5. *A* NEW MODE *of* TRANSPORTATION *by* ICE: *the* RAISED MARINE MUDS *of* SOUTH VICTORIA LAND (ANTARCTICA). By FRANK DEBENHAM, B.A., B.Sc., F.G.S. (Read June 4th, 1919.)

[PLATE IV.]

THE old and somewhat vexed subject of the methods of transportation of material by land- and sea-ice is again brought up in this paper, a subject on which there is so voluminous a literature that any attempt to add to it must have the support of the strongest reasons. It is, therefore, with some temerity that I attempt the description of a set of facts which appears to contain a key to some of the well-known problems of ice-action.

Of all the phenomena of glacial deposits, perhaps the most puzzling are the occurrences of shelly drifts of marine origin in a great variety of circumstances, both as to height and as to composition. The great discussions of the past as to whether they indicated submergence, or merely an upthrust-action of the ice, can only be said to have been suspended and not concluded.

The subject of this paper is a series of deposits on the Antarctic shores which point to an explanation of the origin of many of these shelly drifts and the peculiar circumstances in which they occur. In South Victoria Land we had the good fortune to see these shelly deposits at an early stage of their evolution, a stage now only possible in polar lands with a severe climate.

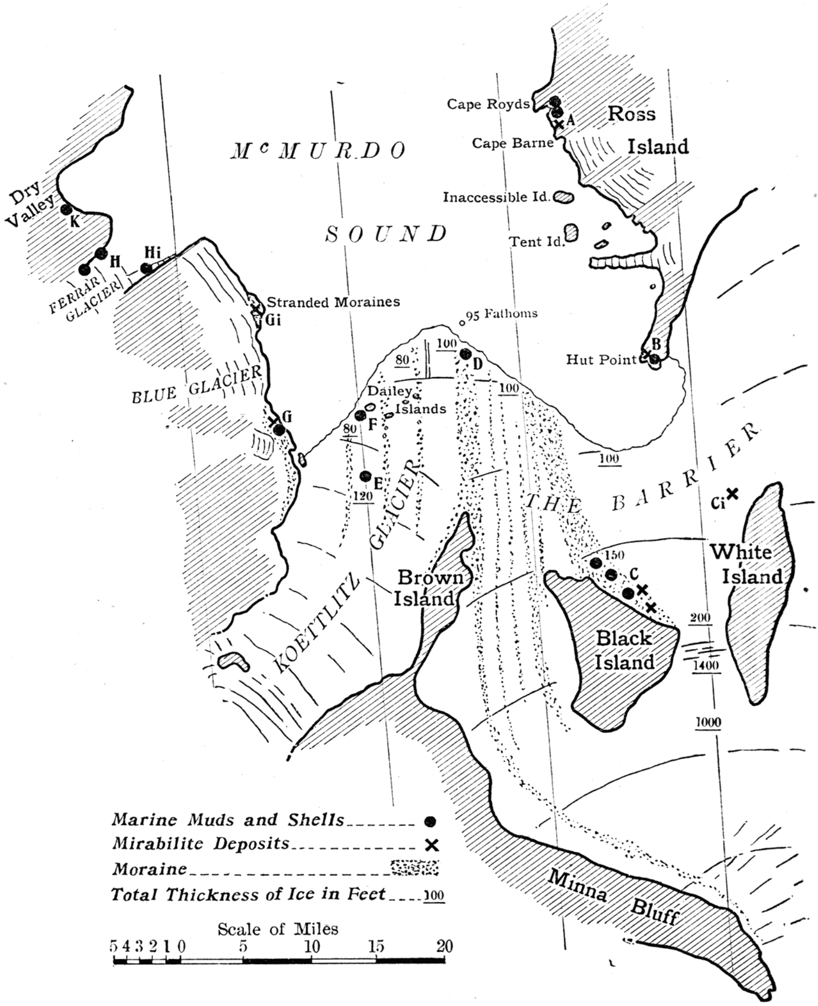
The occurrence of raised marine muds, resting upon ice, was reported by the first Expedition that wintered in the Ross Sea, the British National Antarctic Expedition of 1901–1904. They were described by Mr. H. T. Ferrar, the geologist of that expedition, who mentions several deposits of the kind, but does not hazard any explanation. In association with the muds he found deposits of pure sodium sulphate (mirabilite) also resting on ice, which seemed equally inexplicable.

The British Antarctic Expedition of 1907–1909 made important new discoveries of a similar character, and in its geological report a very clear account of them is given together with alternative theories for their mode of origin.

When we of Captain Scott's Last Expedition in our turn made new discoveries of sea-muds and salts on ice the subject assumed a greater importance by virtue of this proof of its widespread occurrence, and it devolved upon me to search for a satisfactory explanation. It must be admitted that such was not found until the end of our stay, too late to verify some of the assumptions that had to be made.

Since any hypothesis on the nature of these deposits will rest largely upon the details of their occurrence in the field, a full description of the various cases is desirable. The map of McMurdo Sound (below) should be consulted for the exact location of each deposit, remembering that in most cases they rest on slowly-moving ice and are not fixed points. The capital letters in

Fig. 1.—*Map of McMurdo Sound, showing the localities of the raised deposits, moraines, etc.*



parentheses throughout the present paper refer to the positions of the deposits as plotted on this map and on the bird's-eye view of part of the area (fig. 2, p. 54).

The first discoveries are described by Mr. Ferrar in the following words:—

'Among the moraines on the west side of McMurdo Sound (Gi), as well as on one of the Dellbridge Islands (Ai), and among the moraines on the west side of Discovery Gulf (G), great deposits of sodium sulphate in well-formed crystals have been found. Among the isolated moraines in the bay between Black and White Islands (C & Ci) large bosses or mounds of the same white salt have been seen; and at one spot near White Island a mass of perfect crystals was found on the surface of pure ice. In the White-Black Island bay *Balanus* shells and sponge-spicules occurred upon the ice in association with this salt. The occurrence of this salt, mingled with shells and ice-scratched stones, is a freak of Nature which is difficult to explain.'[1]

In a further reference to the matter he describes the mounds above mentioned as five or six in number, 2 feet high and up to 5 feet across. He also mentions a bed of the salt in the moraines on the west side of the Sound as being about 18 inches thick, and traceable horizontally for about 30 feet.[2]

He records the discovery of a *Pecten* shell,

'in gravel 10 miles up the Ferrar Glacier and 20 feet above the sea. The gravel had formed a glacier-table and the ice around was all glacier-ice, but is not above the reach of some exceptional tidal wave' (H).'[3]

On the next expedition to the Ross Sea the geologists, Prof. T. W. Edgeworth David and Mr. R. E. Priestley, found raised marine material in five distinct localities, one of which is outside the region of McMurdo Sound, and is especially important on that account. The latter was discovered by Prof. David on the floating ice north of the Drygalski Glacier-tongue in lat. 75° S. An accurate description of the occurrence is published, together with diagrams which prove it to be quite clearly the exact counterpart of those described from McMurdo Sound.

In brief, it consisted of a bluish-grey clay covering a conical mound of ice to a depth of a few inches, itself covered in parts with large erratic boulders. With the clay and attached to some of the boulders were the marine organisms. They comprised serpulæ, large foraminifera, polyzoa, echinoid spines, and sponge-spicules. To one of the big granite erratics was attached a very large compound sponge, in a state of perfect preservation. The underlying ice was stated to be 'slightly saline superficially, but not as salt as typical sea-ice.'[4]

The organisms were identified by Mr. Hedley & Mr. Chapman as belonging normally to depths up to 100 fathoms, and in general were found to be similar to the collections made by trawling at that depth at the present day. The significance of the exact

[1] 'The Voyage of the *Discovery*' 1901–04, vol. ii, app. i.

[2] National Antarctic Expedition, 1901–04, Natural History, vol. i (Geology) 1907, p. 91.

[3] *Ibid.* p. 79.

[4] British Antarctic Expedition, 1907–9, vol. i (Geology) chapt. xvii.

position of this discovery will be emphasized later when I deal with other instances from this region.

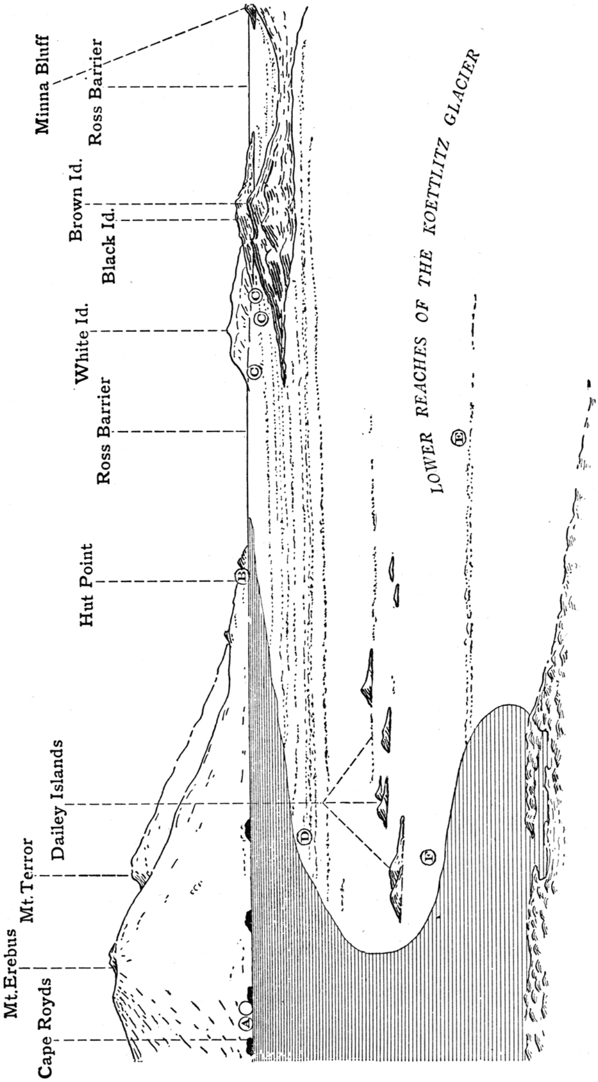
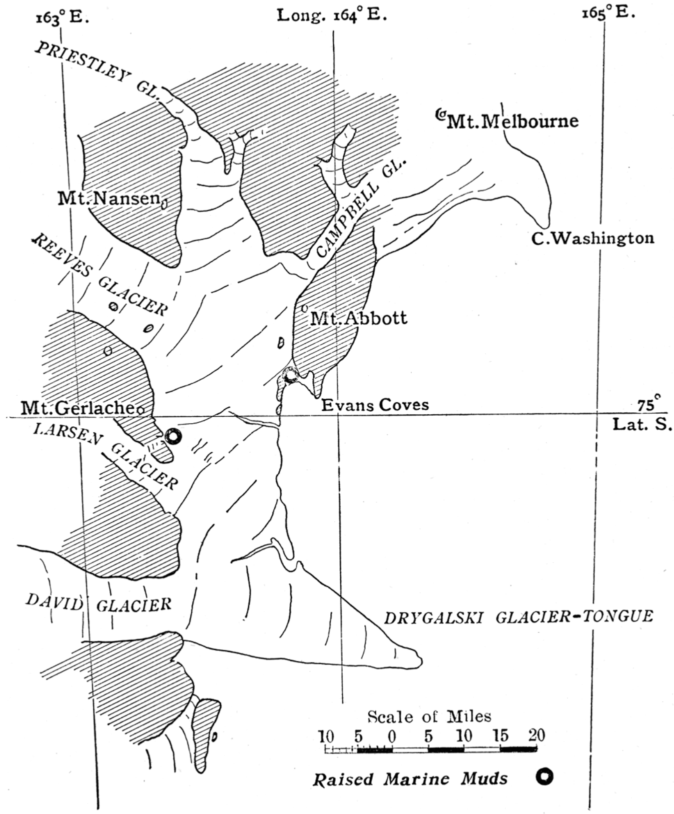


Fig. 2.—*Bird's-eye view of the McMurdo ice-sheet from the foothills of the mainland near G on the map (fig. 1, p. 52).*

An occurrence presenting some variations from the others was discovered by Mr. Priestley at the mouth of Dry Valley (K). It was found some hundreds of yards from the present shore at about 50 feet above sea-level, and consisted of 'a layer of dark gritty sand containing numerous entire valves of *Pecten colbecki* . . . . . associated in abundance with these was an *Anatina* . . . . . Both the pecten and the *Anatina* have extremely fragile shells, yet hundreds of valves, of the pecten especially, were practically intact, ... they have a very recent aspect.'[1]

Fig. 3.—*Sketch-map showing the positions of the raised marine muds on the Nansen Sheet.*



[The occurrence near Evans Coves was discovered by Mr. R. E. Priestley, the other by Prof. T. W. E. David.]

It should be noted that this deposit was not resting on ice, differing in that respect from all the other cases.

The three deposits discovered by David & Priestley on Ross Island were visited by me, and will be described later; they proved to be the most important link in the chain of evidence.

[1] Brit. Antarctic Exped. 1907–09, vol. i (Geology) chapt. xvii.

Our own experience of the raised deposits was equally extensive and puzzling. It began with the finding of a new deposit on the very first day that we landed on the west side of the Sound, at the mouth of the Ferrar Glacier (Hi). The south side of this glacier continues beyond the snout proper in a long tongue, which is afloat and carries a good deal of moraine arranged in rough mounds. On some of these mounds were a great many *Pecten* shells with fine silt. No search for other varieties was made, as at that time it was not realized that they were on what may be considered glacier-ice, although it was some 8 feet above the sea-ice proper.

On the next day we visited the north side of the glacier, close to its seaward end (H). At this point the side of the glacier abuts on the steep scree-covered slopes of the hills as a line of high pinnacles of ice covered with a substance which we at first took to be rock-dust blown from the neighbouring heights. Closer investigation showed that it was true mud, and contained numerous fragments of marine organisms. It was resting both on the high pinnacles seen in the photograph (Pl. IV, fig. 1) and on the low mound of moraine in the foreground. The fragments included felted masses of sponge-spicules, valves of *Pecten*, and tubes of *Serpulæ*, and were in great profusion. The tops of the pinnacles were at least 20 feet above the level of the sea. At first, we concluded that the strange position of the muds was due to the pushing-up of the sea-bottom, but began to have doubts about it when we found that many of the shells were of extreme fragility, and, though perfectly fresh, broke readily in the hand. Had we realized then that they represented the fauna of at least 50 or 60 fathoms depth, the 'pushing-up theory' would have received still less support. There is no tide-crack between the end of this glacier and the sea-ice, and the former is probably afloat for as much as 5 miles back from this point, a fact of considerable importance. This deposit must, I think, be correlated with Mr. Ferrar's discovery of a *Pecten* shell '10 miles up the Ferrar Glacier,' for he mentions it as about 20 feet above the level of the sea, and is obviously reckoning his distance from the end of the tongue mentioned above.

The next instance was during our attempts to find a feasible sledge-route up the centre of the Koettlitz Glacier some weeks later, when we came upon abundant evidence of uplifted marine organisms, though not in any definite deposit. The Lower Koettlitz Glacier, like the Lower Ferrar, is afloat at its seaward end, in this case certainly for 7 or 8 miles. Over an area of 3 or 4 square miles in the neighbourhood of the point marked (E) on the map we found an abundance of sponge-spicules on the ice, sometimes in felted masses, but more often scattered singly. These were probably windblown in the majority of cases, coming from deposits of the size that we found later, and the prevalent wind being from the south-east, they must have come from that direction.

Actually at the point (E) another discovery was made which seems to throw some light on the subject. This was the body of a large fish lying on a patch of silt just beneath the surface of the ice. By careful chopping it was recovered fairly intact, and proved to be about 20 inches long, but without a head. Beneath the skin, which was hardly broken, the body consisted of a mixture of ice and some greasy material, but the bones were quite well preserved. It had certainly never been exposed to the atmosphere for any length of time, or the greasy material would have disappeared. A curious fact about this fish is that in all outward characteristics it was similar to the one captured by the members of the *Discovery* Expedition, also in a headless condition. It further appears to be correlated with their discovery of several skeletons of the same kind of fish in the ice near the point D (fig. 1, p. 52).

The position of this fish embedded in the ice, some 4 miles from the end of the glacier and perhaps 15 feet above sea-level, presents a problem very similar to that of the muds.

It was much too big to be carried by any bird, and would be a very clumsy object to be transported to that distance by a seal, even if seals were known to be in the habit of carrying objects in their mouths. By a stretch of the imagination, it is just possible to suppose that the fish may have worked up some summer-thaw stream to a distance of 4 miles, there to have met its end in the jaws of a wandering seal, who, having eaten the head, left the body to be frozen in. The only alternative, that it came up through the ice from below, seems to me more possible.

On returning from a journey up the Koettlitz Glacier we crossed the Sound to Hut Point on the old ice all the way, the sea-ice having then broken up. At the point (F) about a mile from the westernmost Dailey Island, and a similar distance from the true edge of the land-ice, we came upon the most remarkable instance of uplifted sea-bottom that we had yet seen. The surface here was perfectly level, and probably 8 to 10 feet above sea-level; at this time it was covered with a few inches of recent snow, and our attention was therefore easily caught by two or three small grey mounds on the uniform white expanse. These turned out to be masses of very large sponges, measuring up to a foot in diameter in some cases, and entangled in the masses were the same shells and marine remains as we have already noted in other instances. Again, the most marked feature was the excessive fragility of the bulk of the material. One specimen of a solitary coral was retrieved from a mesh of spicules, and had a peduncle no thicker than a pin, so that it did not long survive the vicissitudes of sledging over the rough ice. The sponges were all in the position of growth, so far as we could see, and there was a small amount of mud and silt with and under them. The mounds were quite close together, as may be seen from the photograph (Pl. IV, fig. 2), but the thick snow effectually prevented us from seeing whether they were continuous or not. This occurrence was most certainly in a position to which no pushing action of the ice could possibly have raised it, and was far too delicate to have withstood any but the gentlest method of transportation.

A few miles farther on, at the head of the rounded cape of floating ice in the middle of the Sound (D), we found that the sponge-spicules were so thickly strewn in the ice that it was impossible to get ice for cooking-purposes that was free of them. There were also fragments of other shelly organisms scattered in the silt of the thaw-water channels. These were for the greater part transported by wind or water, and were much more broken than in the other cases, but they bear testimony to the enormous amount of the material that must be scattered over and in the ice between this point and the volcanic islands south of it.

At Hut Point we found matted tangles of sponge-spicules, as described by Prof. Edgeworth David & Mr. Priestley. The locality is marked (B), but there was no definite deposit, and the specimens were picked up at various points on the low-lying ground. It does not seem likely that these were blown from the direction of White Island, so there is probably a deposit somewhere on the slopes of Observation Hill, similar to those at Cape Royds.

Unfortunately, I was not able to visit the region where there seems to be the greatest extent of the raised deposits, in the bay between Black and White Islands, so nothing can be added to Mr. Ferrar's description of them. I was, however, able to see the occurrences at Cape Royds, in company with Mr. R. E. Priestley, who found them in 1908.

As described in the memoir by David & Priestley, the two deposits of marine muds lie at a height of about 160 feet above the present level of the sea, and consist of a mixture of mud, small fragments of lava, and the usual assortment of *Serpulæ*, polyzoa, etc.

Although the greater part of the shelly material was in small fragments, some of it was very delicate and broke readily in the hand when freed from its matrix. We made a thorough investigation of the deposit at Backdoor Bay, and found that it was resting on ice which was proved to be more than a foot thick, and was perfectly clear and free from bubbles, like old glacier-ice. It may equally well have been sea-ice, from which the salts and the original structure had long since disappeared. Although at so great a height above the sea, these two occurrences fall exactly into line with the others, in that they also are resting on ice.

Besides the new deposits found in McMurdo Sound, an important corroboration of Prof. David's discovery in lat. 75° S. was made by his former colleague, Mr. R. E. Priestley. During their enforced stay at Evans Coves during 1912 our Northern Party made several discoveries of raised marine muds, of which Mr. Priestley has kindly given me the following particulars:—

They were all close to the sea on the surface of the floating ice-sheet which connects Inexpressible Island to the spur of land running south from Mount Abbott. They were about 20 feet above sea-level, and occurred in patches and low mounds, sometimes mixed with big boulders and sometimes by themselves. With the marine mud were the same organisms as those found elsewhere: shells, sponge-spicules, and polyzoa, generally well preserved, and often in the position of growth that they would have occupied on the sea-floor.

I myself paid a short visit to the locality at a later date, and was able to verify the fact that the ice on which they were resting was similar in character to that of the McMurdo ice-sheet, that is to say, much dissected by thaw-streams. See map (fig. 3, p. 55).

The Mirabilite-Deposits.

The deposits of sodium sulphate have a peculiar association with those of the raised marine muds and a very similar distribution, as will be seen by the map (fig. 1, p. 52). It therefore appeared to me at an early date that any explanation for one should include the other. A brief description of them is necessary on that account.

The occurrences of the salt found by Mr. Ferrar, as quoted above, were not visited by me; but, from conversation with Dr. E. A. Wilson and others who had seen them, I gained a very clear idea of their nature. Those near White Island were found on mounds of practically clear ice, generally cracked at the top like a pie-crust. It must be pointed out that there is no genetic connexion between the form of the mound and the presence of the salt, except in so far as the association of the salt tends to lower the melting-point of ice and would therefore conduce to thaw. These pie-crust mounds were very common on the Koettlitz Glacier, and are due to the gradual freezing of a small thaw-pool; the expansion of the lower layers as they turn into ice raises the surface-layer into a dome which finally cracks at the top. The deeper the original pool was the higher will be the dome, until it may even assume the form of a crater.

The salt was not bedded in any way in these deposits. Specimens from this locality were analysed by Dr. G. T. Prior, and were found to be practically pure mirabilite, with 55·86 per cent. of water of crystallization.

The deposit of the same salt near Cape Barne (A), which is described by Prof. David & Mr. Priestley, was visited by me at the same time as the marine muds. It occurs near one of the lakes at about 80 feet above sea-level, in a mound some 5 yards long by 2 in width. It is important to note that it is only about 100 yards from one of the shell-deposits, though lower down the hill. The effloresced salt on the surface is so like snow that, except in the summer, it is almost impossible to tell it from the numerous other mounds in the neighbourhood, and we had some difficulty in finding it.

Digging into the mound we came upon the clear hydrated salt immediately below the surface of the dry powdered variety. It was perfectly pure and clear, in blocks up to a foot thick, and, except for the cleavage-planes, might easily be mistaken for ice. In fact, so close was the resemblance that, after digging down some 4 feet and happening to taste a fragment from that zone, we found that we had passed into true ice without noticing the junction. Careful examination and tasting showed that the salt was only about 2 feet thick at that point, and was resting on perfectly-clear solid ice. It was not bedded, and there was practically no silt with it, although the top of the cone had a slight covering of gravel. It should be remarked that several of the adjacent mounds were also resting upon ice, which could be none other than the original ice of the mass that carried the erratics, the mirabilite, and the marine muds.

The deposit of salt was, therefore, exactly comparable to those found on the moving ice in the bay between Black and White Islands.

The stratified bed of the salt mentioned by Mr. Ferrar in the moraines on the west side of the Sound (Gi) was not found by us; but a very similar one some miles to the south of that point was carefully examined (G). It was in the ice-borne moraine-belt along the coast between Blue Glacier and the Lower Koettlitz Glacier, and was seen from a distance of several hundred yards as a continuous white band in the black moraine. It was cropping out on the side of a small valley which had been thawed out of the underlying ice by a small stream, and appeared as an almost horizontal bed about 2 feet thick, with a definite junction between the bed and the dirt-strewn ice. The moraine itself was of rather fine material, with a proportion of fine mud; the latter, frozen into the matrix of ice, resisted all our attempts at digging a section with a geological hammer. From measurements of the outcrop the deposit appeared to be at least 40 feet long by 20 feet in width. The salt itself was quite free from coarse silt, but contained a small proportion of very fine mud scattered through it, which gave it a dirty appearance. None of it was in clear crystalline blocks as at Cape Royds. On analysis it proves to be almost entirely sodium sulphate, with traces of potassium and of chloride, but the crystal-grains are smaller and more desiccated than in the other cases.

Summary of Occurrences.

The raised deposits are, therefore, found in two distinct regions in precisely similar circumstances, and it will be worth while to note what other characteristics are common to these regions. It will be convenient to speak of the ice-sheet in 75° lat. S. as the Nansen Sheet, as it is immediately under Mount Nansen, the dominant mass of the neighbourhood.

A glance at the map of South Victoria Land will show that, in sailing southwards along the coast, a ship will pass three deep bays, each of which is filled with thick ice, usually called 'land-ice.' The first of these is Lady Newnes Bay, about which little is known except that the ice that fills it is much more massive than in the other two cases, being up to 150 feet thick at the edge, or, roughly, 1000 feet in total thickness.

About 50 miles farther south another wide bay opens, originally called Terra Nova Bay. Its southern edge is formed by the long floating mass of the Drygalski Glacier-tongue between which and the northern edge is a low sheet of ice formed by the confluence of several glaciers and held in by sundry islands and shallows. This is the Nansen Sheet, and it is probably not more than 200 feet thick, except where the glaciers directly flow into it.

Still sailing southwards along the coast, we meet only with glacier-tongues until the southern end of McMurdo Sound is reached, where a similar sheet formed by the confluence of glaciers blocks the way round Ross Island.

These sheets are all more or less completely afloat, and the two last-mentioned are covered to a great extent with morainic débris. The most important point of similarity is their slow rate of movement—proved in the case of the two where the deposits have been found, and inferred from our small knowledge of the northern one. To regard them as remnants of the Great Ross Barrier is hardly accurate, for (although they are stagnant) they are not wasting very rapidly, and have very definite sources of growth.

The raised deposits all present the following features in common:—

(*a*) In each case they are found resting on ice, with the solitary exception of the one at the mouth of Dry Valley.

(*b*) In each case the organisms appear to have been preserved from shock or movement, and from prolonged atmospheric weathering.

(*c*) The organisms in many cases are preserved in the position of growth, and have been raised without tilting or disruption.

(*d*) They occur at all distances from the edge of the land-ice up to 15 miles.

(*e*) Their height above sea-level varies between 5 and 35 feet, except those at Cape Royds, which approach 200 feet in altitude.

Theories as to the Mode of Origin of the Deposits.

The only serious attempt at an explanation of these phenomena hitherto made is that given by Prof. David & Mr. Priestley in the Geological Memoir of the 1907 Expedition. In that closely-reasoned account they make the best possible use of the evidence then at hand, and finally discard the theory that the deposits are in any sense 'raised beaches,' always excepting the occurrence at Dry Valley, which has features at variance with the others.

The above-named writers then offer alternative theories, with neither of which are they completely satisfied. Comparing the deposit on the Nansen Sheet, below Mount Larsen, with those in Spitsbergen described by Mr. G. W. Lamplugh, they suggest that the sea-floor may have been ploughed up by the ice of the glacier during an accession after a temporary retreat. Undoubtedly the Seftström Glacier in Spitsbergen has done so, though that action does not seem to explain all the shelly moraines of Cora Island. But, in the case of the Mount-Larsen deposit, many miles from the front of the ice, a ploughing action cannot very well be conceived. The difficulty is still further increased by the fact that the mound of marine mud does not lie in a direct line with either the David or the Larsen glaciers, but somewhat to the side, as in an ice-eddy or 'backwater.'

An ingenious alternative is suggested by Prof. David & Mr. Priestley, which has chiefly in view the explanation of the organisms being in a position of growth. The portion of the ice-sheet covered with moraine is supposed to have become overloaded with englacial boulders, until its mean density exceeded that of water. It would then sink, and for a time could form a temporary sea-floor for the lodgment of the muds on its surface. The chief objection to such an hypothesis is that, in order to increase the density of ice to that extent, the proportion of included rock would have to be about 1 : 3 throughout the mass, a proportion which is never found in the land-ice of Antarctica.

As the above-mentioned writers point out, to call in any extensive recent elevations or depressions of the land as an explanation is not warranted by other evidence. There are some true raised pebble-beaches and terrace-lines along this coast, and there is no doubt that there have been recent upward movements; but they are limited to some 80 feet or so, and in any case would not explain the occurrence of the muds on floating ice.

In their account, Prof. David & Mr. Priestley do not include the mirabilite as among the uplifted deposits, but consider it as a concentration from a saline lake.

A complete explanation of these phenomena is, therefore, still wanting, and in view of the number of these occurrences now known it is desirable that the problem should be solved. Any agent which can reverse the usual order of things and transport material upwards as well as horizontally is well worth studying, and therefore no apology seems necessary for this detailed treatment. In my view the agency at work is no new one, but rather an old one which has been somewhat neglected by modern geologists. The proof of this will lead into an apparent digression at this point, for it is necessary to describe rather fully the ice-conditions of McMurdo Sound, the type area.

As will be seen in the bird's-eye view of the Sound (fig. 2, p. 54), the whole of its southern end is filled with a sheet of ice which may be regarded as the confluence of two streams: the Koettlitz Glacier coming from the south-west, and the Barrier ice from the south-east. Their union north of Brown Island is marked by a vague shear-crack, showing that there is a slight difference in their rates of movement, and their directions of movement are very clearly indicated by the long lines of moraine streaming northwards to end at the sea in a point usually known as the Pinnacle Ice. The thickness of this sheet varies considerably, and the exact figures are difficult to ascertain except at the edges. Those plotted on the map can only be regarded as approximations, being calculated from various pieces of evidence on the basis of a ratio of 6 : 1, ice below water to ice above. The only evidence for the thickness at a distance from the edge is a series of heights taken by aneroid, by the *Discovery* parties on their journeys in between the islands. These show very clearly that the thickness of the Barrier proper greatly exceeds that of the McMurdo Sheet.

The rate of movement of this sheet has never been measured, but there is no doubt that it is very slow. The Barrier itself, measured some miles south-east of Minna Bluff, is moving at a fast rate, roughly 1 mile in 3 years. Its direction there is north-north-eastward, and its component towards the Sound would be very much less in any case, even if it were not greatly obstructed by the volcanic islands. The eastern half of the sheet must be regarded as an overflow of the Barrier with a direction of movement almost at right angles to that of the parent mass. The western half is also very slow-moving: for, where it abuts against the Dailey Islands, there are practically no pressure-ridges and only very small cracks radiating from the sides.

The whole sheet is, therefore, comparatively thin and stagnant. It is certainly afloat for the greater part, for all the islands are surrounded by tide-cracks, caused by the rise and fall of the ice-mass with the tides. But there may well be portions of it aground, or very nearly aground, without causing any very marked swelling of the surface, and in the neighbourhood of the islands themselves it is naturally aground. At the edges of the ice-sheet it has from 300 to 500 feet of water underneath it.

The sources of supply of ice to this sheet are twofold, as mentioned above, and even the map shows that the supply is not generous. The Koettlitz Glacier is only some 4 miles wide at its point of outflow from the plateau; but it opens out to an average of 15 miles by the time that it reaches the sea opposite Brown Island. If we assume for the moment that the average thickness of the sheet at this point is 300 feet, and that the rate of movement is uniform, then the thickness of the glacier at its outflow must be over 1200 feet, a very high figure. As regards the eastern half of the sheet, the width of the passages through the islands is about 10 miles, and the width of the sheet north of them is at least 20 miles.

The rate of wastage of the sheet is of great importance, and we must look to its surface for evidence on that point.

It is entirely different from that of the Ross Barrier, now so familiar from photographs and descriptions as an enormous plain of an almost level snow-surface, folded and crevassed near the land, but elsewhere unbroken and spotless. Measurements have shown that in the neighbourhood of Minna Bluff it increases by an annual deposit of about 1 foot of compressed snow. A section down to a depth of 10 feet reveals no approach to ice, but only still more tightly-compressed snow. Observations of 'snow-bergs' derived from the Barrier demonstrate that the passage of snow into clear ice is very gradual indeed.

In all these features the McMurdo Sheet presents a complete contrast. West of a line drawn from the eastern corner of Black Island to the north-west the surface is almost completely covered with débris. The actual moraines appear as lines of mounds and ridges of ice thickly covered with gravel; but in between these lines the ice is full of silt and mud, some of it undoubtedly wind-blown and some of it probably sea-bottom. The effect of this débris is to increase the thaw in the summer to an enormous extent, so that the whole of the sheet is seamed and dissected with thaw-streams and pools. The general appearance of the surface is one of picturesque grandeur, most gratifying to the artist but heart-breaking to the sledger. The physical result of this heavy thaw is of the greatest importance, for it reverses the order of things as found on the Barrier, where there is an annual increase by snowfall, and produces a net decrease or wastage from the surface. It would be useful to present figures to support this significant fact, but the difficulties of measuring thaw (except in very general terms) are obvious, and the only alternative is to quote instances to show its magnitude.

The sledge parties of the *Discovery* Expedition, in travelling between Black and Brown Islands, described the surface in the following terms:—

> 'Seen from a distance it appeared like a tumultuous sea with high crested waves curling towards us. . . . . Long distances had to be done by porterage, and in the thaw season we had sometimes to take off shoes and stockings to cross rapid streams of water 2 and 3 feet deep.'

It must be mentioned, too, that they were never there at the height of the summer, late in January.

Our own experience was no less striking, although we did not see it during the thaw season: On the Lower Koettlitz Glacier we sledged over many miles of ice which consisted entirely of frozen thaw-streams with islands of higher ice in between. Many of these had been 15 feet wide and 2 or 3 feet deep when running. On the north side of the glacier a strong stream was still running under a thin covering of ice, even in the beginning of March, and we traced its course to the sea for a distance of over 20 miles. At the mouth we estimated its rate at 3 knots, and its average cross-section at 8 square feet. In the real thaw season this stream must be worthy of the name of river, and in many places its original bed exceeded 30 feet in width.

A very approximate measure of the rate of wastage may perhaps be gathered from our experience at the northern edge of the same glacier. While marching over apparently level ice there we continually fell through the thin coverings of former streams, the water of which had run away since the superficial freezing, leaving a space of some depth between the original surface and the floor of the stream. The average depth of these 'sledge-traps' over a large area was about 20 inches, and it seems legitimate to regard that as a rough measure of the wastage of a single summer. The proportional area of these 'ghost streams' to the solid ice was about 20 per cent., which would give a total annual wastage of 5 or 6 inches over the whole of this area. Moreover, at this part of the glacier there is very little silt on the surface of the ice, and the wastage in the true pinnacle-ice must be very much greater.

The main fact, that the sheet is decreasing from above, does not need figures to support it, for it is proved in other ways. The most obvious proof of this is the accumulation of moraine on its surface. Whereas on the Barrier any moraine which is carried down from the land is soon hidden by the annual increase of snow, on the McMurdo Sheet, moraine which appears on the surface at Black Island is still on the surface at the sea-edge hundreds of years later.

In an ordinary valley-glacier, especially in the Antarctic, there is a zone of surface-increase in its upper reaches, where the erratics are buried as soon as they fall on the ice, and a zone of surface-wastage lower down where the erratics appear on the surface again. The same zones can be recognized on the McMurdo Sheet, the zone of deposition (or surface-increase), with no visible moraine, being near Minna Bluff, a zone of equilibrium somewhere south of Black Island, and the zone of wastage with its exposed moraine lying north of that island.

The change from a superficial increase to a decrease within so few miles is rather remarkable, but is amply accounted for by the combined effects of slow movement and silt covering. Further, in consequence of the annual thaw, the surface of the sheet is formed almost entirely of hard ice, instead of the snow which covers and protects the Barrier surface from too great ablation.

The net decrease of the McMurdo Sheet from the top is, therefore, quite established, but it would be useful to reduce it to figures. To do so involves many assumptions which are open to doubt, on account of the absence of definite measurements, but an attempt will be made later to obtain some approximate measure by calculation.

In the meantime we must now consider the remarkable fact that the thickness of the sheet is approximately uniform north of the volcanic islands. It will be noticed, for instance, that the thickness north of Black Island is 150 feet (from aneroid readings), while 15 miles farther north it is still 100 feet. Now, if we assume that the total loss of surface-ice from thaw is 6 inches per annum we should be well within the actual figure. Then, assuming further that the precipitation is the same as on the Barrier, though it is probably less, there would be an annual increase of 12 inches of compressed snow to set against the thaw. If this be taken as the equivalent of 3 inches of dense ice the net decrease from the surface would be about 3 inches, or 1 foot in 4 years. The rate of movement of the mass is another rather uncertain factor on which to base calculation; but, if we assume that it is 50 feet per year, one-thirtieth that of the open Barrier, we should not be far wrong. At that rate the ice at the northern end of Black Island will take some 1500 years to reach the sea, during which time it should lose about 200 feet in thickness.

This being more than its total thickness, we can only infer that either our figures are very wrong indeed, or that there is addition to the sheet in the only other possible way, by freezing from below.

When we come to examine the possibility of this taking place through so great a thickness we are again met by a lamentable lack of data. The question may be put in this form:—supposing that the ordinary sea-ice were to remain attached to the land for many seasons instead of breaking up and floating away, how thick would it ultimately become? The answer seems to depend entirely on the situation of the ice with regard to sea-currents, as is shown by the few data that are at our disposal.

Off the end of capes, such as at Hut Point, Cape Armitage, and Cape Evans, where the water is shallow and the strength of the current considerable, the ice which had grown to a thickness of 6 or 7 feet during the winter was thawed through again by the sea-water by the end of the summer. On the other hand, in a protected bay like that south of Hut Point the sea-ice does continue to increase during the second year, if it stays in. In 1902 the ice formed in this bay reached a thickness of 10 feet, and stayed in for the summer. By the end of the next summer it had increased to 15 feet, and there is every reason to suppose that if it had still continued to stay in it would ultimately have frozen to the bottom, although this spot is only half a mile from the shallow patch off the cape where the ice is thawed through each summer from below.

The existence of floes of old bay-ice up to 30 feet thick, sometimes met with in the pack in Ross Sea, shows that conduction of heat is considerable through that thickness of ice, even when deeply covered with snow. The governing factors of freezing at these depths would appear to be the conductivity of the sheet itself and the amount of movement in the water underneath it. Comparing the McMurdo Sheet with the Barrier we get these peculiar contrasts: the conduction of the Barrier would be the minimum, on account of its great thickness and the large amount of air included in it; that of the McMurdo Sheet would be the maximum, on account of its comparative thinness, and because it is formed for the greater part of clear ice.

All that we really know of the movements of the water under the Barrier is that there is a constant drift from east to west along its face. In McMurdo Sound, on the other hand, although there is a strong current coming round Cape Armitage and running up the western side of Ross Island, it seems to be very local, and there is nothing to show the existence of a current coming from under the ice-sheet in the middle of the Sound. Icebergs and pack-ice coming down the Sound under the influence of a northerly wind invariably drift back very slowly on the western side and very rapidly on the eastern.

It seems therefore that the conditions for the increase of the sheet from below are favourable enough to warrant our assumption that this is the explanation of the existence of the sheet long after it should have disappeared under the effects of surface thaw.

The case of the Lower Ferrar Glacier is precisely similar. It is afloat, and its movement is very slow; it is subject to excessive thaw, and it is in so deep an inlet that there can be very little movement of the water on which it is resting. The conditions for decrease from above and increase by freezing from below are even more favourable here.

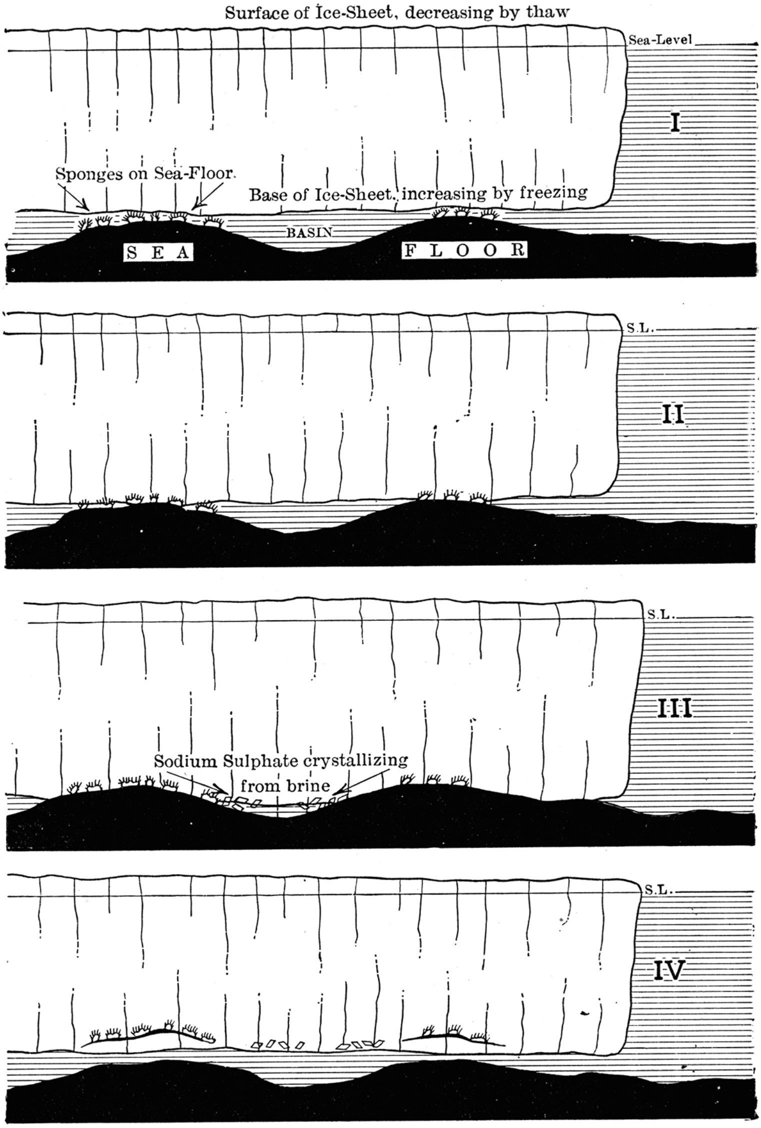
About the Nansen ice-sheet much less is known, but there again the general conditions are favourable. It is sheltered from the coastal currents, and is not very thick. At the points where the raised muds have been found the movement is certainly slow, and the thaw is great.

Probably the freezing on the lower surface of these sheets is not general: for instance, it would not take place close to the sea-edge where the movement of water would be appreciable, or, if it did so during the winter, it would disappear during the next summer. But far under the sheet, where the water is comparatively still, there is probably an annual increase from below which will be inversely proportional to the thickness of the ice and directly proportional to the stagnation of the water.

The origin of the raised marine muds now becomes fairly obvious, and may be described in this way, for the McMurdo Sheet. The overflow from the Barrier moving slowly northwards through the volcanic islands is subject to the two processes, decrease by thaw from above and addition by freezing from below. The rates of both these processes would vary, particularly the thaw, for it is now well known that the weather varies greatly from year to year, and there is possibly a cyclic variation as well. The movements of the ice in a vertical direction would then be of the following nature. A season, or a run of seasons, of heavy thaws and warmer winters would have the effect of decreasing the total thickness of the sheet and lifting it off the bottom wherever it had been touching. On the other hand, a series of colder seasons would thicken the mass, and it would not only rest upon an increased area of the bottom, but would freeze on to some of the muds and enclose them. These would be lifted when next the mass floated at that point, and in the course of many years would finally appear at the upper surface, having been enclosed by ice and therefore perfectly preserved on their way up.

The case of the mirabilite is a little more complicated, but follows from the same conditions. The bottom of the sound, under the ice, is certainly not level, and may be supposed to contain basins. When the ice-sheet rests on the bottom it will enclose a certain amount of water in each of these basins, cutting it off from the rest of the sea. Ice will continue to be deposited from the water, and it will become increasingly concentrated into a brine solution. This happens in all the small lakes on Cape Royds, as mentioned by Prof. David & Mr. Priestley, who found the temperature of the liquid brine residue as low as $-17°$ Fahrenheit. At a certain concentration and temperature the sodium sulphate in the brine would be deposited as solids. The precipitation of this salt from

Fig. 4.—*Diagrammatic representation of the theory.*



I. The ice-sheet afloat.

II. The sheet, having increased by freezing below more than it has lost by thaw from above, now rests upon the sea-floor, freezing-in the sponges.

III. The same at a later stage. The basin has begun to yield sodium sulphate from the brine, some of which is included in the ice.

IV. Milder conditions have caused a net decrease in thickness, the sheet rising off the sea-floor, taking with it the included material.

cooled brine is well known, and occurs in Nature. It takes place in the Great Salt Lake of Utah whenever the temperature of the water falls below about 20° Fahr., and accumulates in such quantities that it can be gathered from the bottom, being a source of the Glauber's salt of commerce.

The ice in the enclosed basin would continue to increase to a small extent, and would enclose a certain proportion of the deposited salt, especially on the borders of the basin. When the ice-mass rose from the bottom again the enclosed salt would be protected from the solvent action of the fresh sea-water which would again fill the basin. Probably a proportion of other salts would be entangled in the sulphate as first deposited, some of which would drain out of it in the course of time, just as in the case of surface sea-ice. The more or less impure mirabilite would gradually rise through the ice precisely as the muds do, but on reaching the surface would probably undergo a further purification in a way that does not concern the subject of this paper.

If we now apply this theory of the origin of the raised deposits, we are able to recognize them at various stages of their evolution from sea-bottom to high-level drift. The first stage is represented by the occurrences of both salt and marine muds immediately north of Black Island. The height of the Barrier immediately south of this island and the existence of long crevasses between it and White Island seem to point to the ice-sheet coming over a submerged ridge between the islands. The original site of the muds cannot in that case be farther south than the northern side of the ridge where the ice again begins to float. In fact, such a position would be a very probable one for the process of freezing to the bottom to take place. The muds off the north side of this island may, therefore, be regarded as having only just come to the surface—the first stage.

A little consideration shows us that this point is a particularly good one for making measurements, and finding out a great deal more about the process.

For, if T = the average thickness of the sheet in that area,

V = the annual rate of movement of the sheet,

E = the distance of the exposure from its origin,

and D = the annual decrease of the surface;

then we have the following relationships:

$\frac{T}{D}$ = the number of years that it takes to reach the surface,

and $\frac{E}{V}$ = the same.

Therefore we have four quantities, any one of which may be found from the other three. Unfortunately, no measurements of accuracy are available, and even the positions of the deposits are only approximate, so that we cannot at present make any calculations without wide assumptions. If we take assumed figures as near as judgment will go, we obtain interesting results, which are here given as an example rather than as a basis for deduction.

Taking the thickness as 200 feet, the rate of movement as 50 feet per year, and the distance between the submerged ridge and the first exposure of muds as 5 miles, we get the annual decrease of the surface,

$$D = \frac{50 \times 200}{5 \times 5280} = \frac{10}{25} \text{ feet,}$$

that is, about 5 inches a year.

Of these quantities the thickness and the rate of movement would be comparatively easy to measure, and the quantity E not at all impossible.

The next stage is represented by the deposits near D (fig. 1, p. 52), where the muds have travelled many miles on the surface of the sheet, and have become sorted by water so that the organisms are to some extent damaged by exposure to atmospheric weathering. The fate of these muds is to be floated away on small bergs that occasionally break off from here, most of which would melt in more northern latitudes and return the muds to the bottom of the sea.

The high-level deposits at Cape Royds exhibit a further stage, and are particularly interesting as showing that, even when the McMurdo Sheet was much thicker than its present 100 or 200 feet, the same process of picking up sea-floor was going on. I have no doubt that there are other deposits at a still higher level, but the difficulty of finding them is considerable. The remnant of ice upon which they are still resting will disappear in time, and they will come to the final stage as shown by the Dry Valley case (K, fig. 1, p. 52) where the ice has entirely disappeared, and there is nothing left to show the origin of the shells.

With regard to the shells and sponges that form the bulk of the organisms in the muds it is interesting to note that they come from all depths down to 80 or 100 fathoms, the zone of the sponges in particular being in the neighbourhood of 80 fathoms. The best 'catch' of living sponges was made by the ship in 78 fathoms off the mouth of the Ferrar Glacier. Some of the shells belong to shallower depths; but, as they are all collected on the surface of the sheet, they will ultimately be deposited in the same narrow bed of mud. The occurrence of the deeper forms shows that the process can go on even when the thickness of the ice reaches 600 or 700 feet.

General Summary.

The results may be recapitulated in a few words, as follows.

The raised marine beds and bottom deposits are found in this part of the Antarctic at all stages of their evolution, and, whatever may be the process of their elevation, it is quite certain that they do rise through the ice, and so are preserved from shock and disintegration. The most plausible explanation of the process is that the sheets decrease from the top and increase from the lower surface, for which the data are not yet sufficient to provide a conclusive proof. Such data would be very easy to obtain by methodical measurements of one or two quantities, and, moreover, such measurements would probably settle the limits of thickness, depth of water, etc. at which freezing from below can take place.

The numerous instances of raised muds already found prove that the vertical transport of material by ice is going on over a wide area and with considerable activity. There is no doubt that only the difficulty of seeing the deposits on snow-covered moraine has prevented the discovery of many more occurrences than have been so far reported.

In short, there is here a process of transport and deposition going on, which in the aggregate must assume large proportions. Owing to the configuration of McMurdo Sound most of the effects of the process are not perpetuated, since the raised muds float away on the ice as it breaks off. If the northern portion of the Sound were partly closed by large islands, we should doubtless find them covered with silt and muds containing shells and mirabilite.

Conclusions.

The importance of this discovery and the theory that is here offered to account for it does not lie so much in the explanation of these particular deposits in a remote region of the world, as in the analogies which it may afford for the origin of similar deposits elsewhere.

We have seen that the conditions necessary for the process appear to be reducible to two: (1) a high rate of surface-thaw to more than counteract the precipitation and produce clear ice, and (2) a comparatively stagnant body of water under the ice-sheet. These conditions are liable to be found in any sheltered bay or gulf that has high sides to aid in the thaw, conditions which must be present in the North just as in the South.

The maze of sounds and deep gulfs north of North America would therefore be ideal ground for such a process, and I have little doubt that it is going on there. On reading the descriptions of 'raised beaches' from that region, one is much impressed by the constant reference to the wonderful preservation of the material and the peculiar associations of organisms, features that are typical of the raised muds of McMurdo Sound. Laminaria, for instance, have been found at a height of 200 feet with their characteristic smell still recognizable, bivalves with the cartilaginous hinge still perfect, and so on. These deposits appear to have been universally ascribed to recent elevations of the land, and the issue is certainly clouded by unassailable evidence to that effect; but I think that closer investigation will show that the other process has been at work also.

In Spitsbergen, again, the requisite conditions prevail at the present day. The summer thaw is excessive, and there should be areas in the deep fiords where the circumstances are favourable to the formation of ice on the nether surface of floating glaciers.

On reading the account by Mr. G. W. Lamplugh of the shelly moraines of the Sefström Glacier,[1] I was immediately struck by what seems to me clear evidence of the same process. The description is so precise and so well illustrated that one can picture the occurrence almost as if one had actually seen it. Without so clear an account I could not presume to add to the observations of the author on this wonderful demonstration of the transporting action of ice. Much of the moraine containing the shells was resting upon the ice, and in fact formed roughly-stratified beds within the body of the glacier, a position which could hardly be attained by any pushing action of the ice on the sea-floor, but exactly what would be expected from the freezing process. In a few patches, seen by Sir Aubrey Strahan, the marine material was in its original order, and included in the ice. Again, the evidence of Mr. H. Trevor-Battye, who saw the glacier at its maximum extension, shows that none of the moraine was supra-glacial, nor was any of it pushed over the land in front of the ice. The moraine now exposed is, therefore, all ground-moraine or englacial. The evidence of the shells themselves, and their wonderful preservation, is a further support to the view that much of it has been transported vertically as well as horizontally, by slowly rising through the mass. Mr. Lamplugh's description of the lateral moraines of the Von Post Glacier shows striking similarities with the deposits in the lateral moraines of the Ferrar Glacier, and I am inclined to think that much of the red boulder-clay has been raised from the sea-floor in a similar way. As in the Antarctic cases, a few measurements of the Spitsbergen glaciers made in the light of the above theory should definitely establish the origin of the raised muds, and it is even possible that the necessary data are already available.

With regard to the deposits left by the Great Ice Age it is obvious that the theory, if accepted, will help to explain some of the anomalies observed in Glacial drifts. Since I can claim no close acquaintance with the shelly drifts of the British Isles myself, it would be presumptuous on my part to attempt any close analogies; but it may be useful to hint at the bearing which this theory may have on the problems that have been investigated by so many great geologists in the past.

One of the difficulties of the shelly drifts is the state of preservation of the organisms. In many cases they are broken and ground down, but in others they are perfectly preserved, with epidermis and ligament intact. On the submergence theory, which means that they were exposed to a gradual elevation, this is difficult to explain; while, if the sea-floor had been forcibly-pushed up by the ice, the motion would hardly leave the shells unharmed.

[1] Proc. Yorks. Geol. Soc. vol. xvii (1911) pp. 216 *et seqq.*

The presence of thin lenticles of shelly drift intercalated between beds of boulder-clay is another anomaly that is quite easily explained in this way; in fact, the same occurrence is observed at Cape Royds, where the marine muds disappear under a covering of normal moraine in one place.

The association of different forms of shells, rock, sand, and mud-loving species all in the same drift, is naturally explained, for the bottom muds from different places are ultimately all collected on the upper surface and would be laid down together.

The classic shell-beds of Moel Tryfaen defy complete explanation from this very character as well as from their great height above sea-level. Edward Forbes described them as

'a confused mixture of fragments of species from all depths, both littoral and such as invariably live at a depth of many fathoms.... Deep and shallow-water species mingled could at no time have lived together, or have been thrown upon one shore.'[1]

It is quite possible for the ice-sheet to have frozen to different depths at different times and places, the muds from which would finally find the same level on the surface of the sheet and be deposited together. Rearrangement by fluvio-glacial action might then leave them as they now appear. The difficulty of their great height above sea-level (1400 feet) does not appear to me to be necessarily due wholly to elevation since the Glacial Period. The Great Ross Barrier in one place mounts overland to a height of 1200 feet above its normal level close to its seaward edge, and there seems reason to believe that it rises to a height of 1800 feet on its eastern side where it abuts on Edward VII. Land.

But it must be left to those who know the shelly drifts well to apply the theory, and to judge whether the same conditions as those now found in the Antarctic may not be postulated for the sheets of waterborne ice that invaded these islands in the Glacial Period.

EXPLANATION OF PLATE IV.

Fig. 1. The northern side of the Ferrar Glacier at H (on the map, fig. 1, p. 52). The marine mud is found on the low hillock in the foreground, as well as on the pinnacles behind.

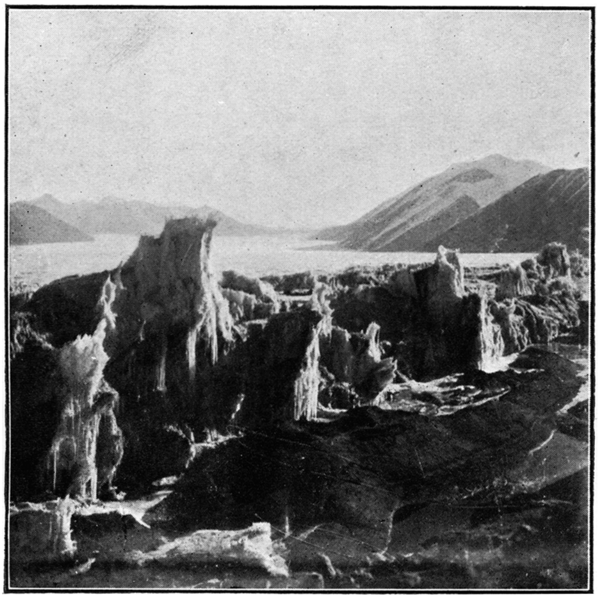
2. Mounds of sponges and polyzoa on the Lower Koettlitz Glacier at F (on the map, fig. 1, p. 52).

DISCUSSION.

The PRESIDENT (Mr. G. W. LAMPLUGH), in thanking the Author for his paper, said that it was of peculiar interest in bringing out clearly the extensive scale on which marine material could be taken up from the sea-floor into an ice-sheet. Such material would afterwards necessarily be transported as far as the ice travelled. In the

[1] Mem. Geol. Surv. vol. i (1846) p. 384.

Fig. 1.—*Part of the northern side of the Ferrar Glacier.*



F. D. photo.

[Marine muds are found on the tops of the pinnacles in the foreground.]

Fig. 2.—*Mounds of sponges and polyzoa on the Lower Koettlitz Glacier, at point* F *on the sketch-map.*

F. D. photo.

shelly drifts of the Yorkshire coast it was evident that the material of the sea-floor had in some cases been detached and transported in strips and slabs, and the speaker had surmised the possibility of 'anchor-ice' as an agent, but had been unable to find evidence that anchor-ice was formed in sea-water. The idea that a floating glacier might receive continuous additions from below by the freezing of the sea-water at considerable depths was new to him, as he had been accustomed to suppose that the limit of downward freezing under such conditions was soon reached. But, if the Author was right in this respect, his theory offered a simple explanation of the known facts.

Prof. P. F. KENDALL said that glacial geologists would be thankful to the Author for furnishing their armoury with a new weapon. It was over forty years since the suggestion was made that the occurrence of marine shells in glacial deposits could be explained without recourse to a marine submergence. Three ways had been indicated by which remains of marine organisms could be uplifted by ice, and the Author had added a fourth. Garwood & Gregory had found in Spitsbergen that the Ivory Glacier, in passing over an upraised sea-floor, had incorporated in its lower layers shells and other objects which, farther down the valley, come out on the surface of the glacier at an altitude of probably 200 feet or more above their place of origin. These writers attributed this to the lessened mobility of the débris-laden basal layers of the ice, which would offer resistance to the flow, and cause the development of a shear that would bring the shells out on the surface of the glacier.

The case of the Sefström Glacier, described by the President in a paper to the Yorkshire Geological Society, seemed to the speaker to indicate the upthrust of subaqueous moraine by the nose of the glacier.

A third method of uplift mentioned by the President was by the formation of anchor-ice. This, the speaker understood, was a common occurrence in the Baltic, and fishermen, when far from land, on the approach of winter watched carefully for the appearance of cakes of ice rising from the bottom to give them warning of the imminence of a general freezing of the sea. Sometimes the warning came too late, and the boats were frozen in, and had to remain until liberated by the spring thaw.

The Author's interesting communication indicated yet another way in which uplift might be effected.

It is not clear how much of the shelly drift of the North of England can be accounted for by each of these explanations. In the Irish-Sea basin, where shells are found up to altitudes of 1200 and 1400 feet, it is significant that, as R. D. Darbishire pointed out, the same suite of shells is found at the highest elevations as in the low grounds; moreover, the fauna is essentially a shallow-water one, and the grouping characteristic of 200 fathoms is nowhere to be found. Again, the shells are of various ages, many of them of Pliocene types, and they often bear striations due to ice-action. A few small patches like those found by the speaker in the Drift of the Isle of Man and by the President at Flamborough Head appear to be true fragments of contemporaneous sea-bottom.

He congratulated the Author upon the lucidity of his exposition and the ingenuity of his hypothesis.

Mr. T. CROOK remarked that the facts brought forward by the Author were extremely interesting to anyone who had tried to understand the means whereby our own high-level shelly gravels had been transported.

The very interesting process outlined by the Author was one in which the time-factor seemed to be important. A sheet of floating ice would have to be very thick indeed to raise englacial muds and gravels by this means to the heights at which they were found in the British Isles. It was difficult to believe that so thick an ice-sheet could renew itself in this way rapidly enough and completely enough to have the desired effect. The speaker therefore asked the Author whether he could give any gravitation data that would enable one to form some idea of the time that would be involved in the renewal of a thick ice-sheet in the suggested way.

The speaker pointed out that overthrust action in ice-movement was a proved factor of much importance (Geol. Mag. 1911, p. 47); and the Author seemed not to have allowed for the possibility of this action as a means of elevation of englacial material within a moving ice-sheet. The operation of thrust-action had been abundantly demonstrated in Greenlandian and other ice-sheets, and it seemed permissible, therefore, to infer that gravel could be elevated by this means. During a phase of recession when melting was in progress, the raised gravel would be left as relics, which would be seen in all stages from englacial débris to stranded patches, much as the Author had described.

Sir JETHRO TEALL said that, although certain links in the chain of evidence were necessarily wanting, the Author's theory correlated so many of the remarkable facts which had been observed in the neighbourhood of McMurdo Sound—for example, the frequent association of mirabilite with the various organisms—that he was most favourably impressed by it.

The overthrusting theory was doubtless applicable to certain areas, but it did not furnish a satisfactory explanation of the phenomena upon which the Author had laid special stress.

The AUTHOR, in reply, said that, with regard to the question raised by the President as to a limiting thickness in the growth of sea-ice by freezing, it must be remembered that the conditions in the open sea are quite different from those in a deep bay, where the water is comparatively stagnant. The formation of anchor-ice is unknown in the Antarctic, and is apparently limited to fresh water moving at a rate sufficient to prevent surface-ice from forming. As it is the result of radiation, anchor-ice could in no case form under a thick sheet, and that convenient explanation of the raised muds is denied to us. Its occurrence in the Baltic, as mentioned by Prof. Kendall, is very interesting, and is perhaps to be correlated with the fact that the Baltic water has a low salinity, and in many places is much affected by the river-currents. Mr. Crook's plea for the recognition of overthrust planes can hardly apply to floating sheets of this nature, for they are moving over a frictionless plane, and the parts aground are very local. His question as to the time required for the uplift of the muds is susceptible to calculation by a method which is outlined in the paper, and may be put in the following form:—

$$\text{Time of uplift in years} = \frac{\text{Total thickness of sheet.}}{\text{Annual decrease of upper surface.}}$$

$$= \frac{\text{Distance from origin to point of first appearance.}}{\text{Annual rate of movement.}}$$

In conclusion, he thanked those present for their kind reception of his paper.