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RECENT AND LOCAL DEPOSITS OF  
McMURDO SOUND REGION.

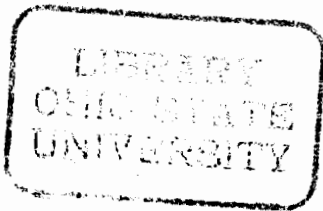
BY

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Fellow of Gonville and Caius College, Cambridge.

Geologist on the Expedition.

WITH NINETEEN FIGURES IN THE TEXT.



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## INTRODUCTION.

CONSIDERATION of the meteorological data furnished by the "Ter. a Nova" and previous Antarctic expeditions establishes the fact that the conditions in Lat. 78° S. are those of an extreme glacial period such as obtain hardly anywhere else in the world, the important point to be noted being the complete absence of rain which is so universal a factor elsewhere in the production of surface land deposits.

For this reason it has been thought preferable to describe the deposits under the headings of the agencies responsible for them rather than on any regional basis.

The McMurdo Sound region (Maps, Figs. 1, 11) only is discussed here, the other parts of the coast that were visited furnishing less material on account of the few ice-free patches found and the short time available for their investigation. McMurdo Sound is the centre of volcanic activity for that part of the coast, but the deposits due to that cause will be treated under a separate heading in another part of the volume.

The general topography may be gathered from the maps, and is treated in detail in the Physiographical Report of the Expedition.

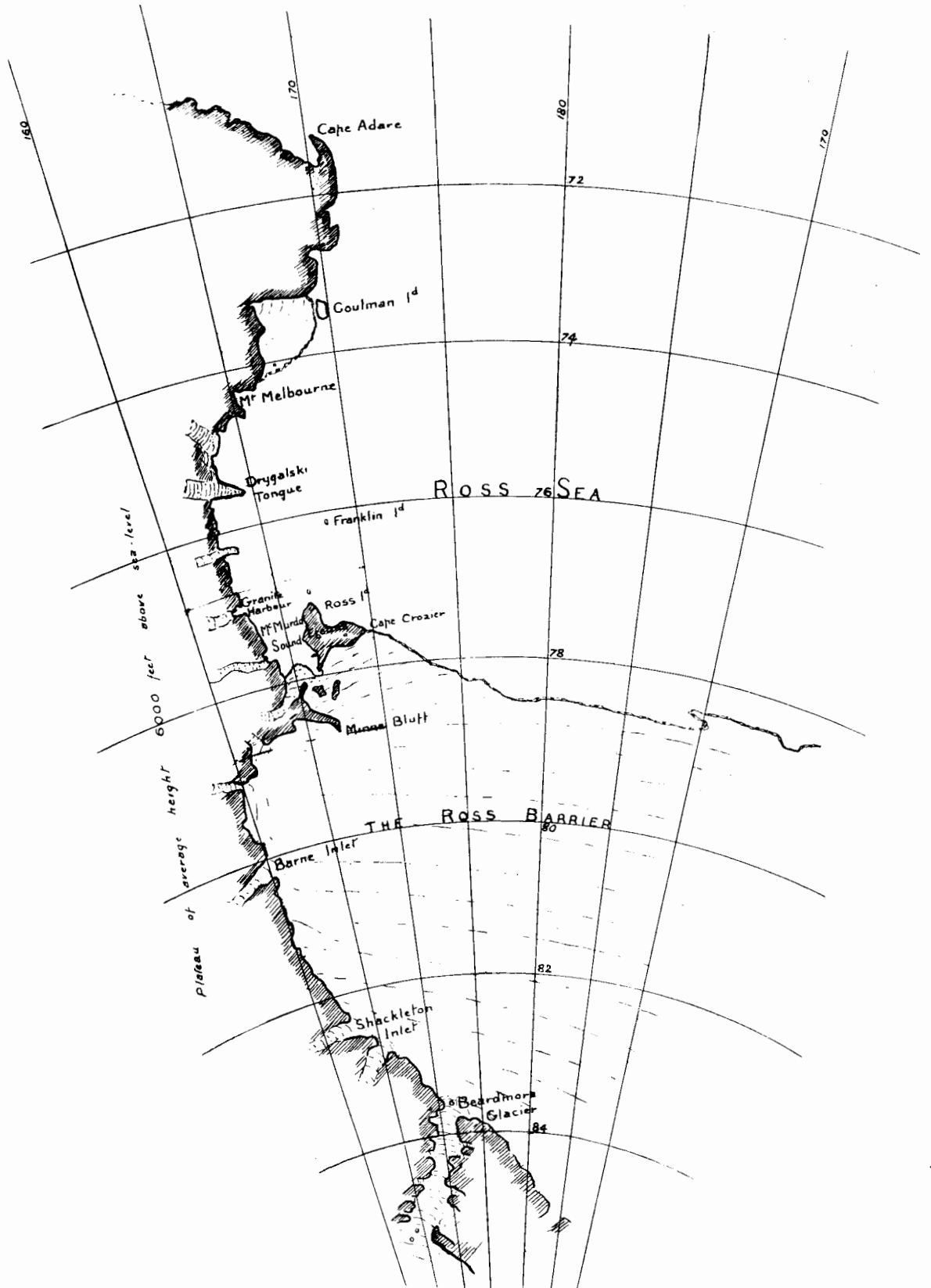


FIG. 1.—Map of Coast-line of South Victoria Land.

## DEPOSITS DUE TO THE ACTION OF WIND.

We may preface the description of these deposits with some notes on the observed power of the winds. On the west coast of Ross Island and at Cape Adare, where our two stations were situated, the wind records were far lower than those obtained by the Australasian Expedition in Adelie Land, and therefore cannot be taken as an overstatement of the case for the rest of the continent. At Yarmouth the frequency of winds over 30 miles per hour is 7 per cent. of the total winds; at Cape Evans, our headquarters, it was 23 per cent. for 1911 and higher for 1912. The mean velocity of the wind throughout 1911 at Cape Evans was 16·7 miles per hour, and in 1912 the mean velocities for the months of June and July were 31·8 and 28·8 miles per hour respectively. But just as in the case of rivers it is the abnormal floods that do the greater part of the geological work, so in the case of winds we are more concerned



FIG. 2.—Gravel- and snow-drifts on Cape Evans, showing the effect of the prevailing south-east winds.

with the maxima than the means. Gusts of over 80 miles per hour were fairly common in 1912, and the highest recorded by instruments was 104 miles per hour. As the hut was in a sheltered place, and the drifting snow always interfered with the registering apparatus, there can be little doubt that the wind velocity in the gusts reached 120 or 130 miles per hour. The strongest winds of the year being in the winter, we were not able to see the transporting action, but some idea of it may be gathered from the following:—About 120 yards to the S.E. of the hut there was a low gravelly hill, and whenever the wind force rose above 90 miles per hour, the roof of the hut was bombarded by large pebbles from this ridge. The size of the pebbles must have been considerable, for they produced a loud rattle on the roof, easily heard above the roar of the blizzard.

A piece of English flint was exposed to the wind throughout our stay, and the eroding action of the wind-borne gravel on the surface was noted. On the hard dark fractures it had no more than a polishing effect, but the white selvage was quickly fretted away on the windward side.

Near headquarters, at Cape Evans, the direction of the strong winds was always within a few degrees of S.E., and such a constancy of direction is naturally responsible

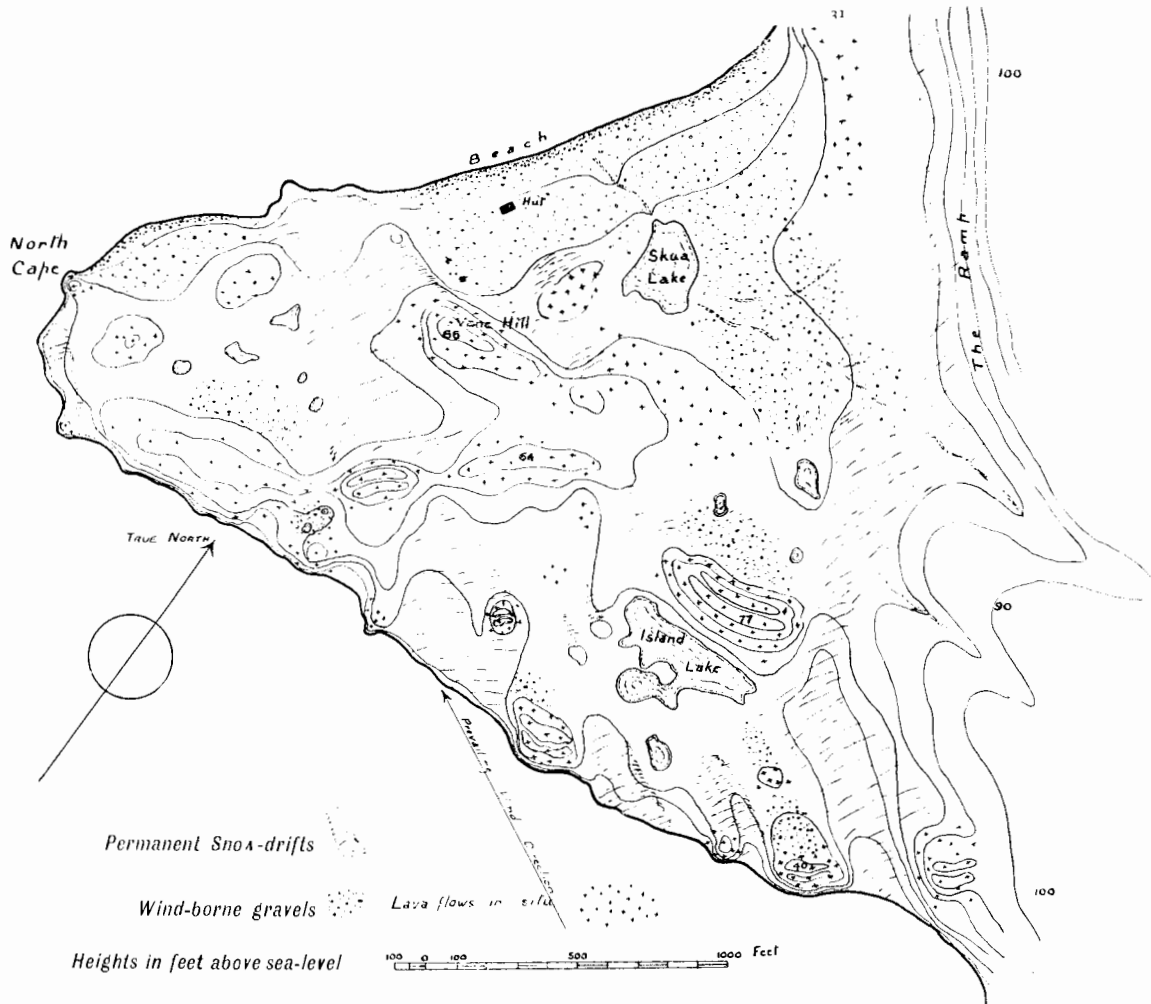


FIG. 3. - Sketch-map of Cape Evans.

for the good examples of aeolian deposits that were found. On the lee side of every hill or mound great drifts of snow mixed with rock-dust and gravel would collect, and where for some reason or other the snow was not permanent, the gravel alone was found arranged in exactly the same way as the snow (Fig. 2).

Cape Evans (Fig. 3) itself shows a typical example of these local drift deposits. It is a small cape, triangular in section, bare of snow except for local drifts, and under 100 feet in height for the most part. The S.E. side is formed of bare bluffs of coarse

lava from which the winds have swept every loose particle, while the N.W. side, only a few hundred yards away, is a gentle slope of gravel, with a few outcrops of rock, leading down to a small definite beach of volcanic gravel. The slopes of gravel were at first taken to be a continuation of the beach, but the shape of the particles and their distribution proved that they were composed of material deposited by the wind



FIG. 4.— Boulder of kenyte, showing the effect of wind erosion ; the felspars, being harder than the matrix, stand out in relief.

as it lost its force in the lee of the south-eastern ridges of the cape. Some of this wind-laid gravel is redistributed by streams of thaw water in the summer, so the next example quoted is taken from a place where neither thaw water nor heavy drifts of snow can obscure the truly aeolian nature of the deposit.

Inaccessible Island is a high (540 feet) volcanic island about two miles from Cape Evans, and presents a steep face towards the south and a more gradual one towards the north. It is roughly lozenge-shaped and lies obliquely to the direction

of the prevalent wind. On account of its high steep face towards the south, there is naturally an area on the north side of the ridge where the wind suddenly loses its force and drops its load. At that height there is very little surface drift snow in the air, and consequently its only load is gravel from the arrêtes and couloirs of the south side. This is dropped in a very remarkable ridge of gravel, coarse at the top and finer below, which runs obliquely along the upper slopes.

The same thing is taking place at Turk's Head, a cape to the south of Cape Evans. At all these places the abrading action of the wind-borne gravel produces peculiar weathered forms. The local lava, being for the most part coarse, with large phenocrysts of felspar, is never worn smooth, but develops a rugged appearance in which the

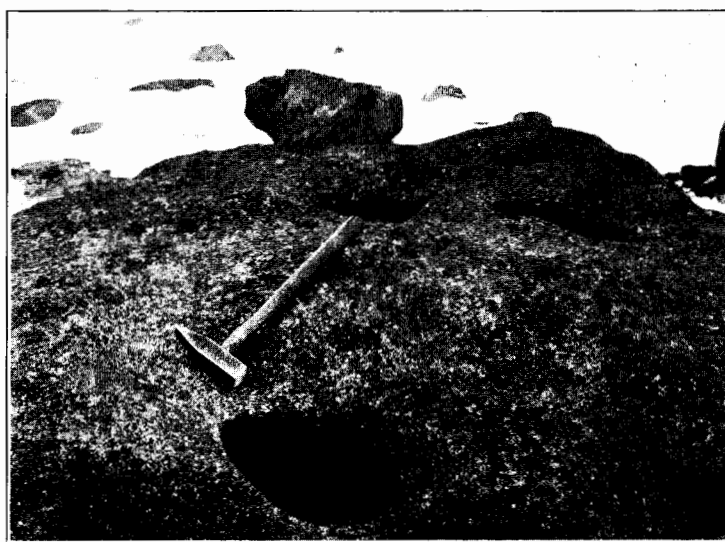


FIG. 5.—Potholes worn by wind action in dense granite. Summit of Redcliffs, Mackay Glacier, Granite Harbour.

felspar forms the projecting points (Fig. 4), but this and other rocks are sometimes worn into deep potholes or basins (Fig. 5).

Naturally a great part of this blown gravel leaves the land and finds a temporary resting-place on the sea-ice, where towards the middle of summer it forms a dark covering in the lee of capes, greatly accelerating the thaw and ultimately floating off to the north. Since, however, the maximum snow-free surface is exposed to the wind in the autumn when the sea-ice is normally absent, it is obvious that a great deal of the gravel must collect on the sea-bottom in the vicinity of land, and soundings show that such is the case.

Passing across McMurdo Sound to the mainland, generally referred to as the "Western Mountains," we find much larger areas of bare land, and consequently the effect of the winds is much more pronounced. Here, however, the winds are not so constant in direction, and the two blizzard directions are from the south and the west.

Reflected by the high sides of the valleys, the actual direction of wind in any one spot may be altered continually; in fact, in the deeper valleys a strong transverse wind would be transformed into gusts alternately up and down the valley. Such variations have the effect of hiding to some extent the aeolian character of many of the deposits, even though they increase the abrasive action of the wind on the surface.

In the west, therefore, we do not meet with the prominent gravel-drifts in the lee of hills that have been described on Ross Island. On the other hand, the amount of gravel in the beds of the ice-free valleys is far greater than anywhere on the east side of the Sound. The greater part of this gravel is angular and has only reached the bed of the valleys by the agency of the wind, but as it has been mostly re-sorted by thaw water the description of these immense beds is left to the sections on lake- and stream-deposits.

It was pointed out that the rough lavas of Ross Island are never worn smooth by the wind, but the case is quite different on the mainland, where there are many fine-grained dense rocks. In the Dry Valley in particular there are many beautiful examples of small pieces of rock worn into facets by the wind. Some of these showed by their position, firmly embedded in the fine gravel, that the facets were due to the winds that blew alternately up and down the valley, cutting on each side according to their strength.

A striking feature of the wind deposits is that they all consist of moderately coarse gravel, and in no place of any finer material. Any rock-dust formed, owing to the strength of the wind, is either whirled away over the sea or else entrapped in the snow. In the centre line of broad glaciers this rock-dust appears as stratified bands, increasing in frequency from the top to the bottom. It is true wind-borne dust and not "rock-flour" from the bed of the valley, for it can be traced down from the surface to the lower levels, where it seems to accumulate. The muds at the end of these glaciers, therefore, were originally largely due to the action of wind, and not to the eroding action of the under-surface of the glacier.

To sum up the effects of wind in the deposition of material, it is clear that, although the winds are of exceptional frequency and strength, the amount of rock material they can reach is small on account of the few bare surfaces. Consequently, the total amount of material so removed and deposited is probably far less than in more temperate lands. Since, however, the effect of water as an agent of deposition is very small, the percentage effect of wind becomes very large under these conditions.

Still farther south this effect becomes more important, for in the glaciers of 85° S. there is very little thaw indeed, and transport of material can only be effected by the ice itself and the wind. In this region all the glaciers from the plateau reach sea-level, and no permanent land deposits exist. The transported material becomes absorbed in the Great Ross Barrier, and is ultimately dropped by melting icebergs to the sea-floor.

## LAKE-DEPOSITS.

As in other glaciated countries there are many small lakes and tarns scattered over the land which is bare of ice. We may classify them shortly into those that are temporary, caused, for instance, by the stoppage of a stream by ice, and those that are sub-permanent. Each class is forming deposits of its own, though usually on a small scale.

The sub-permanent class is particularly well developed in the Cape Royds region of Ross Island, where there is a large expanse of low-lying ground. The lakes themselves generally occupy depressions in the lava flows, though some are due to moraine blocking a natural channel or groove. Professor T. W. E. David and Mr. R. E. Priestley, in an account of these lakes,\* show that the only deposits of any importance that are now being formed in them consist of layers of dried algous peat up to three feet in thickness.

This alga, like all the fauna and flora that manage to survive the conditions, is extremely tenacious of life and seems to be the only one at present able to leave a geological record of itself. That it does so there is no doubt, as deposits of it up to one foot in thickness were occasionally found covered by gravelly moraine which, if undisturbed, will eventually preserve it as thin lenticles of peat in a cemented breccia. The most striking deposits of the kind were found by us in the small temporary lakes amongst ice-borne moraine on the western side of the Sound. These lakelets are subject to frequent changes of level, and in many cases were surrounded by small terraces of the dried plant marking the former height of the water. The thaw each year is much more prolonged than on Ross Island, and the plant grows to a greater size, so that we are led to the conclusion that the deposits of this algous peat will increase rapidly with increasing mildness of conditions. The only other type of vegetation that occurs in sufficient quantity to form deposits is moss, but this is local in extent and insignificant in thickness.

Returning to the lakes of Ross Island, there is naturally at the bottom of each a deposit of mud, consisting of the fine dust that is blown on to the surface and silt washed into the lake by the small thaw streams. This mud is rarely of appreciable thickness and is so mixed with larger particles of gravel, wind-borne or otherwise, that it can hardly be called a mud in the strict sense.

The lakes of similar character on Cape Evans, as shown on the map (Fig. 3, p. 66), formed quite an appreciable proportion of the cape, though they are all very shallow. These small lakes of the volcanic district provide still another contrast with those of Arctic regions, where the smallest has a steady flow of water into it, bringing considerable amounts of fine silt and mud to form a deposit on the bottom.

On the mainland, on the other hand, we meet with much larger lakes, and as the general meteorological conditions on the coast of the mainland are much milder than

\* British Antarctic Expedition, 1907-09, Geol. Report, Vol. I, pp. 229, 278.

on Ross Island, with the increased thaw, even though rain never falls, all the agents of deposition become more active.

The valleys in the foothills of the Western Mountains are not all equally supplied with snow from the ranges behind, and consequently quite a number of them are free from ice. The annual snowfall is so small that it is easily ablated where it falls, and, wherever supply by flow from the plateau fails, the valleys become quite bare during the summer and thinly covered with snow during the winter. These "dry valleys" occur only to the south of New Harbour, the coastal strip to the north of it being occupied with a continuous covering of piedmont glacier. Their very local occurrence is due to the drainage from the plateau being interrupted by the Royal Society Range.

Taking the northernmost valley first, named Dry Valley by Captain Scott on his

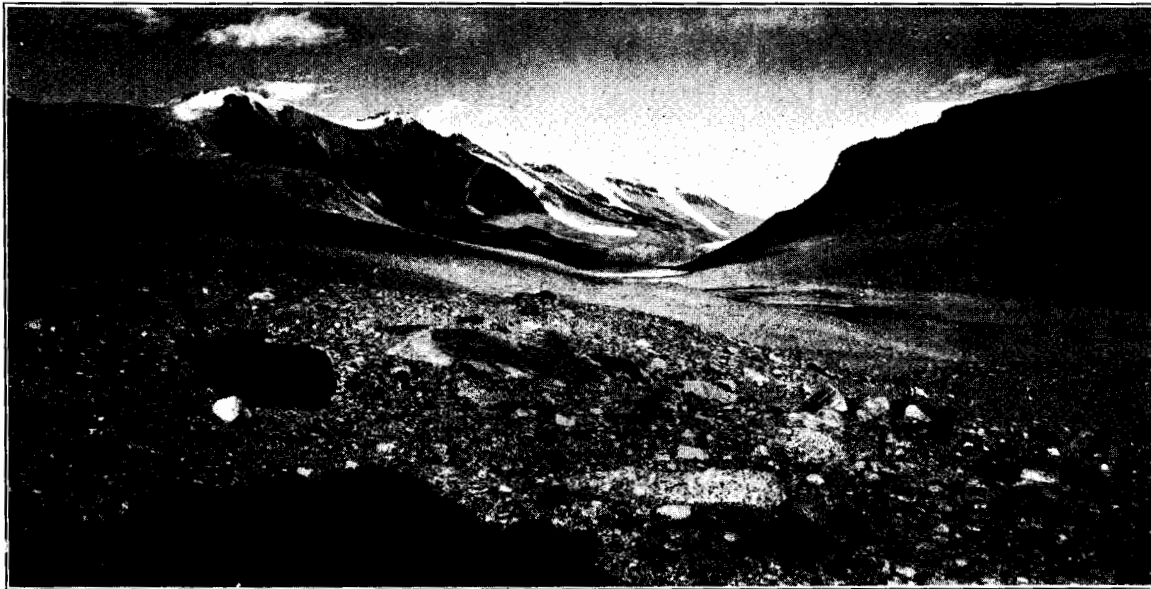


FIG. 6.—Upper part of Dry Valley. Old lake-beds in right foreground. Lake Bonney in middle distance. Recent craters on sides of valley in the distance.

first expedition, we find a series of lakes from the foot of its shrunken ice-flow, the Taylor Glacier, at intervals all the way to the sea (Fig. 6).

The largest of these is Lake Bonney, which is at present about three miles long and  $1\frac{1}{2}$  miles wide, and lies at the upper end of the valley immediately below the snout of the Taylor Glacier. It has obviously been much larger in the past and lies in an area of inland drainage of considerable size. The topography of Dry Valley is remarkable, as can be seen from the sketch-map (Fig. 14. p. 90), and the lake occupies two broad basins linked by a deep gorge.

The whole of Dry Valley is covered with moraine left by the retreating glacier, but in the neighbourhood of Lake Bonney this moraine has undergone a good deal of re-sorting by water. Many streams had cut little V-shaped valleys in it, and the blocks showed some evidence of erosion.

As the lake was frozen when we saw it, we could not determine its depth or the nature of the lake bottom, but in the gorge it must be well over twenty feet in depth. Everywhere there was a considerable amount of the grey-green algous weed we have already noticed on Ross Island, but it was on the outskirts of the present lake that we were best able to judge of the deposits now hidden at its bottom. Like all lakes without an outlet, it is subject to marked changes of level, a fact that was evident in many ways. The most curious of these was that in the centre of the lake was a low platform of ice, much pinnacled and weathered, which represented the level of some former year and had not since been thawed out.

At the sides of the lake the terraced effect to be expected from such alterations of level was not very marked though visible. The former strand lines were represented by lines of dried algae rather than by the usual miniature beaches. The absence of beaches is accounted for by the fact that, in spite of the size of the lake, wave action can rarely be of much importance, as the thaw is usually partial and acts only for a very short period. The lake is shallow at both ends, where the main accession of water takes place from streams. Silting of the lake is taking place here and small deltas are being formed, but there is a general absence of fine mud, the particles of material being all above "dust" size and the water running quite clear everywhere. The reason for this is that, since frost action is the chief disintegrating agent, rock-dust is rarely formed, and the strong winds sweep away what little may be the result of its own action. Beyond the lake to the east, and at a higher level, there are four very definite deposits from former lakes, which give an insight into the types of deposit now being laid down. These were level patches of gravel mixed with finer silt, and were so remarkable on the otherwise irregular surface that they were named "Football Fields." They were connected with each other and with Lake Bonney by stream-channels which had traced small valleys of their own. The farthest field was about 250 feet above the level of the large lake and distant about 3,000 yards. These fields represent old lakes which have been completely silted up or have found a drainage to lower levels which emptied them, the floors being now almost level. The nature of the deposits thus exposed is particularly interesting. One would expect to find the material graded from inlet to outlet, the length of some of the fields being half a mile, but this is not the case. The finer material is everywhere mixed with a considerable amount of coarse gravel the stones of which are sub-angular and sometimes reach the size of a walnut. Moreover, one would hardly expect the whole bed to be of an even level, yet it is definitely so. The reasons for these peculiarities seem to be as follows:—The lakes were probably shallow in any case like the present ones, and were only thawed out for a small part of the year. The normal action of water depositing mud in still water would therefore be taking place only for an inconsiderable period and at long intervals. On the other hand, the action of the wind conveying angular gravel from the sides of the valley would be continuous throughout the year and would spread the gravel more or less equally over the lower parts of the valley. The gravel would be especially

entangled in the rough surface of the frozen lake, and, when the thaw came, would melt its way down to the floor of the lake, mixing with the true water-laid silt and obscuring its nature. As could be seen in the sides of the small channels, these lake-deposits do not show the marked bedding that one finds in normal deposits. A definite bedding plane might run for a few feet, but there was little to show that the whole of the material was laid down in water. This appears to be an important observation in its application to the glacial drifts of past times, for it seems that under the conditions named—that is to say, a very short season of thaw—any deposits in basins will be of this hybrid character, a proportion of angular unstratified material with a proportion of finer bedded material. One might almost go so far as to say that the ratio of the one to the other is in direct proportion to the length of the summer, or, in other words, to the time during which the action of streams can produce deposits to cope with the action of wind for the remainder of the year.

Further down the Dry Valley there were other and smaller lakes than Lake Bonney, though of a similar kind. The floor of the valley is everywhere coated with wind-blown gravel which, in the basins, covers the original moraine. The action of the lakes is merely to collect this gravel rather more definitely than elsewhere, and to mix it with a small proportion of finer silt which in places is bedded. It should be noted also that the result of a lake freezing solid as the Antarctic lakes do is to disturb the deposits at the bottom, especially towards the side, and still further obscure what bedding there may have been.

In the large glaciers of the outlet valleys, lakes are frequently found on the upper side of tributaries entering at grade or anywhere at the side of the glacier where the normal flow of the thaw water is obstructed by the ice itself. Some of these lakes are of considerable size, such as the one under the Solitary Rocks on the Taylor Glacier and another to the east of Cathedral Rocks in the Ferrar Glacier. They are peculiar in that they fulfil a double rôle, for in the summer when they are thawed they are definite lakes and receive the lateral streams with their load of material, but when they freeze again they become part of the glacier, sharing in its movement to some extent on the glacier side. The case of such temporary lakes is particularly interesting, as the deposits they collect will remain, when the ice departs, in a most unusual position high up on the shoulder of a valley. One such instance may be described. The Mackay Glacier, in Granite Harbour, passes round several large islands or nunataks which deflect the stream on the upper side. On the lower side is a "backwater" between the reuniting streams, and this depression is always filled by a lake of thaw water. The best instance is that below the nunatak of Mount Suess (see sketch-map, Fig. 16, p. 96). Besides the lateral moraine in this depression, there are long patches of water-borne silt and several small terraces showing the former levels of the lake. At the upper end this lake is sharply marked off from the glacier by an ice slope, almost a wall in places, but at the wedge-shaped lower end it merges into the ice of the glacier so that the junction is invisible.

The small patches of silt and the small terraces in this locality are repeated on a large scale at the mouth of the Davis Valley immediately south of Blue Glacier. The glaciers of the small valleys along this strip of the coast are all far up their

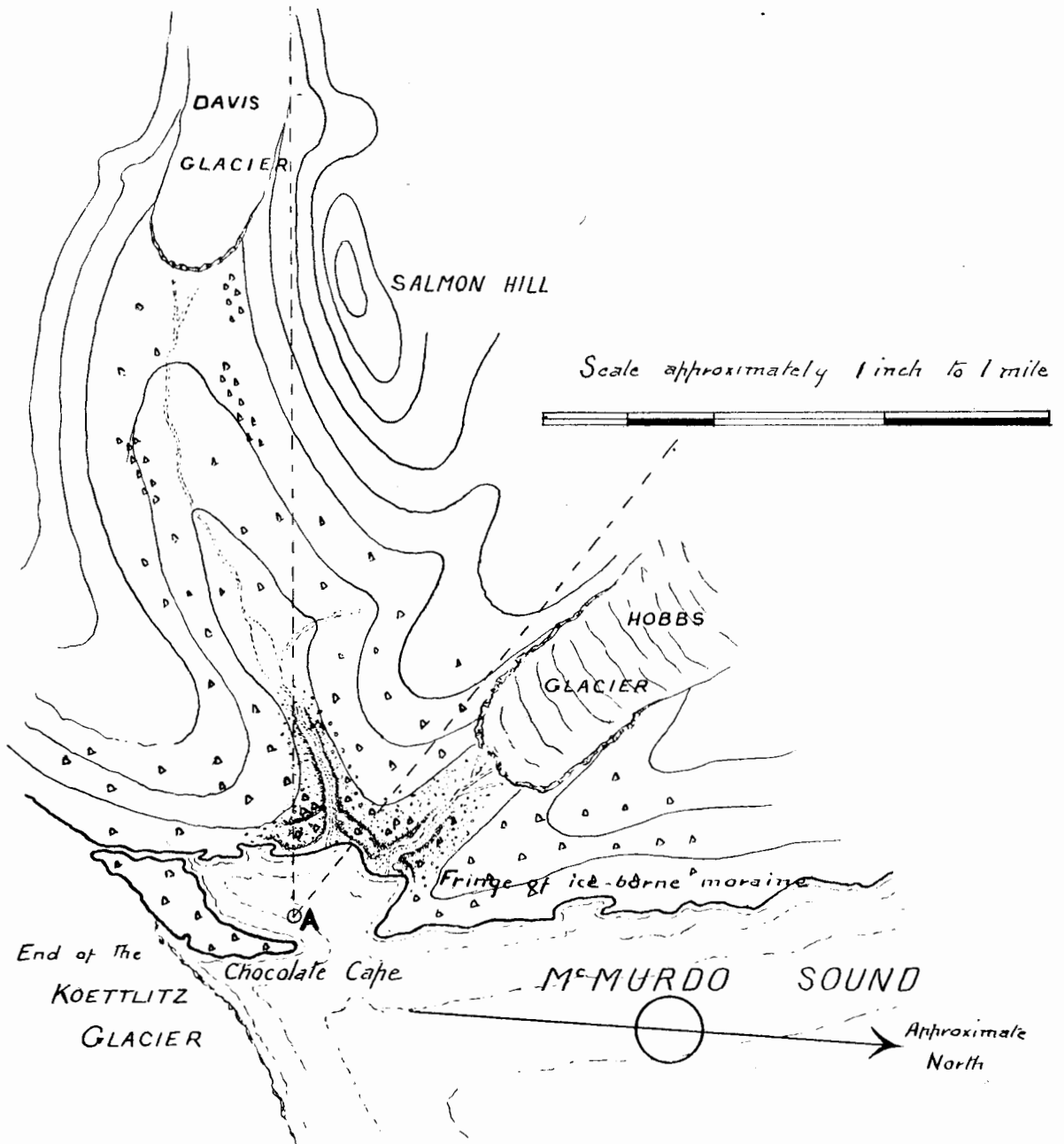


FIG. 7.—Sketch-map of Davis Valley, to show gravel terraces.

respective valleys and have left their moraine on the sides and floor of the valleys just as in the case of Dry Valley, but comparatively recently they were much larger and reached the main Koettlitz Glacier, then a huge stream some fifteen miles wide and

some 400 feet higher than it is at present. As the ice began to retreat, the Koettlitz formed an immense bar to the thaw water from these valleys, and large lakes were formed, which, as the ice still retreated, dwindled in size and finally disappeared, leaving their deposits exposed.

An excellent example of this occurs at the mouth of the Davis Valley, and is represented in the map and sketch (Figs. 7 and 8). The terraces here are up to 50 feet in thickness, with level surfaces, and have since been cut through by streams to that depth. At the bottom of the small ravine so formed were large boulders rounded by water action, showing that the short summer thaw can nevertheless account for considerable erosion even in such a severe climate. The material of the terraces is for the most part coarse gravel with a small proportion of the fragments water-worn, but the most striking feature about the whole is the presence of outcrops of the original moraine protruding above the approximately level surface of the gravels. These



FIG. 8.—Sketch showing old lake-terraces at mouth of Davis Valley.

From point A in sketch-map (Fig. 7).

outcrops are similar to other moraines all along this coast, and show that the gravels were laid down round them as islands.

We have here the same kind of processes at work as in the Dry Valley, but on a larger scale, the recent history of the locality being somewhat as follows :—

At some time since the maximum extension of the ice the Davis Glacier had begun to recede from the Koettlitz, leaving the opening of its valley free for the collection of the thaw water from it and its neighbour the Hobbs Glacier, with the result that a large lake was formed against the side of the Koettlitz. The deposits of water-borne silt and wind-borne gravel were then formed over and round the original flooring of coarse moraine. When the main glacier itself receded past the opening of the valley, the lake escaped to the sea, leaving the deposits well above sea-level and arranged in a gradual slope towards it. The streams from the two valley glaciers then proceeded to cut ravines through the loose material, and the much larger stream from the side of the Koettlitz cut back its

seaward face. The very definite slope of the terraces as now seen is therefore not due to wave action, which in Antarctic lakes can never be a great factor, but to the transverse washing of a thaw stream. Though terraced in form, they are not lake-terraces in the ordinary sense.

These deposits of silt and gravel are still very loose, and there can be very little binding in the mass for two reasons, firstly, because the proportion of fine material is very small, and, secondly, because there is no water to percolate through it. The snow which falls in the winter disappears in early spring by ablation, and what little water may find its way through the upper surface is permanently frozen a foot or so below.

From the above description it is clear that a section through the whole deposit would expose a most anomalous set of sediments, all the more so since the thaw streams often shift their beds in a lateral direction, leaving the water-worn material to be covered with gravel and moraine falling down the sides of the ravines. The greater part of the section would consist of rudely stratified silts and gravels with only a very slight rounding of the grains. Mixed with this there would be occasional lenticles of water-laid silt and other patches of angular boulders, while through the whole mass would be large mounds of the original moraine. The sequence would be still further obscured by the presence of stream boulders under the unworn gravel, very possibly resting on the original striated pavements of the foundation.

In each of the valleys in this neighbourhood something similar is to be seen, that is to say, there are lake-deposits in the beds of the valleys either on the foundations or on the moraines. The placing of a bar of moraine across these valleys by the Koettlitz Glacier has helped to form these lakes, some of which are of considerable size, as may be seen from the maps.

In summarising the nature and extent of the lake-deposits we must emphasise two main points. The first is that the sediments do not present the usual characters of those of lacustrine origin and would be difficult to recognise as such apart from their original surroundings. The proportion of true mud is so insignificant, the bedding so indefinite, and the sorting of material so little marked, that there is little in common with temperate lake-deposits.

The other important point to be remarked upon is the short geological life of most of these deposits. Situated as they are for the most part in the beds of valleys, it is difficult to see how they can be preserved. Should the glacial conditions continue to moderate, the fluvial action down the valley would quickly transform or remove them; while if the glaciers were to increase again, they would be disturbed and disrupted. The deposits formed by the temporary lakes at the sides of glaciers stand a better chance of being preserved for a considerable period.

The net result should be that after a period of severe glaciation there is no very striking accumulation of lake-deposits, and those that do survive are of a peculiar character.

## STREAM-DEPOSITS.

It is somewhat surprising to find that in a region where no rain ever falls the streams can reach such a magnitude as was constantly observed, and if asked for the outstanding feature of Antarctic conditions one would be inclined to say the summer thaw.

On a calm summer day in the vicinity of rocks the thaw is intense, though the air temperature may be hardly above freezing-point. It very soon became obvious to us that the short thaw season was the real geological year on land, and that most of the alterations, whether of erosion or deposition, take place in that brief period of the year.

The true air temperature, as we have seen, is rarely above 32° F., but on calm days close to the ground it may be higher. The most important factor, however, is not the air temperature but the rock temperature, in other words, the heat absorbed by the rocks and passed on to the snow or ice in contact with it. The effects of this action were little short of astonishing, for we frequently observed thaw going on at an air temperature of zero Fahrenheit, and copious streams came from the moraines at air temperatures between 10° and 20° F. Where the moraines are intimately mixed with the ice on which they lie, as in the lower levels of the Ferrar and Koettlitz Glaciers, tiny streams were observed well into March, that is to say, some six weeks after the height of the thaw.

The action may be described as somewhat similar to the warming of the air in a conservatory, for immediately the water came into contact with the air it would be coated with a thin film of ice, which acted as the glass does in letting through the radiant heat and preventing convection of the cold air. One therefore often met with a cliff of silted ice with a skin of thin clear ice on it and thaw water dripping down behind the film and running away under thinly frozen streams at the base of the cliff. The true thaw may take place any time in December and January, and is, of course, subject to complete interruptions by cloudy weather or cold winds.

The following instances will show the order of size of the glacial streams, and it will be seen that they are comparable with those of glaciers in more normal climates, with the limitation that they only run at that rate for a few days, or even hours, in the year.

On the Ferrar Glacier, at a height of 3,000 feet above the sea, a thaw stream was seen in December seven feet in width, averaging nine inches in depth, and running at the rate of 360 feet per minute. Much larger streams than this have been seen on the same glacier, but no exact measurements are available. Nearer sea-level the size of the streams is much increased, and they may even assume the proportions of rivers. It was on the frozen surface of one of these rivers at the side of the Koettlitz Glacier that a party was able to sledge for about 20 miles at the end of February. At this time it was covered with three to six inches of ice, but its former size was easily seen by the limits of the clear ice. At a point 15 miles from its outfall into the sea, the water beneath the ice was

at this time 18 inches deep and up to 15 feet in width, but lower down these dimensions were probably far exceeded. It was such a permanent feature that it was named the Alph River (Fig. 9), and its size may be further gauged from the fact that the seals regularly used it as a highway to travel inland as far as 20 miles, so that it must everywhere be well over a foot in depth. An average for the lower portion would be about 20 feet wide by 3 feet deep for the date mentioned, and its rate there was rapid, about 400 feet per minute. Its bed for the whole of its length is the ice of the glacier, so that it is not doing any erosion, but it affords an example of the size of the streams that are possible in the South.

Naturally it is only where the streams descend from the glaciers on to bare ground that any permanent stream-deposits are found, and this takes place in only a few valleys.

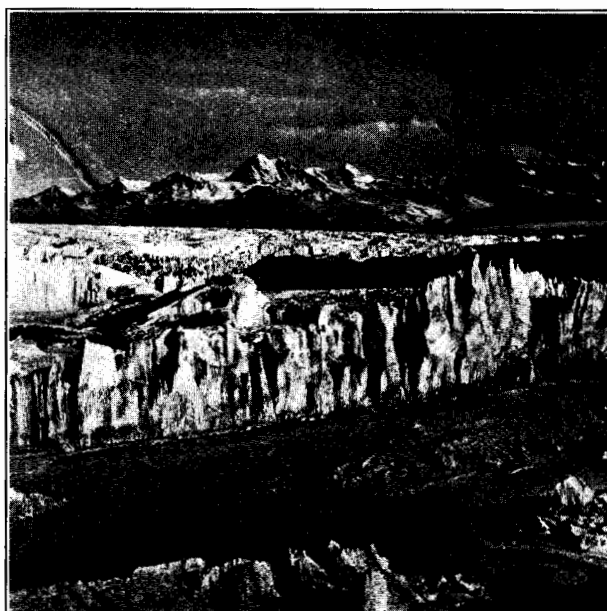


FIG. 9.—Scene on the Koettlitz Glacier, showing results of extreme thaw. Alph River in the foreground. Twenty miles from the sea, but only 100 feet above sea-level.

At the end of the Taylor Glacier in Dry Valley a series of streams run off the ice, and are joined by the streams from the lateral moats before running into Lake Bonney. There is here a large area of 20 to 30 acres of stream-laid silt, flattened in places into the form of a plain, but for the most part uneven and hummocky. The reason for the rough appearance is that, except under special circumstances, the silt is permanently frozen a few inches below the surface, and though originally almost level, in process of time it becomes hummocky through the escape of the ice by ablation or differential thawing. The hexagonal tessellations so typical of water-logged soil which is frozen were particularly well developed in these silt areas, though not confined to them. Small deltas of finer silt were to be found at the edge of the lake.

The important point noted about these silts was their comparative coarseness, the

grains being rarely less than the size of ordinary beach sand and often that of a coarse gravel. There was very little true mud, and everywhere the water ran perfectly clear. Washings for heavy minerals were made in the finer silt, and even vigorous stirrings only clouded the water for a moment or two. This fact is of great interest, for it is in contrast with the conditions in other glacier lands. We never came across a stream in the Antarctic that was milky. The point must not be strained too far, however, for all the streams are surface ones, and probably very little of the true ground moraine would be reached by them.

The best instance of stream-deposits that we met with was immediately north of the Davis Valley, already described. Here the Hobbs Glacier comes nearly to sea-level and ends about a mile from the sea itself. The intervening strip was covered with an extraordinarily even deposit of silt, much finer than the terraces of Davis Valley and definitely due to stream action. There were terraces also similar to those in Davis Valley, and indeed the two instances are much alike, except that the grain of the silts was finer in this case, and the wandering stream-beds were so evident that the deposit is classed as a stream-deposit. The tessellations were very well marked, and there is much ice in the silt still. Again the amount of true mud was very small, and the bedding not very pronounced. This is, however, an instance of a more advanced stage of water-laid deposit, and the only one which is truly comparable with those in the Arctic.

### RAISED MARINE MUDS AND MIRABILITE DEPOSITS.

A very important series of recent deposits is that of marine muds containing shells of present-day forms. These are found occasionally on the land, but more often on the surface of floating glaciers and ice-sheets. Associated with them are deposits of massive pure mirabilite (sodium sulphate). The origin of these deposits has given rise to much speculation in the past, and has therefore been treated in a special paper\* of which only a précis is given here.

The raised marine beds occur in such positions and so perfectly preserved that no pushing action of the ice masses can explain them.

Their general appearance and preservation make it probable that they have risen through the ice. In any ice-sheet where there is decrease by thaw from above and increase by freezing from below, the bottom ice must ultimately reach the surface. If the sheet were occasionally to freeze on the bottom and also to isolate basins of sea water, both shelly muds and sodium sulphate would become entangled in the ice and would ultimately reach the surface.

The numerous instances already found (see Figs. 11 and 12) in South Victoria Land prove that this vertical transport of material by ice is going on over a wide area

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\* F. Debenham. A New Mode of Transportation by Ice: the Raised Marine Muds of South Victoria Land (Antarctica). *Quart. Journ. Geol. Soc.*, 1920, Vol. 75, p. 51.

and with considerable activity. Although most of the effects are not perpetuated, being on floating ice, the few cases where the salts and shells are left high and dry on land provide a problem which is perhaps paralleled by many of the shelly drifts in other parts of the world, and these may be susceptible to a like explanation.

### THE MORAINIC DEPOSITS.

Under the above title are included all deposits connected with ice moving on land, even where water has played a part in their arrangement.

They fall naturally into three groups differing in age and general appearance. The old moraines of the maximum extension of the ice are easily recognised both by their height above present levels and their disposition. The moraines quite recently deposited are distinguished by their own characteristics, not the least marked being the frequent occurrence of old ice still under them. Finally there are the present "active" moraines on moving ice or in the process of deposition. We will consider the last group first of all. It has frequently been stated that there is very little surface moraine on the Antarctic glaciers, and that in this way they differ radically from those of more temperate lands. This appears to be a somewhat dangerous generalisation and needs qualification. It is quite true that the glaciers in the south appear at first sight to be remarkably free from the long lines of moraine so typical of the Swiss and New Zealand glaciers, and none of them have their proximal ends completely hidden by surface moraine. In making a comparison, however, we must be careful to choose similar zones, and on doing so the difference assumes much smaller proportions. Thus the end of a temperate glacier is normally well below the snow-line, where the ice comes under very different conditions of temperature from those obtaining in the Antarctic. If we proceed up such a glacier until we are above the snow-line, the conditions are more similar, and we find that the moraines are quite comparable. In both cases we get the usual curving lines of moraines, with the difference that the temperate glacier moraine contains material of all grades, while the polar one consists chiefly of large blocks, and there is a decided scarcity of gravel or sand on the surface. The actual difference in amount of material is not great, for it varies considerably with the glacier chosen for comparison. For example, in the photograph (Fig. 10) the moraines of the Priestley Glacier are seen to be quite equal in amount to some normal temperate moraines. The real difference, therefore, is with respect to the size of the boulders.

It has already been remarked that the melting of the ice by air-temperature is rare, and the seasonal thaw is almost entirely due to the heat passed on from the rocks to the ice with which they are in contact. The net effect of this action is to bury the smaller blocks. The line of moraine of the Ferrar Glacier, for instance, is marked by a series of large boulders at a considerable distance apart, but a closer examination shows that there are many other boulders half-embedded in the ice, and frequent patches of clear ice show that there are still more a few inches below the surface. These still belong to

the supra-glacial moraine, and are not sinking through the ice to the bottom of the glacier.

The sequence of events appears to be somewhat as follows :—When a boulder first appears above the *névé* in the upper reaches of the glacier, it begins to form a basin for itself by its annual heating effect. As it proceeds down the glacier into warmer levels, this thaw basin increases in size and depth until, if the boulder be only of moderate size, it completely covers the boulder. Under normal conditions the boulder will complete the journey a little below the surface, but variation in the seasons generally causes it sometimes to project above the surface, and at other times to be covered over with snow on top of the thaw ice.

The actual amount of surface moraine on Antarctic glaciers is, therefore, hard to

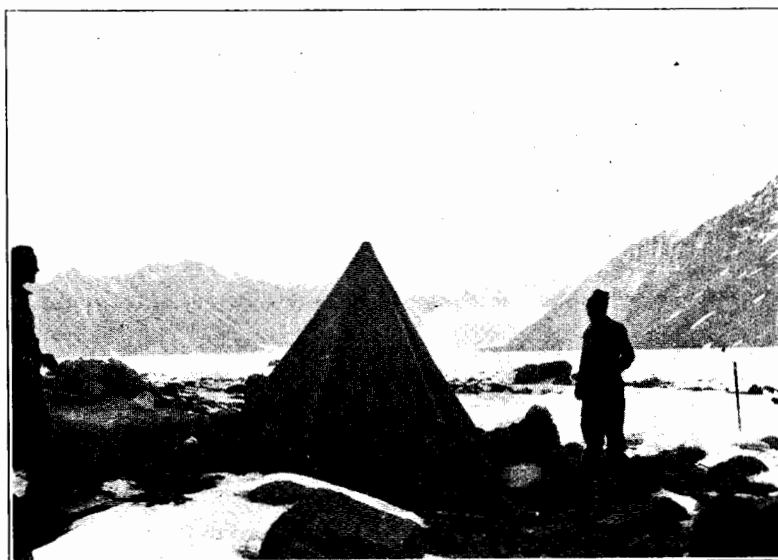


FIG. 10.—Moraine of the Priestley Glacier, lat.  $75^{\circ}$  S., quite equal in amount to moraines on many glaciers of temperate latitudes.

determine, but it is probably little less than that found on glaciers of temperate latitudes under similar conditions of catchment area, etc.

In the present instance we are more concerned with the deposit of the moraine after it has been brought down to lower levels by the ice.

Here, again, we are apt to infer from the comparatively small amount of deposited moraine that the action of polar glaciers is less than that of glaciers in other parts of the world. The real difference lies in the fact that in the Antarctic there is only a very small amount of bare land on which morainic deposits can collect, and that the greater part of the morainic *débris* from the land is deposited in the sea. It must again be emphasised that the normal end of a South Victoria Land glacier is at sea-level, and that the few that are found to end on the land itself do so on account of local conditions affecting supply, and their number is comparatively small.

We therefore find but few terminal moraines, and those of a peculiar nature, so that

most of our description is limited to the lateral moraines of the main outlet glaciers which have been left on the sides of valleys by the general shrinkage of the ice supply. It will be convenient to deal with them in approximate order of age, beginning with the old high-level moraines, presumably deposited at the maximum of glaciation.

#### OLD HIGH-LEVEL MORAINES OF THE MAXIMUM GLACIATION.

The most remarkable as well as the best known of these are the deposits found on Ross Island itself. The accompanying sketch-map (Fig. 11) shows the general distribution of these moraines, and it is at once evident that they are referable for the most part to the Ross Barrier and not to local valley glaciers. On Ross Island their study is of particular interest, as the erratics, being nearly all of granites and other continental rocks, are very easily recognised as such against the typical lavas of the island.

Their greatest extension is on the south-east slopes of Mount Terror, where the force of the Barrier expends itself in a glancing direction against the land. The moraine here is piled up in a large terrace, the maximum height of which above sea-level is from 800 to 900 feet.

The curious projection of volcanic rock known as Minna Bluff causes the Barrier to pile itself up in grand folds on the southern side and mount the peninsula to a height of some hundreds of feet, the exact height not being known. The reason for mentioning the fact here is to show that the great height above sea-level at which some of the moraines occur does not mean necessarily that the Barrier was once of that extra thickness. In most of these cases they may have been deposited at that height by the mounting of the ice sheet on to the land. On the northern side of the Bluff, where no such mounting has taken place, the moraines are found only to a moderate height.

On the southern parts of the Hut Point Peninsula, where there is bare rock, a small number of erratics are found. They are all very small and rarely exceed an ounce or two in weight, and consist of the usual collection of granites, granulites, porphyries, and sandstones which characterise moraines from the mainland. They are found chiefly on the high ground north of the Gap, even in the deep crater of Crater Hill the summit of which is 1,100 feet high and has a sharp edge. These have usually been regarded as a moraine from the Barrier at its maximum extension, suggesting that it not only reached a height of over 1,000 feet above sea-level but that the perfect forms of craters were once overridden by the ice, two ideas which seem exceedingly improbable. The uniformly small size of the erratics seems to be evidence of the greatest importance, and obviously it refers the deposits to wind action. They are of a size which could easily be raised and swept for long distances by the strong winds of that area, and the fact that they are particularly common in comparatively sheltered places, such as the bottom of a crater, is additional evidence for the same conclusion. The winds at present being prevalent from a S.E. direction, we may for the moment assume that

they came from a large moraine which ran from White Island to the slopes of Mount Terror over an area where there is at present no surface moraine.

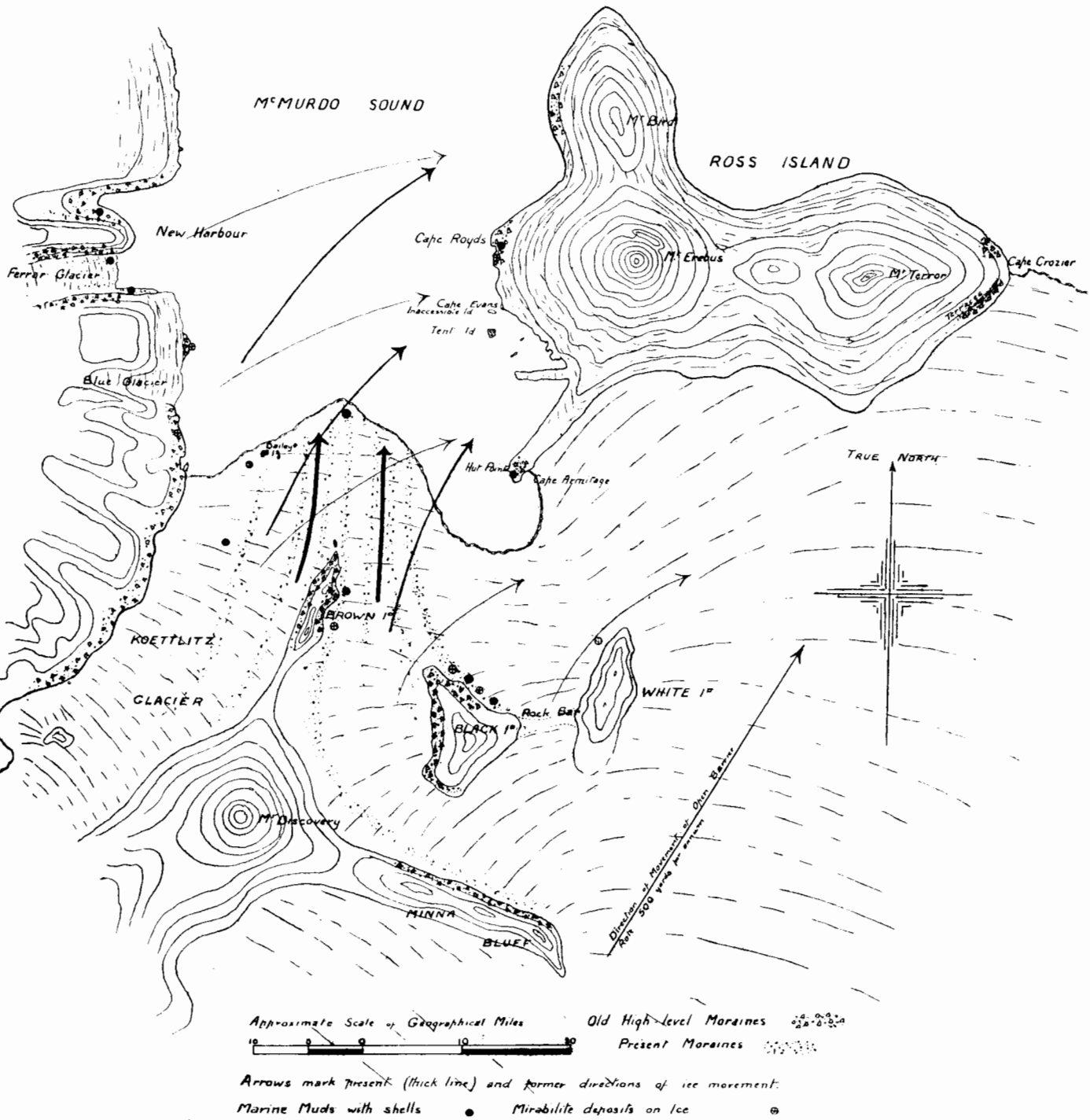


FIG. 11.—Sketch-map of McMurdo Sound region.

Proceeding up the west coast of Ross Island, we meet with a few erratics, some of large size, scattered over the upper surface of Tent Island at heights of 200 to 400 feet.

None have been found on Inaccessible Island which is everywhere steep, nor on Cape Evans which is low, two facts which will be referred to again. On the large extent of bare land in the vicinity of Cape Royds and Cape Barne we find, however, a wealth of morainic material, which supplies the fullest evidence we have of past ice action and has been mapped and studied more carefully than any other part of Ross Island.

The area (Fig. 12) consists of the coastal strip between Horseshoe Bay and Cape Barne, which, unlike most of the coast of Ross Island, has a comparatively low gradient to the sea and is not covered by moving ice. It is due, in fact, to the existence of a number of parasitic cones in the past, the largest of which was at Cape Barne, where the remnant is still well preserved. The whole of this surface is sprinkled more or less thickly with morainic material, which on close inspection proves to be capable of classification into types, and of these it may be possible to infer the approximate origin, and hence the nature and extent of the former glaciation.

It is quite clear that here one glaciation has been superseded by another, and it is necessary, therefore, to classify the moraines less on their rock content than on their mutual disposition.

The most striking feature of the area is the large proportion of *terraced moraine*, which gives a very definite stepped appearance to the topography. It occupies the north and centre of the area, and consists of terraces, cones, and table-mounds of fine morainic material. The terraces are convex towards the lower ground, *i.e.* to the west, and in places are as marked as those already mentioned in Davis Valley. The material is to some extent water-sorted and even rounded, and some of the ridges look very like eskers; at the same time, there is reason to believe that a certain proportion of these gravels are resting on ice still. It consists for the most part of basic volcanic rock with kenytes in moderate quantities and comparatively few mainland rocks.

The direction of the terraces and the recent character of the whole deposit point to the Erebus ice-flows as the chief agent.

There is also a small but very definite moraine which has been deposited on the sides of a small valley to the north of the Cape Barne hills, which includes Terrace Lake. It is entirely composed of kenyte, the typical lava of Erebus itself, and of friable tufaceous muds; the latter show a hexagonal structure due to being frozen while saturated with water. It is obviously due to an overflow of the present Barne Glacier, which, when a hundred feet higher, would be deflected in part into this valley by the coastal basalt hills.

The most interesting of the types of moraine in the area, however, is the one that is almost destroyed by later deposits, the erratics of mainland rocks. These are not deposited in any definite arrangement, as is the case at Cape Crozier, but are found over most of the area; and the rough rule holds that the nearer the sea the larger the blocks. They are reported up to a height of 1,200 feet, but we found none above 900 feet, and those were small. Allowing for the possible action of wind, it seems

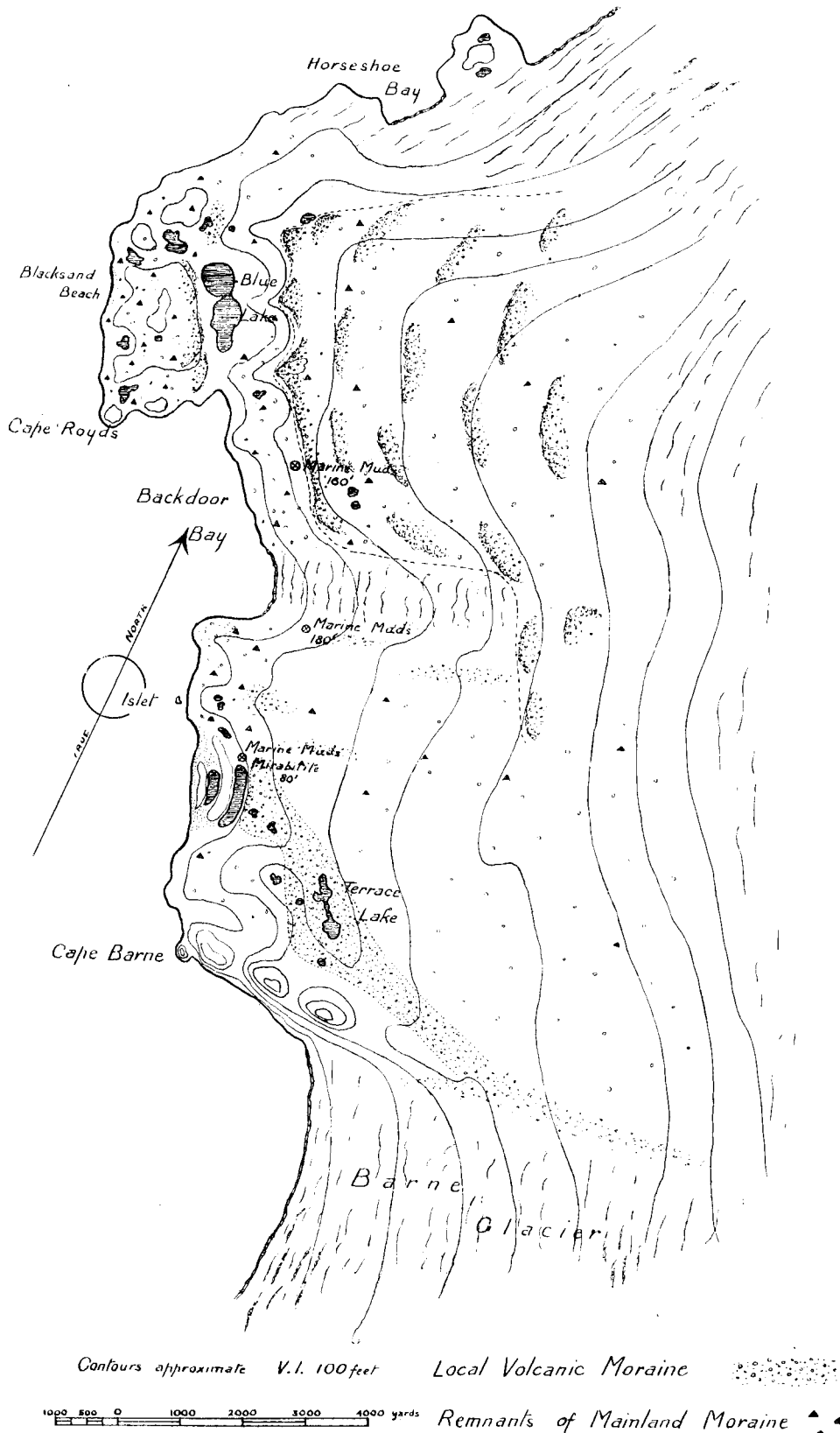


FIG. 12.—Drift Map of Cape Royds.

safer to take the maximum height of erratics of these rocks as in the neighbourhood of 1,000 feet. The types of rock, in descending order of frequency, are as follows :—

Grey Granites,	Schists and Gneisses,
Pink Granites,	Sandstones,
Dolerites,	Crystalline Limestones.

To these might be added basalts near the top of the list, but it is difficult to differentiate between a Ross Island basalt and a dolerite from the mainland in hand specimens. Erratics of similar types are common along the coast of South Victoria Land from Granite Harbour down to the region of the Beardmore Glacier in 84° S. Most of them are rounded, from frost action rather than from water, and many of the granite blocks lie in a bed of their own weathered gravel. No definite inclusions of these erratics were found in the local lava, and they are therefore probably later than the youngest lavas of this area. It is seen, therefore, that there is a sprinkling of mainland rocks over most of the area without very definite arrangement.

These erratics have been hitherto referred to the ice flood of the Barrier, and it has been assumed that to deposit them the Barrier must at one time have been at least 1,000 feet higher above sea-level than it is now. It is true that, if these erratics were deposited as a lateral of the former Barrier extension sweeping up McMurdo Sound, it would be natural to assume that the average surface of the depositing ice was about the height of the moraine, but there appears to be no need to regard it as a lateral.

The difficulty of reconciling an extra thousand feet of ice-sheet above sea-level, that is, a total thickness of something like 5,000 feet, with the other facts of the maximum extension are too great to be ignored, and I take the view that not only was the Barrier not immediately concerned with these moraines, but that another 600 feet only of total thickness of the McMurdo ice-sheet would suffice for the deposition of these erratics.

A glance at the sketch-map (Fig. 11) shows that the present McMurdo ice-sheet is composed of two parts, the western part being derived entirely from the Koettlitz Glacier and the eastern being an overflow from the Barrier, the real direction of motion of which takes it well outside White Island in the direction of Mount Terror.

The two component parts of this sheet have at present an equal value as to rate of motion and supply of ice, for their moraines combine to form a large medial moraine of great width whose direction (thick arrows on the map) is up the middle of the Sound. Let us see what would be the effect of an increased precipitation and supply over the whole area, and let us assume that it be of such dimensions as to bring the surface of the sheet to a height of 150 or 200 feet above the level of the sea, the same height, in fact, as a great deal of the eastern end of the Barrier face is to-day.

We must first examine more carefully the nature of the Barrier overflow into McMurdo Sound. As shown in the map, there is a rocky bar between Black and White Islands, which must come very near sea-level. There is also good reason to suspect similar but lower bars between White and Ross Islands and between Black and Brown Islands.

In any case, it is clear that the only unrestricted course for the present overflow is the sinuous one to the south of Black Island and between that island and Brown Island. If now the surface of the Barrier were 100 feet higher, the overflow, while being greater, would be still restricted by these bars, besides being probably aground between the islands mentioned. Such an increase in supply would, however, have the opposite effect on the Koettlitz and other western glaciers whose course in the Sound itself is barred by nothing more serious than the small group of the Dailey Islands.

The actual course of the ice-flows and of their surface moraines depends on the depths of the sea at the southern end of the Sound, about which little is known. If we suppose in the first place that the overflow from the Barrier would be still of some importance under the postulated conditions, we should get a general direction up the Sound, as shown by the medium arrows on the map. The present nice balance between the two halves of the sheet would be greatly disturbed in favour of the western half, and the moraines would be swept round to the east after leaving the shelter of Brown Island and reach the western coast of Ross Island more or less at right angles. The ice-flows from Ross Island itself would, of course, be increased under such conditions, and the McMurdo sheet would only make direct contact with the land where the local glaciers were thinner and could be deflected or reversed. This would especially be the case on the Cape Royds area and on the present bare land to the west of Mount Bird. The erratics reaching these places would, therefore, be largely composed of rocks from the Royal Society Range, and those found there are certainly common in the foothills of the west. Tent Island and Inaccessible Island would be covered with the sheet, and as it retired would receive a proportion of the moraine. This is definitely so in the former case, but in the latter the steep sides of the island have prevented them from finding lodgment. As the precipitation decreased, the sheet would not only retire, but the general direction of the moraines would swing back towards the centre of the Sound. The reason why there are no western erratics on Cape Evans is because the Barne Glacier itself under such conditions would flow over the low cape and prevent the main ice-sheet reaching it.

If, on the other hand, we suppose that the depth of the sea-floor in the south-east of the Sound is so little that with the increased supply all the overflow from the Barrier would be aground, we should get still another direction of flow, as shown by the thin arrows on the map. The region of Black and White Islands would become a sort of ice-eddy with comparatively little movement and a large amount of surface moraine, while the main mass moved past it to the east of White Island. The western glaciers would then be still less deflected from their natural course across the Sound. This direction of movement would explain the massive terraces of mainland rocks on the slope of Mount Terror and also the wind-borne material on the Hut Point Peninsula, which must have come from a south-east direction under the present wind conditions.

According to the above views, therefore, the erratics of Cape Royds were deposited by an ice-sheet abutting more or less directly on the land, under which conditions it is quite

possible for it to mount to a height of 1,000 feet above sea-level, as is now happening at the eastern end of the Ross Barrier. The moraines were probably deposited as a series of rough terraces like those on the slopes of Terror, but as the main sheet retired these would be invaded by the local glaciers and redistributed on the lower slopes. One very definite flow came from the side of Erebus in the direction of Cape Royds itself, and deposited both its own moraine and that gathered from the older moraines in the series of terraces now found there. In the formation of these, water has evidently played a considerable part, but it is not easy to see under what circumstances. Possibly a series of lakes was formed in which the deposits were laid down in the way we have outlined for the terraces of Davis Valley. A certain proportion of the original mainland erratics was left over all the ground formerly covered by the old moraines, the larger ones being for the most part removed to the lower ground.

The last stage in the deposition of moraine on the area is very recent indeed, when the Barne Glacier lodged the kenyte in the little valley to the north of Cape Barne.

It will be of interest to observe what the valley glaciers of the west were doing during this maximum period of glaciation, and the record is particularly clear in the valleys of the Ferrar and Taylor Glaciers.

The sides of both these valleys are clothed up to a certain level with a mixture of talus and old moraine, the limits of which are easily recognisable from a distance. The height to which this old moraine reaches varies a good deal, both with the distance from the plateau, and, what is more important, with the bed of the valley itself. Notwithstanding the higher figures that have been given in the past, I am of the opinion that the moraines are rarely found more than 1,500 feet above the present surface of the ice, and in the valley of the Lower Ferrar they cannot definitely be said to be more than 800 feet above the present glacier surface. The higher figure, 1,500 feet, was obtained from a climb up the side of Dry Valley immediately above the end of the Taylor Glacier. We must be cautious, however, in applying figures to the former extension of the ice over the whole area. In this particular case, for instance, though the glacier did definitely reach to a point 1,500 feet above its present level and nearly 2,000 feet above the bed of the valley, it was because farther down the valley there is a huge barrier to the flow of the glacier, now called Mount Nussbaum, which would cause the ice to pile up behind it. The high-level moraines at a similar position on the sides of the neighbouring Ferrar Valley are not more than 700 or 800 feet above the glacier. Even with these qualifications the height of the old moraines is sufficiently difficult to account for. We have the choice of two explanations—one, that the former precipitation was such that the ice did actually reach a thickness of over 2,000 feet; and the other, that since the highest level of the ice the bed of the valley has been worn down. Without going into the arguments on either side, we may assume that both theories are applicable, with rather less evidence in favour of the heavy erosion of the valley. The height of these old laterals has been cited as additional evidence to prove that the original Barrier surface was about 1,000 feet

higher than at present in the Sound and helped to bank up the valley glaciers, but it does not seem necessary to credit the Barrier with such huge proportions.

An interesting discovery was made in the Dry Valley in connection with these high-level moraines. On the shoulders of the valley just below the highest moraines, there are two or three centres of volcanic activity (Figs. 13 and 14), one of which at least was active after the maximum extension of the ice. The existence of a small active crater just above the ice of a large outlet glacier must be somewhat unusual.

Another large series of moraines which requires notice is that which borders the valley of the Koettlitz, and may be called the low-level laterals of that glacier. These are the most extensive of any moraines in the Ross Sea as far as known, covering a stretch of

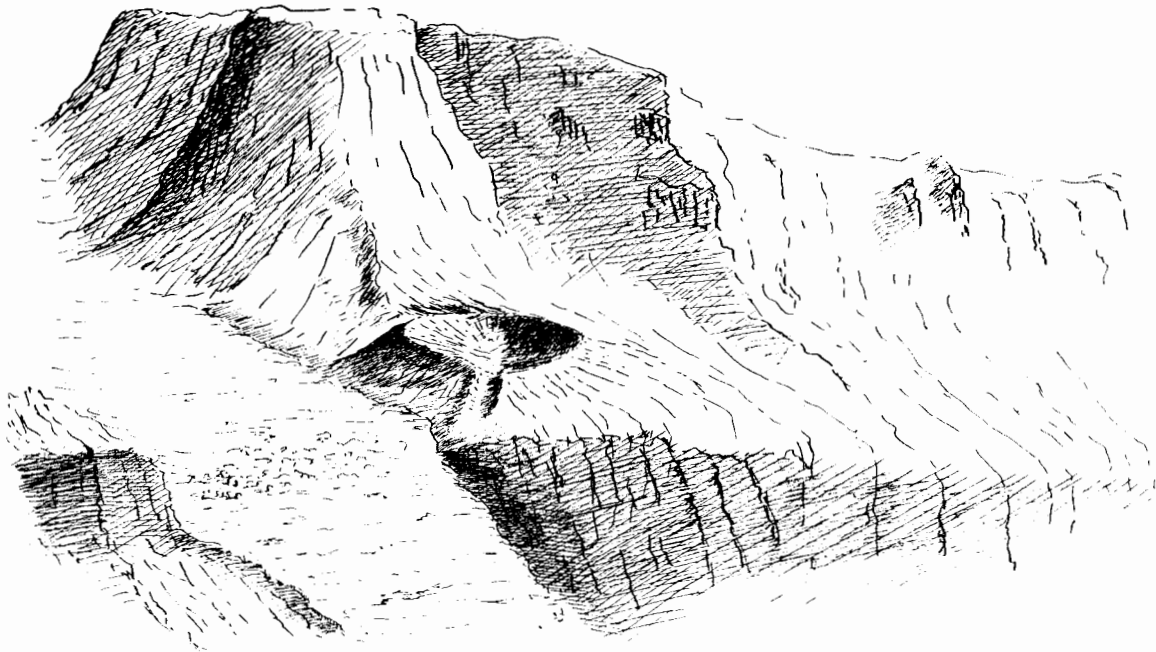


FIG. 13.—Recent crater in high-level moraines of Dry Valley.

coast at least 30 miles long to an average width of about one mile. They represent the lateral moraines of the former Koettlitz, together with the contributions of the small tributary glaciers on the north side which are now all withdrawn to the upper ends of their respective valleys. The height of the moraines above the present level of the lower glacier is of the order of 400 feet at the northern end, but it is somewhat difficult to decide how much is due to the tributaries and how much to the main flow, so that the height cannot be applied without care to the solution of the former height of the McMurdo sheet.

The material of the moraines is very diverse, consisting as it does of all the varieties of rock met with on the mainland except the sandstones which were either absent or very rare. This is not remarkable, since the Beacon Sandstone is generally very friable

and does not stand transportation over long distances without disintegration. The most constant constituent of the moraines is volcanic rock, chiefly basaltic with a large proportion of olivine, but occasionally blocks of kenyte, the typical lava of Erebus. Kenyte had formerly been found in the neighbourhood of the Ferrar Glacier, and had been cited as evidence of transport from the eastern side of the Sound to the west. The finding of these kenyte blocks in the Koettlitz region

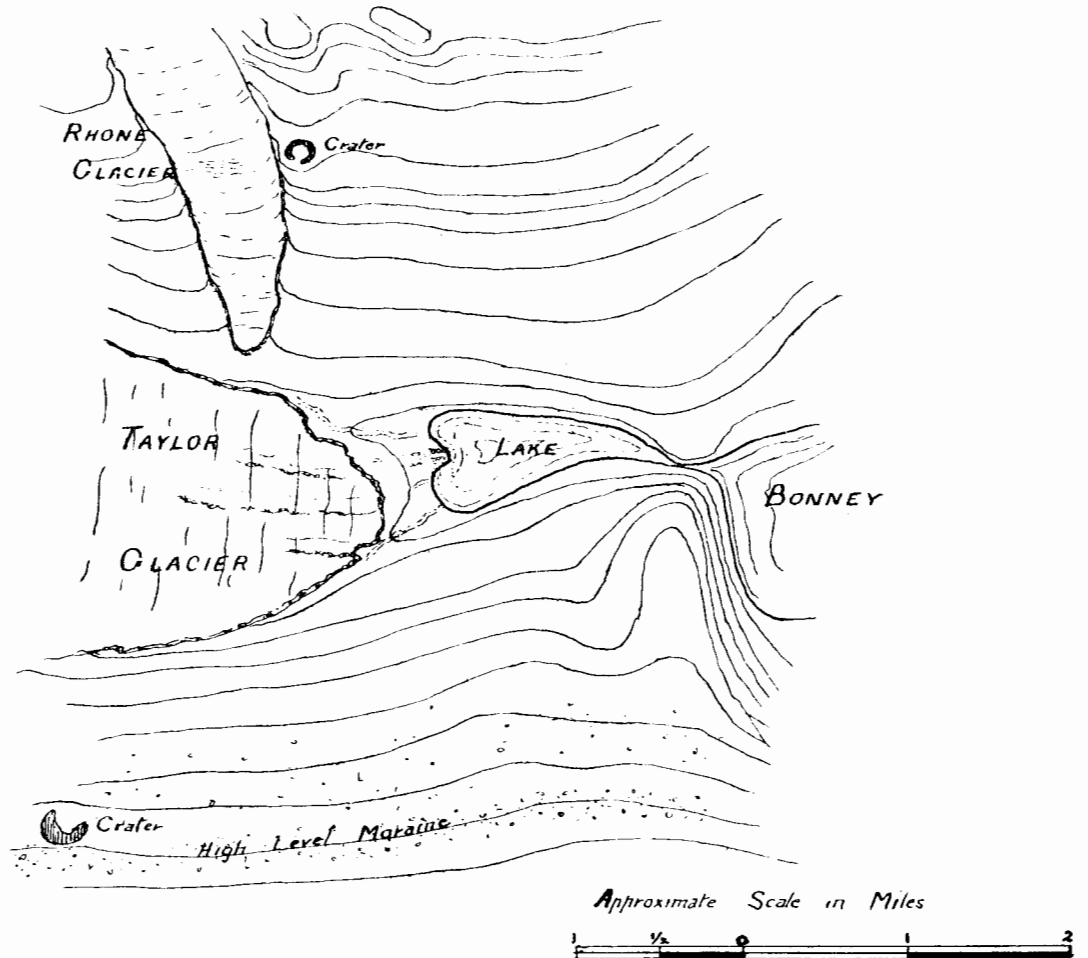


FIG. 14.—Sketch-map of recent craters in Dry Valley.

disposed of this theory and established the existence of another centre of kenyte lavas in the west.

The most striking feature of these lateral moraines, however, is that a very large part of them is still resting on ice which is protected from superficial thaw by the thickness of the covering. It is, in fact, similar to the lower end of many of the New Zealand and Swiss glaciers, where the ice of the glacier is not seen for perhaps a mile or two from the snout. The difference in the climate and the fact that the Koettlitz ice is not moving are the cause of further differences of an important character, which will be dealt with more fully.

In the first place they are unlike the surface moraines of a temperate glacier in their topography which is somewhat unique and deserves description.

These ice-borne moraines resemble nothing so much as giant relief models, or whole countries in miniature (Fig. 15). It is as if Switzerland, for instance, were dwarfed until Mont Blanc was only 50 feet in height. All the forms of topography are reproduced. Here are inland seas the size of a large room, with rocky islets dotting their surface. Here are winding rivers, complete with watersheds, tributaries, and deltas, emptying into the seas after a course of some hundreds of yards through canyons the height of a man, and over falls the height of a water-butt. They are frozen for fifty weeks in the year, but during their short spell of active life they mimic with perfect fidelity the rivers and lakes of a normal size.

Between the watercourses are mountain ranges, plateaus, and dissected peneplains

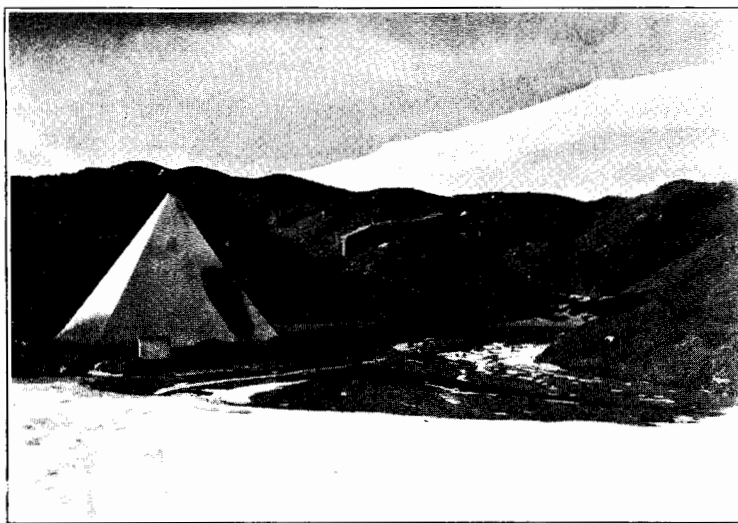


FIG. 15.—Ice-borne moraines stranded on the west coast of McMurdo Sound. Showing the miniature scenery.

of every variety, and no better testimony can be given than that the whole system would form a perfectly ideal model on a large scale for lectures on physiography. The commonest feature of all, however, was the existence of innumerable circular lakes, rarely more than ten yards or so in diameter, which displayed miniature terraces on their steep sides, not of water-worn material but of algae which had lived at the edge of the lakelet when it was at that level. All this may be seen for a mile or so without coming upon any evidence of the ice underneath, and, in fact, the miniature scenery was a source of great argument until the solution was found on coming to a small cliff-face of ice.

The moraine covering the ice is everywhere fairly thick, and for the most part consists of small stones, chiefly black basalt and fine silt, though here and there a larger block would crown a small peak.

The moraine being thick enough to protect the ice from direct thaw, and the ice

itself being almost stationary, the formation of this miniature landscape is somewhat as follows :—

Wherever a small stream began, it would eat its way down into the ice in much the same way as stream erosion takes place on land. As the ice itself is full of silt, the thawing is very slow, and may be held up altogether for a while by the fall of loose material into the bed. Wherever the bed is approximately level, the small silt brought down by the stream will be deposited as a miniature river alluvium and will help to preserve the ice underneath, and where the stream reaches a lakelet a delta of the silt is formed. Where there is no outlet for the first stages of thaw in any place, the pool of water collects in any depression and itself continues the thaw. During the winter the surface of the pool loses by ablation, and for the next summer the depression is deeper. The deeper it gets, the more thaw takes place from the heated sides of the basin until, when the latter is some 20 feet deep, the water itself may be as much as 6 or 8 feet deep. The algae take advantage of these warm pools and flourish in the summer. Occasionally the water will escape from a contraction crack forming in the ice, and a sudden change of level will take place, the line of algae remaining to mark the former strand line. Again, where the moraine is so thick that no heat will penetrate through to the ice beneath, no thaw will take place, and a plateau will be formed.

The whole process is perfectly clear when the key to it is provided—that is, the existence of the ice below—and its results are unique.

The moraines are, therefore, stranded on ice, and whatever movement there is appears to be quite local and independent of the remains of the parent glacier which lies to the south and east of the fringe of moraine, generally separated from it by some such large stream as the Alph River mentioned above (p. 78). They are of course gradually shrinking under the process, and the final result will be a fringe of what would be called normal moraine with a high proportion of silt, except for two contrasted deposits which a careful search would reveal. These deposits are, firstly, the layers of algae which in places may reach a thickness of a foot; and, secondly, the occurrence of sodium sulphate and recent marine shells (page 79). These two were found by us in actual juxtaposition, and at the time were completely beyond our explanation.

It is easy to see that under warmer conditions, such as in the Arctic regions, where there is an abundance of forms of life, such a moraine might include even thick peat deposits with fossil bones long before the ice had completely disappeared from beneath the deposit.

The proportion of ice under the surface increases as one ascends the glacier, if one can speak of ascent when the actual rise is only about 100 feet in 20 miles, and opposite Heald Island the ice-borne moraine is seamed with really large stream-channels and gorges. Here the walls of ice are easily seen, and the water has cut for itself long tunnels through the ice as in any temperate glacier.

The ice-borne and the true moraine cannot be easily distinguished, but I am

inclined to think that the former may in places reach the height of 80 or 100 feet above the present level of the glacier. Beyond that, the more normal moraine covers the slopes of the broad valley sides up to a height of 400 feet or so, and much more near the mouths of the tributary valleys.

#### TERMINAL MORAINES.

In a terminal moraine one generally expects to see a huge rampart of mixed rocks lying athwart a valley, as in the case of the Alpine glaciers. This form of terminal is never met with in the Antarctic, and its absence requires some explanation. Although in the tributary valleys of the Koettlitz Glacier there are huge bars across the mouth, these are definitely due to the lateral deposit of the main glacier and not to the terminal deposit of the tributary. In every case where a glacier has been retreating up its valley, as in these cases or in the case of Dry Valley, the deposit of moraine has been gradual, and the bed of the valley is more or less evenly coated with the *débris*. The same thing also occurs at Cape Bernacchi, where the Wilson Piedmont Glacier has already retreated some miles.

Not only are there no ancient terminal moraines, but there are no present-day ones worthy of the name. Every glacier that ends on land ends in a sheer face and has below it merely silts and muds washed off the glacier, together with a small proportion of boulders. Yet, as shown above, there is ample surface moraine of large erratics to form respectable terminal moraines, and the question is what becomes of these, or, rather, why do they not collect at the end? The answer to the problem appears to lie in the small differential movement of these glaciers.

In a normal temperate glacier the rate of movement of different parts of the glacier may vary enormously. It may, for instance, have a high rate of movement at the middle of its course and yet be stationary or retreating at its end. The reason for the apparent anomaly is, of course, the great change in temperature conditions along its course, and the effect is to pile up all the material at the lower end and form the gigantic ramparts that are so common in the Alps and elsewhere. In the Antarctic, however, and almost equally so in the Arctic, the change in temperature conditions along the course of a glacier is not very marked and may be so little as to be negligible. (It must be remembered that the temperature change which is of extreme importance is what may be called the thaw-point—that is, the condition under which thawing from air temperature takes place—and this is rarely reached in the Antarctic.) The result is that there is very little differentiation of rate of movement in the glaciers.

Putting the matter in another way, two boulders that fall on the *névé* of a temperate glacier 100 yards apart will decrease this distance on the journey down the glacier, and may be together at the end. In an Antarctic glacier, on the other hand, they will remain at 100 yards distance, or nearly so, all the way.

The question then follows as to what is happening at the end of these glaciers,

since the loss by thaw is so inappreciable ; why do they disappear at all, and how do they get rid of material ? The answer is that, as stated above, the normal end for an Antarctic glacier is in the sea where it breaks off periodically, and the material is never collected together. When abnormal conditions supervene, such as a shrinkage of supply, so that the glacier can no longer reach the sea, it does not mean so much that it has not time to reach the sea before melting, as that the supply, coupled with the very slow motion, is gradually ceasing. It gradually disappears by thaw, as in the case of the Dry Valley Glacier, but very slowly and evenly, and there is still too little differential movement to collect the moraine together appreciably.

The absence of piled-up terminal moraines is therefore due, I think, almost entirely to the temperature conditions, which affect the differential movement and tend to prevent the accumulation of material anywhere on the glacier itself. A contributing cause is the slowness of the motion and the continuous and even retreat of any glacier whose supply is failing.

Whatever explanation be accepted, the undoubted fact of their absence is a point of considerable importance and leads us to the conclusion that, where the snow-line is truly at sea-level, glaciers will normally reach the sea, and there will, in any case, be no large terminal moraines.

While on the subject of moraines, it will be convenient to include some remarks on striated boulders and rock platforms, since it is by these that many moraines are recognised as such in temperate countries.

The scarcity, in fact almost complete absence, of striated boulders in the moraines of the Antarctic has been noted by several former geologists, and needs explanation, for it is apt to be taken as direct evidence of a small amount of ice erosion.

In the course of the examination of many miles of moraine, we found only a few specimens of striated boulders or small stones, certainly not more than fifty good cases, whereas on the terminal moraines of many temperate glaciers they may be picked up every few yards. This is a very striking contrast, but it appears to be capable of a perfectly normal explanation.

In the first place, there are very few true terminal moraines in the Antarctic, and consequently few boulders which have been in the ground moraine of a glacier. By far the greater majority of moraines are composed of rocks which have never been below the surface of the carrying glacier. The true ground moraine, which undoubtedly exists in the glaciers, is carried to its proper termination, the sea, in all cases except the comparatively few where the glacier now ends on land, and in these cases the motion and consequent ability to erode is deficient. We should, therefore, seek for striated boulders on the sea-floor rather than on the land, and such a search is rewarded. In the dredgings which have brought up a number of rocks in Ross Sea there is often a striated boulder, and the proportion is far higher than is ever found on land.

Another reason for the rarity of striated boulders on land is the rapid weathering of the rocks by sub-aerial agents, notably wind and frost. This has been pointed out

by Professor David for the Cape Royds area, where striations are never seen on the upper surface of rocks, but an occasional example may be found by examining the under surface where it has been protected from the air.

If there is a normal amount of sub-glacial erosion taking place in the South, and one product of it, striated erratics, is lost to view in the sea, we should be able to find the other product, striated platforms, in fair proportions, and this is so. On account of the rapid effect of the sub-aerial weathering, we do not find very clear striations on rocks that have been for a long period uncovered by the ice, though the general effects of erosion, the "roche moutonnée" form, remain distinct. These are very definite along the coast, where not hidden by lateral moraine, and on a large scale are best seen in the Dry Valley, where the massive bars of rock present a very rounded aspect and the curve of the valley-bed is characteristic.

Where the surface of the rock has but recently been uncovered by the ice-stream, however, striated platforms are found in great profusion. The best examples were found on the Mackay Glacier in Granite Harbour, and a short description of them may be of interest.

The map (Fig. 16) shows that this glacier meets many obstructions which it has either surmounted or passed round, and most of these show the recent gradual retirement of the ice, or rather the decrease in supply. Taking two cases at sea-level first, the points which have been named Cuff Cape and the Devil's Punchbowl, it will be observed that in each case the ice-flow has obviously only recently ceased to pass right over the rock. At Cuff Cape, in fact, it is still fringing the upper portion of the small cape like a white cuff on a dark hand, and the rocks bear witness to its recent retreat. The Cape is formed of coarse granite intersected by numerous small dark basic dykes, and the former, being more susceptible to frost weathering, shows the rounded forms only, except close under the present front of the ice where the striations are clear. The dyke rock, being very hard and fine-grained, has all over the Cape retained striae. There were also several striated erratics on the Cape, as one would expect, for the ground moraine of a glacier in full action is here intercepted and dropped.

The Punchbowl, at the south side of the Harbour, is a most interesting place for many reasons, and shows by its form alone how recently it was covered by the glacier. Striated platforms of rock were to be found all along the narrow ridge on the southern side as well as on the summit of the Thumb, which is now 250 feet above the glacier. As on Cuff Cape, the best striae are found on the fine-grained dyke rocks.

Some six or seven miles up the glacier from the sea there is a large numatak named Mount Sues by Professor David, and on the northern end of this outcrop the rock is comparatively low and has only been recently uncovered by the ice. The gradient of the ice-flow is very steep here, and all the conditions for erosion are present, so that we find ample evidence of its effect. All over the low promontory were striated pavements of the red and grey granite that is the chief rock, and piled over them were numerous

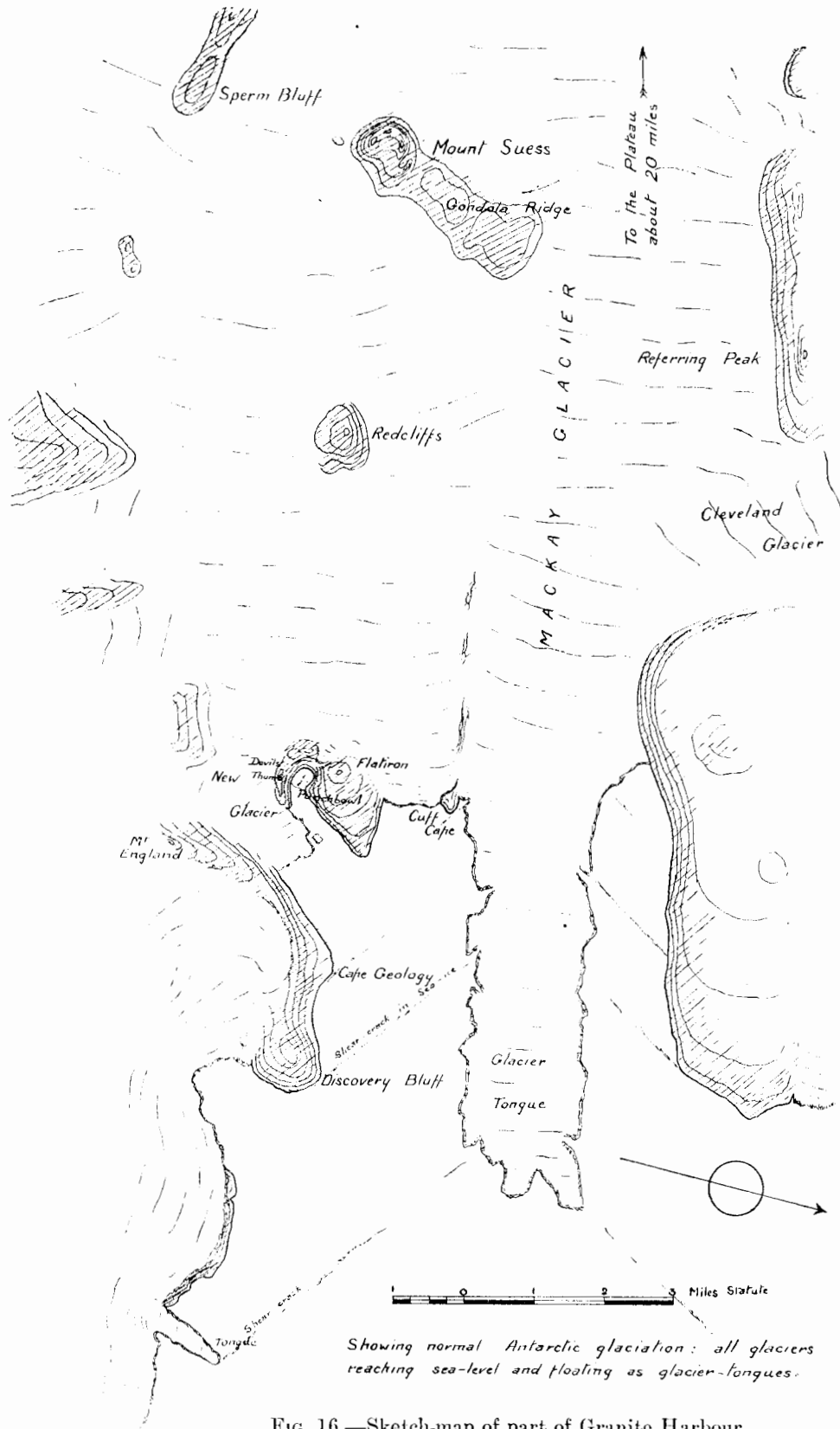


FIG. 16.—Sketch-map of part of Granite Harbour.

erratics, many of them perched in the most insecure and transitory positions (Fig. 17). A considerable proportion of them were themselves striated, and specimens of perfect parallel striae were to be found at every step in both the coarse and fine varieties of rock.

To sum up on the subject of striations, it should be clear now that the rarity of striated stones and boulders is natural under the circumstances, and that it cannot in any way be used as an argument against effective erosion. When looked for in the proper places they are as abundant as in any other glaciated region, but in the valleys south of the Ferrar Glacier, which contain stagnant ice only, they are reduced to a minimum, the products of erosion here having been distributed in the sea when the glaciers were active and reached their proper level.

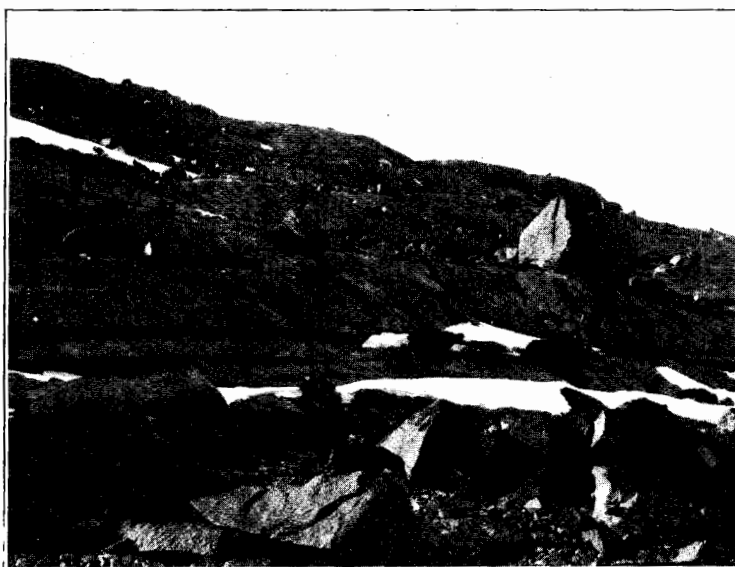


FIG. 17.—Stepped structure of the granite of Gondola Ridge, Granite Harbour, showing the effect of a recent covering of moving ice which has deposited the erratics.

#### BOULDER CLAY.

Just as the rarity of striated boulders in the South is at first sight a great surprise, so is the almost complete absence of boulder clay on land, for those two in other regions are the chief marks left of an ice age; but again a little consideration shows that this absence is only natural at the present stage of glaciation.

It is clear that the material which forms the till or boulder clay is that which is included in the ice chiefly towards the base. Whether it consists of "rock-flour" or of wind-borne particles does not concern us now. In many places the sheer walls of glaciers can be seen, and almost invariably the lower part of the ice is filled with fine material which is arranged in fine bands (Fig. 18). This material is so thick towards the base that it is often impossible to say where the ice ends and the floor of the valley begins. In these respects the Antarctic glaciers are precisely similar to those of North Greenland and Spitsbergen.

Together with the fine material is a certain proportion of coarse gravel and an occasional larger block. We must pay some attention to the finer material in order to understand the absence of real clays, and we find that very little of it can be considered as smaller than fine sand, and it may be called a silt rather than a mud. Naturally this material when deposited in mass will form a till without the clay. To understand this, we must refer to the nature of the rocks of South Victoria Land. As we have said before, there are no recent sedimentaries, and what there are consist for the most part of sandstones. In the sandstone there are a few thin bands of shale of insignificant



FIG. 18.—Terminal face of Barne Glacier, Ross Island, showing bands of silt.

proportions. The remainder of the rocks consist of a very hard dolerite, coarse granites, and a series of metamorphic rocks. There is, therefore, no rock in the vicinity that will form a clay except by excessive trituration, which is a slow process. It seems probable, therefore, that not only are the silts of these basal moraines free from much very fine material on account of the nature of the rocks over which they pass, but further, that most of the very tough boulder clays which have been formed on land in other regions are due to the presence of soft sedimentaries in the district which require very little breaking up to form a clay.

The case is a little different on Ross Island for this reason. Amongst the rocks that clothe the sides of the volcanic cones are a number of very fine and soft tuffs, and

accordingly we find that the material at the base of glaciers such as the Barne Glacier is very fine indeed, and would, when deposited, form a clay (Fig. 19).

In the few places where it is possible to see this basal moraine deposited in mass, as in Dry Valley and the tributary valleys of the Koettlitz Glacier, we do find a till, but it is not elastic on account of the coarseness of the material, and can only be recognised as such by comparison with the basal moraine still in the glaciers.

In other places, as we have seen when discussing striated boulders, the natural end of the basal moraine is on the sea-floor, and the dredgings again show that such is the



FIG. 19.—Tuff boulder in face of Barne Glacier. The bands are of very fine volcanic dust, capable of forming a true boulder clay. Note the grooving of the boulder due to differential movement.

case. The clay is rather more definite in this case, as might be expected from the action of the sea-water and from the addition of marine organisms. In most of the dredgings the clay is naturally soft and washes free from the larger pieces, but in one haul off the edge of the Barrier pieces of a hard clay came up interspersed with grit and small pebbles. The clay itself contained many fragments of sponge spicules. Throughout Ross Sea there must be a continual rain of particles of all sizes from the bases of floating bergs, which is forming a thick bed of marine boulder clay. The occasional larger organisms in the shallower parts should be giving it a very definite marine character, for the large sponges and some of the corals are very durable.

## SUMMARY.

The most general conclusion to be drawn from the preceding remarks is that the recent deposits due to polar conditions are comparatively small in amount, far smaller, for instance, than is the case in Greenland or Spitsbergen, and that the chief cause is the fact that the air thaw-point is very rarely reached. The thaw is, therefore, local, instead of universal as it is in the above-mentioned countries. In spite of that fact, however, thaw water does play an important part in the distribution of material and even to some extent in erosion. The deposits which have been transported by water are, however, difficult to recognise as such for two reasons. First, because the action of the wind is almost equally important and masks that due to water; and, secondly, because the deposits are very rarely bedded or composed of water-worn particles. One may legitimately infer from this that, where glacial deposits contain much fine material without bedding or rounded particles, they have been laid down under severe conditions of climate, which prevented the thaw water from exerting its maximum effect and increased the proportions of wind-borne material.

It is clear also from the above that a lake-deposit formed under these severe conditions is unlike that of a normal lake, and, except for occasional bedding and some remains of the lake flora, can hardly be recognised as such.

Occasional deposits of rough but even-grained material in a glacial series may further be recognised as due to wind alone, and several such were found in the South.

While it is impossible to state the correct proportion of deposits due to wind as opposed to water, there is no doubt that the former is of far greater relative value than under any other conditions except those of an arid, hot, desert region.

Coming to the deposits due to the action of ice alone, we find a new or, rather, an obscure process at work in the raising of marine muds. The conditions for the process are not confined to the Antarctic, and possibly it will be found to have been at work in the Arctic in many places. The quantity of material which might be transported in this way is small, but the kind of material is of great importance, for in it land and sea deposits are mixed up in a very irregular and puzzling manner.

The moraines of the Antarctic, while differing in a few characteristics from those typical of milder conditions, are formed in the same way, and the anomalies can be explained. The absence of high terminal moraines is a characteristic due to the climate, while the absence of true boulder clay is chiefly due to the lack of soft sedimentary rocks in the region. One may conclude that where the chief moraines are lateral there has been little differential movement in the glaciers.

The factor above all others which is responsible for the difference in these deposits from those of temperate regions is the height of the true snow-line, or air thaw-line, which is everywhere at or below sea-level.