perhaps by the multiplication of crystals through splitting in the upper parts of the cloud, will probably be responsible for any precipitation which falls.

Acceptance of Langmuir's ideas would thus entail a modification of the importance hitherto attached to the part which ice nuclei may play in precipitation, particularly in tropical and warm temperate zones. But they still possess a sufficient field of action to warrant a continued investigation of their character and activity.

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AN ESKER IN PROCESS OF FORMATION: BÖVERBREEN, JOTUNHEIMEN, 1947

By W. V. Lewis (Cambridge University)

Eskers have been variously defined but it is now generally agreed that they consist of winding ridges of cross-bedded or current-bedded sands, gravels and sometimes boulders. The best formed are flat topped and steep sided, and they may exhibit contortion, faulting and other disturbances which can well be attributed to the presence of ice during their formation. The nature of the bedding clearly indicates that the materials were laid down in water and their association with glacial deposits suggests that they were formed by melt water streams emerging from glaciers or ice sheets. They may extend any distance from a fraction of a mile to 150 miles if the gaps which usually occur in the longer eskers are included. They cross the country, continuing uphill and downhill over the minor features of the landscape. This latter characteristic favours Hummel's [1] explanation which regards them to be the casts of sub-glacial streams. This raised the question as to why sediments should be deposited in such places where one would have expected the streams to have flowed swiftly under hydrostatic pressure and so to have been fully capable of clearing out their channels. Also the frequently claimed perfection in the form of the cross section hardly suggested that they had been formed under moving ice. Furthermore the Moray Firth and other eskers subdivide and rejoin just like the distributary pattern of a glacial stream well laden with glacial outwash. This led me to follow Wright [2] in favouring Shaler's suggestion [3] that eskers originate when outwash streams end in standing water, as did the great eskers of Sweden in the waters of an expanded Baltic in Yoldia and earlier times. Where no such semi-permanent bodies existed the eskers were supposed to have been deposited in lakes formed by the ice blocking the normal drainage channels. It is easy to understand why an esker formed in such a manner would remain in an excellent state of preservation after the lake waters had disappeared.

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Fig. 1 (above). Böverbreen esker from the glacier snout

Fig. 3 (below). The esker emerging from under the ice

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Fig. 2.

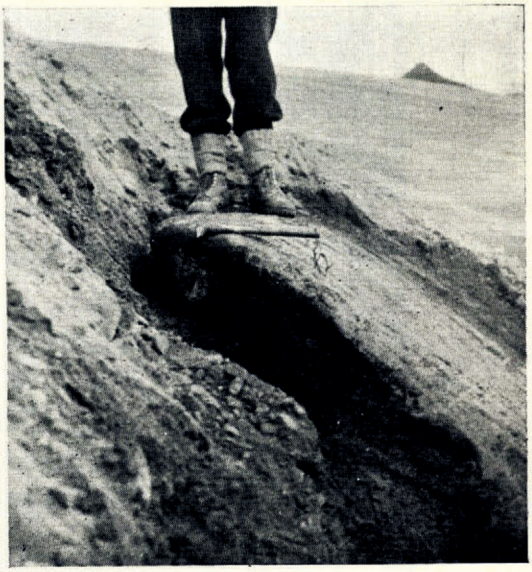

Fig. 4.

Fig. 5.

Fig. 2. Topset and foreset beds exposed in the side of the esker

Fig. 4. Part of an ice arch (beneath the figure) uncovered by digging into the side of the esker

Fig. 5. Ball Ice off King George VI Land, Antarctica (see p. 340)

Photograph: Commonwealth of Australia, Department of Information

A visit to the Rondane district of eastern Norway in 1946 under the guidance of Professor K. Münster Strøm, of Oslo University, introduced me to esker series of a type excellently described by Mannerfelt [4] that had undoubtedly formed under ice. Evidence is also accumulating in Denmark favouring the development of a wide range of features under the ice.[5] The Rondane area is particularly suited for glacial studies because it was the meeting place of the main continental ice sheets and the lesser sheet formed over Norway. Features marking the recession of both ice sheets are very well preserved. An esker series was seen on the eastern slopes of l Kringla immediately north of the great bend of the Atna as it leaves the mountains. They extend some distance directly up the fairly steeply sloping valley side; but they do not have the flattened top and steep sides. They are rounded in cross section, with a gently undulating long profile. The many admirable sections depicted by Mannerfelt show that in eskers of this type a layer of boulder clay usually covers the water-laid deposits of the esker proper. The capping of boulder clay confirms what their appearance and their position in the sloping hillsides suggest, that they were formed under the ice. In this case the ice was a tongue of the main continental ice sheet that had first crept up the valley, and, as it slowly melted away during the retreat phase, had left the eskers and other related deposits. If, as in the examples cited by Mannerfelt, the eskers were due to extra-glacial streams plunging down the steep valley sides and entering tunnels melted under the glacier, one can again understand why the material was deposited. Movements of collapse, even in a relatively stagnant glacier, may block such a tunnel and cause the waters to be diverted into new channels leaving the old ones choked with debris.

The Rondane visit and the many discussions that took place between the members with knowledge of glaciers and glaciated scenery in different parts of the world emphasized the great importance of dead ice in helping to account for the many complicated features of glacial deposition. The perfect state of preservation of the great terraces of Doraalen [6] left one in no doubt as to the stagnant condition of the ice in its last phase of retreat when these features were formed. Their flat surfaces grading steadily downstream, and cut off abruptly short of the present stream, continued for miles along the south side of the valley and resembled a great railway embankment. In places several terraces rose tier upon tier high above the valley floor. Some of the higher ones were pitted with kettle holes the slopes of which were as steep and fresh as the ice-contact slopes which bounded the terraces. The occasional exposures, due to undercutting by the present streams, reveal current-bedded, and in places disturbed, deposits, and one could not avoid the conviction that they were formed of debris dumped between the valley sides and the stagnant glacial tongues that occupied the centre of the valley.

Professor Flint [7] in an admirable summary of the different views on esker formation favours their sub-glacial origin. Even when referring to those formed where lakes lapped against the retreating ice front he follows de Geer [8] in suggesting that the narrow parts of eskers were formed in the sub-glacial tunnels leading to the lakes.

Thus recent authorities on the subject of eskers vary in their emphasis, if not in their actual interpretation, from Wright, who advocates the theory of their origin in lakes, to Flint who considers that this only accounts for what is really a variant of an esker rather than the true form. Whilst Flint is probably very much nearer the truth than Wright, rival theories continue to claim supporters because no one yet seems to have described an esker in process of formation. It is for this reason that it gave particular pleasure to a party of Cambridge students visiting Jotunheimen in August 1947, on a geographical field meeting, to come across what may be claimed as an esker in process of formation.

The esker in question has formed at the end of Böverbreen about a mile south of Krossbu. The glacier ends on a gentle slope down which have slowly streamed boulders, gravel, sand and silt. Some members of the party can be seen in the left of Fig. 1 (p. 315) struggling in this solifluction quagmire. The photograph was taken looking down on the esker from the glacier. The main stream can be seen crossing the field of view in the middle distance. In the centre is a tributary stream which emerges from the glacier on the left of the esker. A second independent tributary follows the right bank of the esker. The whole feature was found to be only 40 yd. (36·6 m.) long, and 12 ft. (3·6 m.) high at its lower end, but the flat top and steep sides were excellently formed. The flat top was almost horizontal and the contrast between this and the steady slope of the solifluction surface in front of the glacier made the esker attract the eye at a distance. Several small kettle holes, some still being formed, broke the surface near the glacier.

The more or less horizontal topset beds were clearly noticeable without digging. On the very top was a flakey layer of compacted silt about 0·1 in. (2·5 mm.) or less in thickness. This had not suffered the slightest disturbance. It did not even show tiny pittings formed by water dripping on to it from above. Digging into the side of the esker revealed well developed fore-set beds below 12–18 in. (30–45 cm.) of topset beds (Fig. 2, p. 316). This confirmed the view that the whole feature had been deposited in standing water in spite of the fact that the valley could not have contained a lake anything like as recently as the time when the esker had been formed.

The upstream end that had just emerged from beneath the glacier had slabs of ice resting on it and showed other signs of disturbance, including the kettle holes. Fig. 3 (p. 315) shows the collapsed nature of the ice tunnel, together with the freshly formed ice-contact slope falling away on the left of the glacier stream which is not quite included in the photograph. The dark colour of this slope was caused by dampness from the melting of ice buried under the debris.

In accounting for this esker the first problem is that of supplying the standing water in which the stratified deposits came to rest. The valley floor, which sloped away from the glacier, could not have held up the waters of the lake. This leaves the only alternative of assuming that ponding back of the water had occurred under the glacier. We had penetrated ice caves on several occasions in Jotunheimen that summer. A particularly good one had formed in the snout of the glacier leading northwards from Leirhöe in Midt-Jotunheimen. It contained quite large pools of standing water in which sediment was collecting, and, as usual, melt water dripped freely from the roof. The fresh appearance of the esker, and the fact that it was steadily being washed away on both sides by the streams issuing from under the glacier, made one wonder how it could have existed long enough for the ice to have uncovered it. Professor Werenskiold and Professor Münster Strøm, who had accompanied us earlier in the meeting, had stressed the exceedingly rapid ablation which had occurred that summer. Also an ill-fated attempt to measure over-thrusting by inserting 4-in. screws into a face cut in the end of Heillstuggubreen failed because of the rate at which the screws melted out. A layer of ice nearly 1 ft. (30 cm.) thick melted away in two days. Even so, we did not anticipate anything quite on a scale sufficient to account for the recent emergence of the esker until Professor Faegri, whom we met subsequently in Bergen, assured us that the ends of many glaciers had receded in the course of the summer at the rate of 30 m. a month. If Böverbreen had retreated at this rate it would only have taken about six weeks to release the ponded waters and uncover the whole esker to the stage in which we saw it.

The steepness of the right-hand bank shown in Fig. 1, which helped to give the esker such a typical cross profile, was due, not to the slumping of the deposits after the supporting ice had disappeared, but to the little stream which can be seen cutting into the foot of the esker. The irregular valley occupied by this little stream separated another flat-topped terrace-like feature from the esker. If the two were once joined, such a broad spread of bedded gravel would hardly merit the term esker, but would appear more like a kame. However, one could hardly envisage an ice tunnel at the end of the glacier wide enough to include both these deposits, so they were probably formed either by different streams emerging from the glacier, or by the same stream at different times.

The active kettle holes in the top of the esker near the glacier showed that some ice was still incorporated within. Digging soon revealed that buried ice also occurred near the lower end. The outer side of this ice sloped at between 30° and 35°, the natural angle of rest of the debris which covered it. As is usual with such features the ice had been melted back to this angle, after which further melting was retarded by the protecting cover of debris.[9, 10] The position of this ice in the esker can be seen in Fig. 4 (p. 316), which also shows that the ice curved back underneath so as to form a bent slab or segment of an arch resting on the body of the esker. The black debris a foot or so below the handle of the hammer consisted of frozen mud and gravel, and contrasted markedly with the relatively clean ice on which the man was standing. A possible interpretation is that this ice represented a fragment of the walls of the ice cave in which the current-bedded materials were laid down. These deposits continue 2 ft. (0·6 m.) or more above the top of the ice, indicating, if this interpretation is correct, that either the upper ice had melted away or the whole slab had subsided. The latter alternative would appear the more likely judging from the evidence of collapsing seen at the entrance to the tunnel (Fig. 3).

As the enclosed ice gradually melts away there will be further collapse and disturbance of the deposits in the esker. The stream will almost certainly remove this incoherent ridge standing in its path, and redeposit the material in the partially graded reaches further downstream near Krossbu, and eventually carry at least the finer fractions to the lake at Lom leading to Gudbrandsdal. As long as it lasts it will form a very fine example of esker formation of the type which is not covered by supra-glacial deposits such as those so well described by Mannerfelt. It developed near the end of the glacier and under ice which was very free from debris. The perfect state of preservation even of the fine capping of silt suggests that at least this part of the esker may have formed when the cave was open to the sky. Otherwise the surface could hardly have been free from drip marks, unless water had covered it until such time as it was open to the sky. We were fortunate to visit the glacier in a season when the rate of retreat was phenomenal, perhaps representing conditions that obtained widely during the retreat phase of the Ice Age. Had the glacier ended as a tongue fanning out over a level plain the chances of survival of the esker might have been greater, because then the streams would have been more likely to have been diverted to other exits from the ice after the esker had been formed. On the other hand, such streams subdivide and swing very freely across their graded gravel floors, and tend to remove the incoherent deposits of moraines and eskers unless these are protected from the encroaching stream channels by knobs of rock.

A further lesson that we may learn from this example is that an esker, as perfectly preserved as the outer part of this one, must form very near to the margin of the glacier where no ice masses tend to be incorporated in the gravel deposits. The inner part of the Böverbre esker was already much disturbed by the melting of included ice, and would have been much more so by the time all the buried ice had melted out.

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