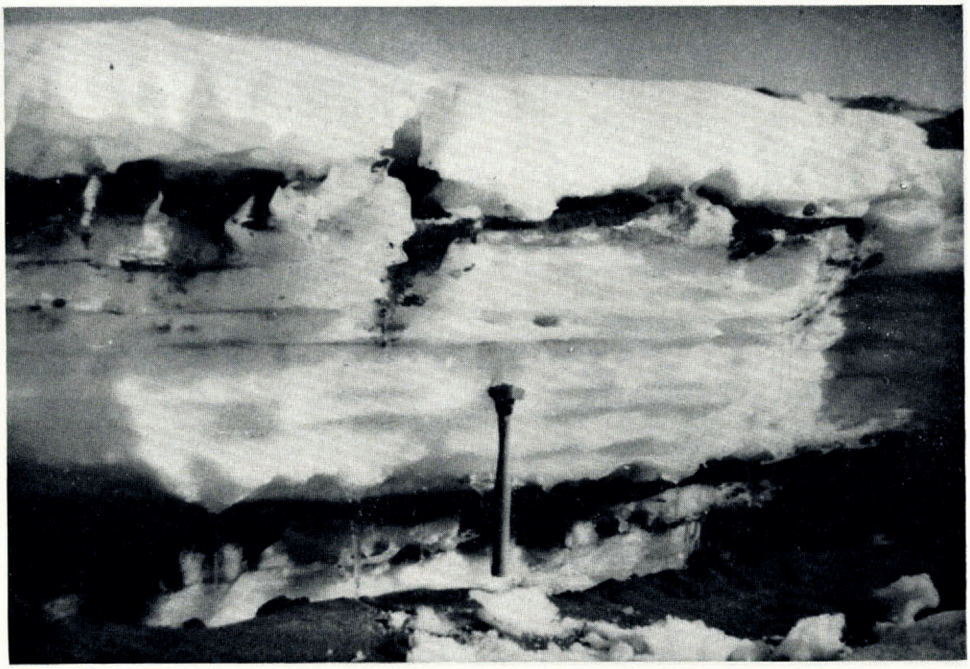

Fig. 7. Section of stratified snow and sand exposed by irregular ablation near the head of Sandy Glacier

entire thickness undergoing ablation during the period of observation had been deposited during the preceding 8–10 months since the previous short Antarctic summer. Some of the snow layers were undoubtedly the result of direct precipitation; others probably record accumulation of snow undergoing re-distribution by wind. One layer of sand was much thicker than the others present. It is likely that this major accumulation occurred at the end of the summer when ablation of the glacier tongue, which had released large quantities of sand, had ceased, melt water was no longer present to wet the sand and prevent blowing, yet no new snow cover protected the loose sand. The minor sand layers present would record short-term weather fluctuations during the year when unprotected dry sand would be available to the wind for a short time.

Virtually nothing is known about weather patterns and occurrences in the dry-valley area of southern Victoria Land, especially during the three-quarters of the year that comprises the Antarctic winter. Certainly, there is little relationship in detail between this mountainous region on the edge of the continent and the island environment of McMurdo station where observations are made on a regular basis. It is believed, however, that the typical dry-valley storm begins with snowfall under conditions of quiet air, but it often ends with strong winds that re-distribute the snow and could transport some of the loose sand beneath. And it should be recorded that during the austral summer of 1965–66, snowfalls of 10 and 15 cm. accumulation did occur in the area of Sandy Glacier. All of this snow disappeared from exposed areas, mainly by evaporation, but a little remained in locations particularly well protected from sunlight by cliffs or high peaks.

It is tempting to suggest that the gross sand and ice layers within Sandy Glacier are similar to varved clays in that each pair records annual accumulation, even though no direct proof of this was found in the field. Surface banding on many glaciers studied by various investigators in the Northern Hemisphere, the pattern being a consequence of the outcrop of numerous parallel layers of ice, has frequently been cited as an expression of annual accumulations in the *névé*. Gibson and Dyson (1939), discussing Grinnell Glacier in Montana, believed that the bands were the result of "successive snowfalls" or annual accumulations. The concept of annual banding was completely accepted during studies of Norwegian cirque glaciers by W. V. Lewis and his co-workers (Adie, 1960; Grove, 1960[a], [b]; McCall, 1960).

IMPLICATIONS OF THE STRUCTURE

The fundamental structure of Sandy Glacier consists of alternating layers of ice and sand that strike parallel to the margin of the glacier and dip inward at very steep angles. The shape of this glacier is a long narrow tongue and so the line of outcrop of any individual layer has the form of a narrow "U". Actual exposures of the ice and sand strata were limited to the lower half of the glacier but further extension of the bas-relief expression of blocks and furrows demonstrated conclusively that this stratigraphy was present at least as close as 200 m. from the base of the cirque head wall.

The occurrence of ice layers striking parallel to the margin of a glacier is not at all uncommon but the angle of dip of the strata in Sandy Glacier, nearly constant at about 82° in the areas where the ice was not covered by sand or snow, is much steeper than dips noted in other glaciers. Gibson and Dyson (1939) measured a maximum dip of 45° on Grinnell Glacier. Lewis (1949) suggested a maximum dip of 45° from studies in Iceland and up to 50° from Norway (Grove, [1952]; Grove and Lewis, 1951). Later investigations in Norway recorded dips up to 70° (Grove, 1960[a], [b]).

Conditions at Sandy Glacier also differ in that the steeply dipping beds are present both well within the zone of ablation at the snout and close to the head wall in an area that should be, or at least should have been in the past, close to or within the zone of accumulation. It has previously been noted, especially in the Norwegian studies referred to above, that in the usual situation dips are steepest in the mid-part of a cirque glacier and decrease toward both the snout and the *névé* area.

It has been assumed (Gibson and Dyson, 1939; Lewis, 1949; Grove and Lewis, 1951; Grove, 1960[a], [b]) that the ice bands that are dipping up-glacier at a near-snout location were originally formed in the zone of accumulation with a slight down-glacier inclination, thereby indicating the occurrence of rotational movement of the ice. The sand layers in Sandy Glacier unequivocally demonstrate that rotation does indeed take place. The thin well-sorted laminations within the gross sand layers could not have formed on other than a very gently sloping surface. Rotation to the present steeply dipping attitude must have occurred after the sand layers were solidly encased by bordering ice. Furthermore, the presence of undeformed micro-cross-bedding within the sand layers and of unbroken well-stratified ice columns and wedges projecting into the sand layers from both sides shows that negligible shearing has taken place either between or within layers. These are bedding bands, not flow bands.

In his studies of cirque glaciers in Iceland, Lewis (1949, p. 147) commented that these glaciers showed "dozens of these bands many of which mark undoubted overthrusts" and noted that many stratification planes seemed to pass gradually into glide planes. He added that "this inter-relation between stratification layers and thrust planes has probably led to the great controversy in the literature as to whether the banded structure represents annual stratification planes or thrust planes" (Lewis, 1949, p. 151). The importance of thrust planes was re-stated after early studies in Norway (Grove, [1952]; Grove and Lewis, 1951) but continued investigation led to the conclusion that most of the supposed thrust planes were actually ablation surfaces (Grove, 1960[a]; McCall, 1960).

The observations made at Sandy Glacier clearly show that at least some glacier banding is the result of true accumulation stratification, and they cast further doubt on certain evidence previously used to indicate a thrust origin of the banding. Lewis, as well as other field workers, have noted the presence of tabular boulders jutting from the ice at the outcrop of a band (Lewis, 1949, fig. 7) and used this as evidence of the thrusting of basal ice upward to the glacier surface. It might equally well be that these boulders were deposited on the surface of the *névé* by rock fall or avalanche and that they now project from the glacier surface at an angle because that is the attitude of the bedding plane cropping out at that point.

A second fundamental aspect of the structure of Sandy Glacier is that the sand layers, each one originally continuous over much if not all of the area of the glacier, have been broken into numerous short blocks, generally with preservation of their original orientation. This indicates that the sand layers, and therefore the entire glacier, have been stretched, clearly upholding Nye's (1963, p. 785) theoretical analysis that "vertical plastic compression makes a given layer progressively thinner, in terms of water equivalent, as it descends more deeply into the ice sheet. There is a corresponding plastic extension in the horizontal plane." The ice was able to deform plastically, the sand was not, and so it was ruptured, forming the blocks. Exposures in the third dimension were not sufficiently deep, however, to tell whether the sand layers are broken into rough squares, rectangles or irregular shapes.

One of the main purposes of the second visit to Sandy Glacier was acquisition of additional quantitative data, especially regarding the average thickness and spacing of the ice columns separating sand blocks. This information would permit rough determination of total extension parallel to the bedding within the glacier. These measurements could not be made at that time but it is estimated that breaking of the sand layers and separation of the resulting blocks caused an overall lengthening of the glacier of the order of 20 per cent. Field observations showed that the internal bubble stratigraphy of the gross ice layers was deformed only by plastic bending or flowage into the ice wedges and ice columns that penetrated the sand layers. There was no rupturing of ice layers.

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