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INVESTIGATIONS OF TWO ESKERS AT EASTERN BREIDAMERKURJÖKULL, ICELAND

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ABSTRACT

Vertical aerial photography of Breidamerkurjökull flown in 1945 and 1965 has shown that an area containing a sandur in 1945 has developed into an esker ridge surrounded by kettle topography. Photogrammetric measurements from this photography indicate that the esker was produced by the melting out of buried ice from beneath sandur deposits on either side of the ridge.

Field mapping of a second esker which was melting out of the glacer during the period of study has shown that planimetric and height changes have occurred as a result of the melting of buried ice. The plan shape of the ridge appears to be controlled by ice structures giving a distinct rectilinear pattern to the esker. A cross section dug through the ridge revealed that the gravels were underlain by ice, indicating an englacial origin for at least part of the esker. This cross section, as well as others, have shown varations in the shape of the tunnel containing the gravels. The mechanism by which the esker is lowered to the proglacial surface to form a single ridge is also discussed.

INTRODUCTION

During the summers of 1965 and 1966, members of the Department of Geography at the University of Glasgow carried out a series of geomorphological, glaciological, and photogrammetric studies at Breidamerkurjökull in southeast Iceland. The area was revisited for a short time in the summer of 1968. As part of the project the author investigated the formation of esker ridges in the eastern half of the proglacial area. This paper presents the results of detailed studies of two of the more interesting eskers.

Breidamerkurjökull is one of the largest southern outlet glaciers of Vatnajökull. Its ice front is approximately 16 km in length and is bounded on either side by steep cliffs of volcanic rock rising to about 1,000 m (Figure 1). The glacier reached its recent maximum extent about 1890 (Ahlmann and Thorarinsson, 1937, p. 196). Since then it has been generally retreating to reveal a surface that rises gently from the sea to altitudes of a little over 50 m close to the present ice front.

The eastern half of the proglacial area is divided from the western half by a large proglacial lake, Jökulsarlon, and its outlet river, Jökulsa (Figure 1). Close to the lake the distance from the sea to the ice front is approximately 3 km. The width of the proglacial area gradually increases eastwards to a maximum of 5.5 km at the eastern margin of the glacier.

Drainage from the eastern half of the glacier is at present dominated by the Stemma Lake and river system. During the retreat of the ice front, the meltwater streams became gradually concentrated into the Jökulsa and Stemma

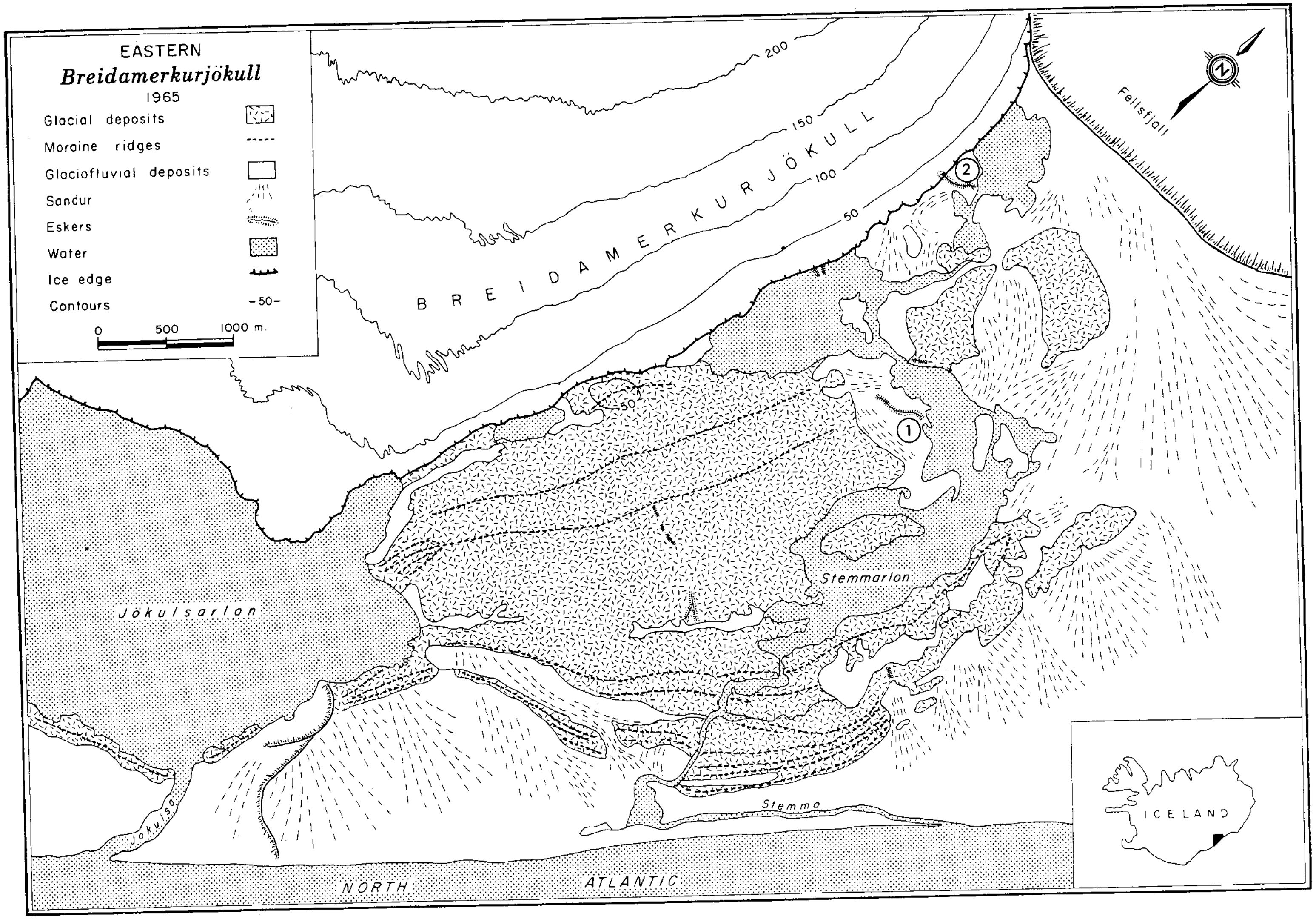

FIGURE 1. The eastern half of Breidamerkurjökull. Eskers 1 and 2 are numbered on the map.

drainage systems, thus leaving many areas of glacial and glaciofluvial deposition undisturbed by meltwaters since the time of their formation (Price and Howarth, 1970). This has aided the the study of the eskers which might otherwise have been destroyed by meltwaters.

INVESTIGATIONS OF ESKERS IN PRESENT-DAY GLACIAL ENVIRONMENTS

It is generally accepted that most eskers are formed in subglacial tunnels, but other hypotheses have been put forward which suggest that eskers may be formed at the ice edge or in supraglacial or englacial positions (Flint, 1957, pp. 157-158). Although the formation of eskers has resulted in a great deal of discussion in geomorphological literature, comparatively few studies of these features have been carried out in present-day glacial environments.

Eskers melting out of glaciers have been studied in Norway by Lewis (1949), in North America by Meier (1951), and in Spitsbergen by Szupryczynski (1965) and by Jewtuchowicz (1965). All the observations presented in these papers, however, consider the state of the eskers at only one moment in time.

Using sequential aerial photography, Petrie and Price (1966) and Price (1966) were able to introduce the time element into their studies of the development of eskers at Casement Glacier, Alaska. Changes over time were accurately measured using a photogrammetric plotting machine. Similar techniques were used by Welch and Howarth (1968) in the study of an esker at western Breidamerkurjökull. In both cases, lowering of the esker ridges due to the melting of buried ice indicated either an englacial or a supraglacial origin for the eskers.

METHODS OF STUDY

Vertical aerial photography of the ice front and proglacial area was flown in 1945 at an approximate scale of 1:46,000 and in 1965 at an approximate scale of 1:27,000. In addition, parts of the area were photographed in 1960, 1961, and 1964. Photogrammetric maps have been produced from the 1945 and 1965 photography (Howarth, 1968), and detailed measurements from this photography have been used to determine the changes that have occurred in Esker 1 over the 20-year period.

Esker 2 did not begin to appear from the glacier until about 1960 when the scale of photography available was too small to study the esker photogrammetrically. Field methods were, therefore, used to investigate the esker. In 1965, twice in 1966, and once in 1968, the esker was mapped at a scale of 1:500 using a plane table and a Kern R K self-reducing alidade. In addition, cross sections were dug through the esker to determine the nature and shape of the contact zone between the ice and the esker gravels as they melted out of the glacier.

ESKER 1

Morphology

Esker 1 is the largest esker in the eastern half of Breidamerkurjökull and is complex in form. It consists of a main ridge, 350 m in length, which ranges from 5 to 15 m in width and from nearly 1 m to approximately 5 m in height. On the northern side of the main ridge there are small minor ridges reaching approximately 8 m in width and 2 m in height. The minor ridges connect at both ends with the main ridge of the esker and for the most part are lower than the main ridge (Figures 2 and 3).

At its proximal end the esker is discontinuous. Toward the central section of the esker the main ridge divides in two for a short distance. Over most of its length the esker is comparatively straight, but towards the distal end there are some sharp bends in its course. The esker, in this section, descends into a large kettle hole and rises out again at the far side close to a crag-and-tail. A small ridge, up to 3 m high, descends into the Stemma river and may form a continuation of the esker.

The general slope of the ground surface and of the crest of the esker is away from the glacier. Except at the distal end, where the ridge descends into the kettle hole, the crest of the esker is very regular and flat over much of its length (Figure 3).

The proglacial surface surrounding the esker is distinctly hummocky, and from south to

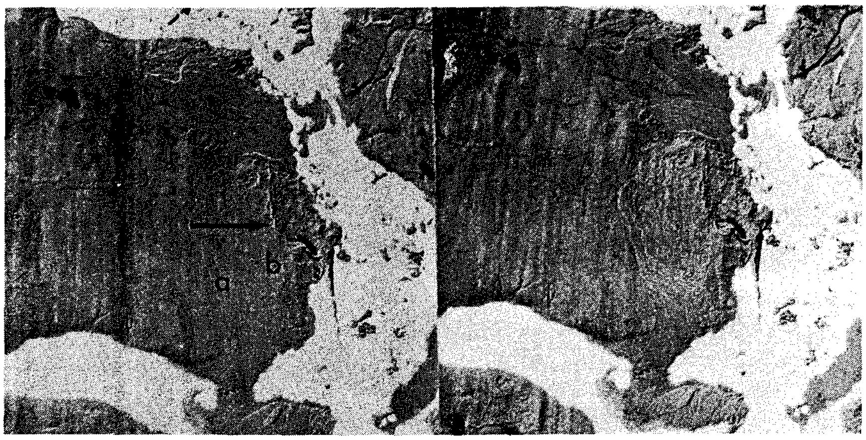

FIGURE 2. Stereogram of Esker 1 in 1965 at an approximate scale of 1:27,000. The esker is indicated by the arrow. Note the way in which the sandur at "a" grades into kettle topography at "b." The kettling becomes more pronounced on the opposite side of the esker from "b."

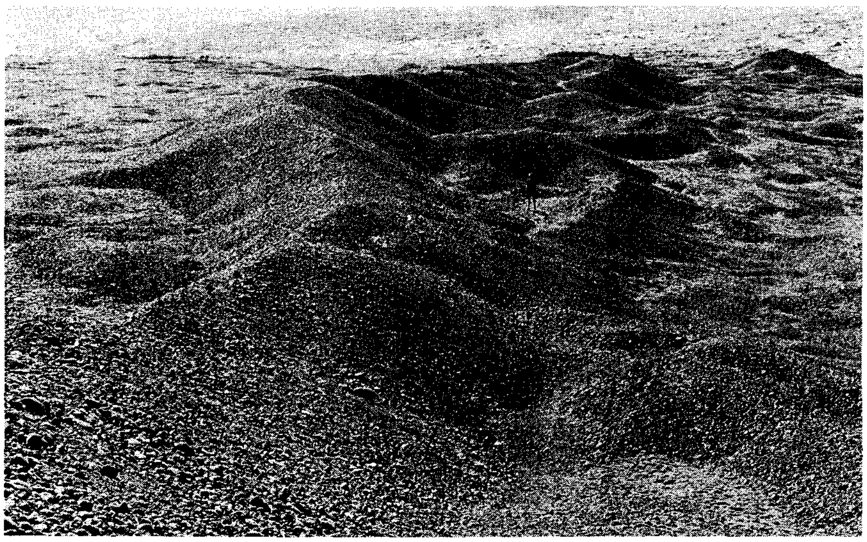

FIGURE 3. View looking west along the central and proximal parts of Esker 1. The glacier at its 1965 position can be seen in the background. Note the minor ridges on the right hand side of the esker, and the flat top that occurs along the major part of the main ridge.

north there is a definite increase in the degree of kettle development. At the southern edge of this area a braided channel pattern on a small sandur can be clearly seen (Figure 2). Moving northward, the channel pattern becomes increasingly disturbed by the kettle development until finally the channel pattern can no longer be distinguished and a hummocky topography predominates. In this area on the south side of the esker, the difference in height between the bottom of a hollow and the top of a mound is rarely more than 1 m. Although the kettling is more strongly developed on the north side of the esker, there are few deep kettle holes.

MORPHOLOGICAL CHANGES FROM 1945 TO 1965

The aerial photographs indicate that in 1945 the ice edge was situated at the present position of the proximal end of the esker (Figure 4). All that could be see of the esker was a small

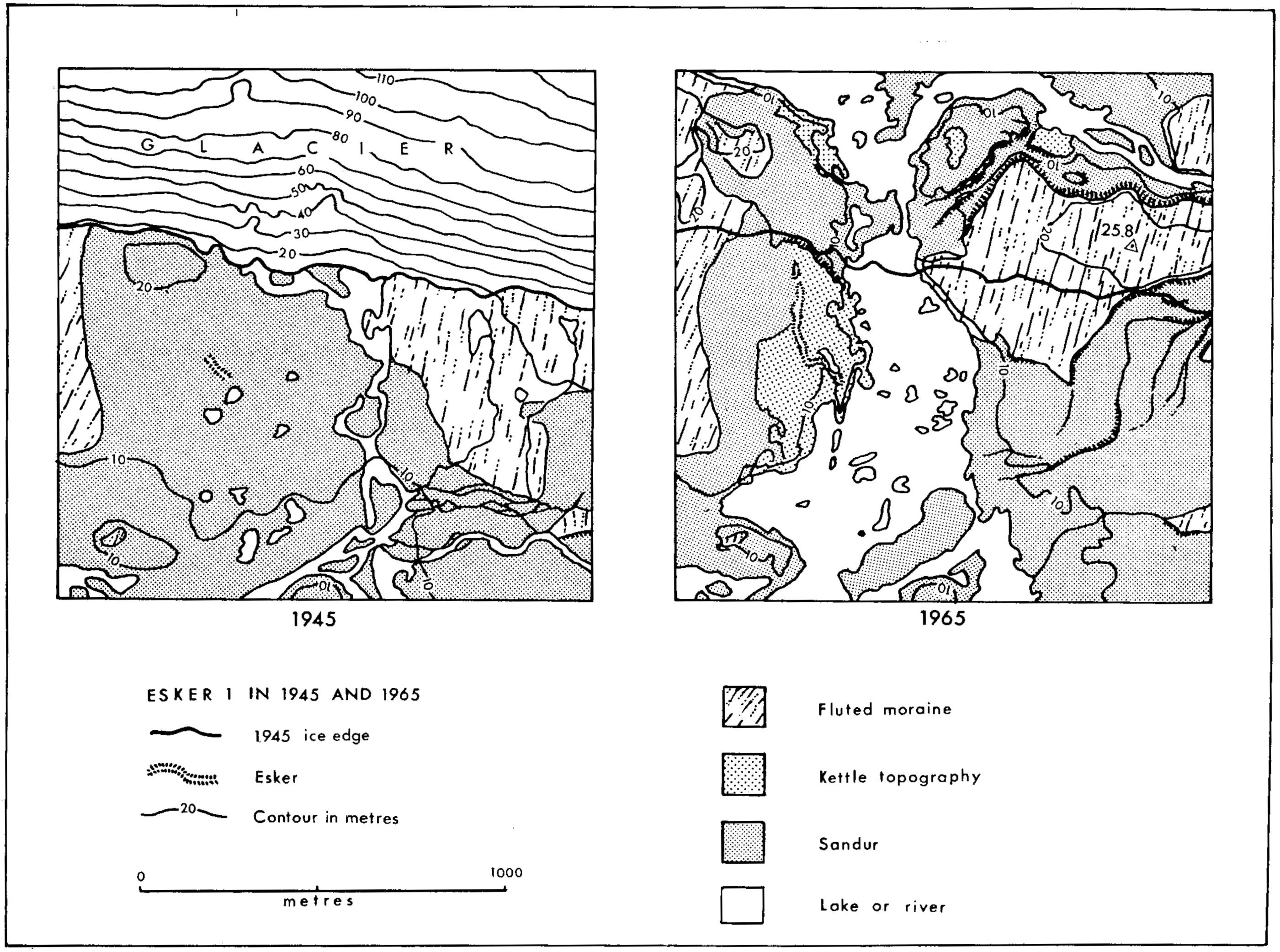

FIGURE 4. Maps showing exactly the same area in 1945 and 1965. The development of the esker ridge and the area of kettle topography surrounding it can be seen. To aid the comparison, the 1945 ice edge has been superimposed on the 1965 map.

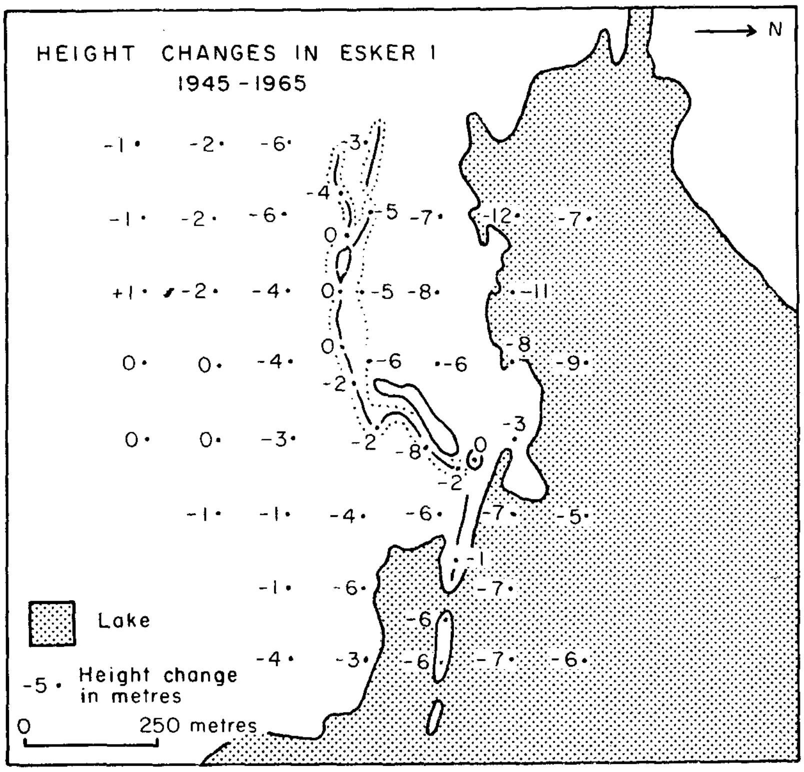

FIGURE 5. Height changes on and around Esker 1 between 1945 and 1965. Photogrammetric spot heighting accuracy is correct to ± 2 m. Little or no change in height has occurred along most of the crest of the esker. Height differences over the water are minimum values.

ridge that now forms the distal end. It is apparent that in 1945 the central and proximal parts of the esker did not exist.

To investigate the planimetric and height changes that occurred between 1945 and 1965, photogrammetric techniques were used. Ground control points, surveyed from the Icelandic trignometrical system and situated on stable ground well outside the area of study, were used to scale (at 1:15,000) and level the photography in a Wild B8 photogrammetric plotting machine. By using the grid intersections on a 0.5 cm grid of squares placed over the plot sheet, it was possible to obtain height measurements at the same planimetric position from each set of photographs. The difference between the two recorded heights at the same planimetric point gave the change in height at that point. In areas that had not changed between 1945 and 1965, height differences of no more than ±2 m were recorded. This agrees with the theoretical spot heighting accuracy for the scales of photography used.

The results of these measurements are shown in Figure 5. Along the crest of the central part of the esker ridge, the recorded differences in height are within the accuracies of the photogrammetric measurements. On either side of the ridge, however, large differences in height indicate that the surface of the sandur that existed in 1945 has been lowered by up to 8 m.

ORIGIN

From the photogrammetric height measurements it is apparent that the main part of the esker has been formed by the general lowering of the surface on either side of the ridge. For this to have occurred, it is suggested that in 1945 most of the sandur in this area must have been underlain by ice. The melting of the ice on both sides of the ridge has led to the development of the kettle topography. The increase in the hummocky nature of the kettle topography from south to north, and the greater height differences recorded on the northern side of the esker suggest that the thickness of the buried ice also increased from south to north. Photogrammetric height measurements of points on stable ground in the surrounding area have indicated that the increase in height difference from south to north is definitely not due to an uncorrected tilt in absolute orientation of the aerial photographs in the plotting machine.

Although there was ice underlying the sandur, it appears that there was no ice beneath the esker ridge, except at its distal end and perhaps at its proximal end. This suggestion is supported by the fact that along most of its length, the esker has a very flat crest line which probably formed part of the surface of the sandur in 1945.

The photogrammetric measurements indicate that buried ice has been important in the formation of the esker, but a major problem is to explain the way in which the ice became buried. Evidence from other parts of the proglacial area suggests two possible ways in which this may have occurred.

First, gravels may have been carried into the ice along shear planes. Along many parts of the ice front, layers of gravels carried into the ice along these shear planes become exposed on the surface of the glacier as it melts. The layer of gravels then protects the underlying ice from melting. Resorting of the gravels and further deposition by meltwater streams could ensure the almost complete burial of the ice. It is difficult to explain the occurrence of the esker, however, unless it had already been formed within the glacier prior to the melting out of the gravels from the shear planes. If this occurred the esker could have been buried by the later deposition. Melting of the buried ice from areas surrounding the esker would then expose the ridge.

A second explanation is that the gravels burying the ice were originally deposited in the glacier by englacial streams. This suggestion is supported by observations at the ice front in 1965. A horizontal layer of gravels was melting out from within the glacier in an area where there was a subglacial stream. It is possible that this stream deposited the gravels in their englacial position before it cut down through the ice to produce its subglacial course and expose the gravels. This mechanism can be applied to explain Esker 1, except that in this case the subglacial stream course would also have to become filled with gravels to eventually produce the esker ridge.

ESKER 2

This is perhaps the most interesting esker in the eastern half of Breidamerkurjökull because it was gradually melting out of the glacier during the period of study. Preliminary observations of the esker in 1965 have already been presented (Howarth, 1966), but a great deal more information was obtained during the summers of 1966 and 1968.

Morphology

The esker appeared on the surface of the glacier and extended across the proglacial surface between two lakes (Figure 6). In 1965, the crest of the esker covered a length of 420 m, but by 1966 this distance had extended to approximately 470 m as more of the esker melted out of the glacier. Although the esker ridge varied in height and width, it was generally 15 to 20 m wide and 5 m high close to the ice edge, but only 5 m wide and 1 m high at its distal end.

Beyond the small river at the distal end of the esker it can be seen (Figure 6) that a series of small ridges in a crows foot pattern extend into a sandur. The sandur gravels, 1 to 2 m thick, overlay ice which was being eroded by the meltwaters of the lake during the period of study.

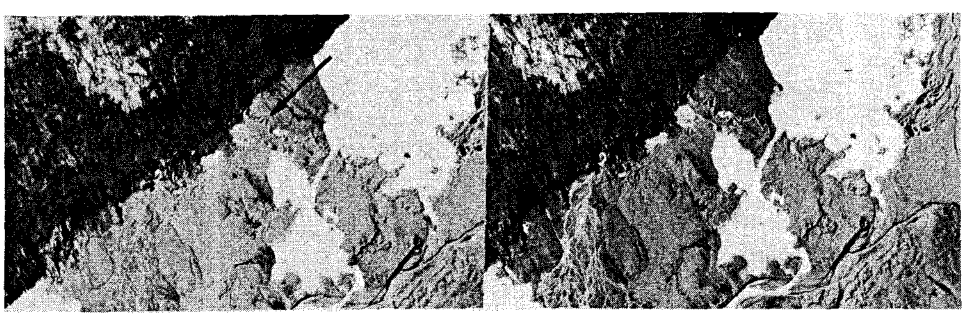

Figure 6. Stereogram of Esker 2 in 1965 at an approximate scale of 1:27,000. The esker, indicated by the arrow, can be seen melting out of the glacier. Note the "crows foot" pattern beyond the small river at the distal end of the esker.

Morphological Changes from 1965 to 1968

In order to determine the changes that were taking place, the esker was mapped by plane table and self-reducing alidade (at a scale of 1:500) at various times during the period of study. Planimetric positions were calculated and plotted to the nearest meter, while heights were determined to the nearest 10 cm. A comparison of the maps in the areas that did not change indicates that heights are correct to ± 20 cm, and that errors in planimetric position are probably no more that ± 2 m, the greatest errors occurring when sightings were taken over long distances.

Planimetric Changes

A study of the maps indicates that during 1965 and 1966 the esker gradually melted out of the glacier revealing sections running either parallel with or at right angles to the ice edge. Major changes, however, occurred between 1966 and 1968 when a meltwater stream started to flow from beneath the ice edge in this area. The stream removed the proximal end of the esker which had melted out of the glacier in 1966 and left in its place a small sandur between the esker and the 1968 ice edge. A meltwater channel was also cut through the esker which drained a large pool that formed against the esker at the end of August 1966.

Height Changes

Comparisons of the four maps indicate that there have been comparatively large changes in height along the crest of the esker. From the points surveyed along the ridge crest each time the esker was mapped, it has been possible to plot profiles to determine the height changes that have taken place during the period of study (Figure 7). It can be seen that during the year from August 8, 1965, to August 8, 1966, maximum changes in height of 4 to 5 m occurred along part of the esker. Further height changes occurred between 1966 and 1968, resulting in a maximum lowering of the crest of the esker by 5.5 m over the 3-year period. During this time there was no apparent change in altitude at the base of the esker. In 1968, it appeared that the remnants of the esker had almost reached a stable situation since there was little evidence of buried ice or rapid lowering of the crest of the esker ridge.

As care was taken not to disturb the crest of the esker during mapping, all the changes may be considered a result of natural causes. In part, the changes were due to collapse of gravels from the crest of the ridge, but as will be shown later, the melting of buried ice was also important.

Cross Sections through the Esker

From the changes in height along the crest of the esker it was impossible to tell whether the sands and gravels of the esker extended to the subglacial floor or whether they were underlain by ice. Thus, in order to determine whether the esker was formed subglacially or englacially, cross sections were dug to the base of the esker. This was an extremely difficult task because of the hardness of the glacier ice and the slumping of the unstable material forming the esker. In 1965 the base of the esker was not reached, but in the upper parts of three cross sections it was possible to study the nature and position of the boundary between the sands and gravels of the esker and the surrounding glacier ice (Howarth, 1966, pp. 7-8). This boundary will be referred to as the ice/esker contact. The cross sections indicated that where the esker ridge ran parallel to the ice edge, the ice/esker contacts on both sides of the ridge dipped up-glacier at a steep angle. Where the ridge was at right angles to the ice edge, the ice/esker contacts dipped away from the crest of the ridge.

By 1966, a surface stream had cut completely through the esker to reveal a fourth cross section. The cross section showed without doubt that this part of the esker had an englacial origin (Figures 8 and 9). Although it was impossible to measure the thickness of the ice beneath the esker accurately, it was estimated that the gravels overlay approximately 3 m of ice. On the up-glacier side of the esker (G), the ice/esker contact dipped up-glacier at an angle of 80° to the horizontal. On the down-glacier side of the esker (H), the ice had melted away. This side of the esker faces the sun, and it is likely that the heating of the sands and gravels caused the buried ice to melt away more rapidly. However, it has been shown in another cross section that the ice/esker contact on this side of the ridge dipped up-glacier (Howarth, 1966) and it may be suggested that this was originally the case in Cross Section 4 as the two cross sections were only 3 m apart.

One of the most interesting aspects of Cross Section 4 was a band of sands and gravels dipping up-glacier at an angle ranging from 10 to

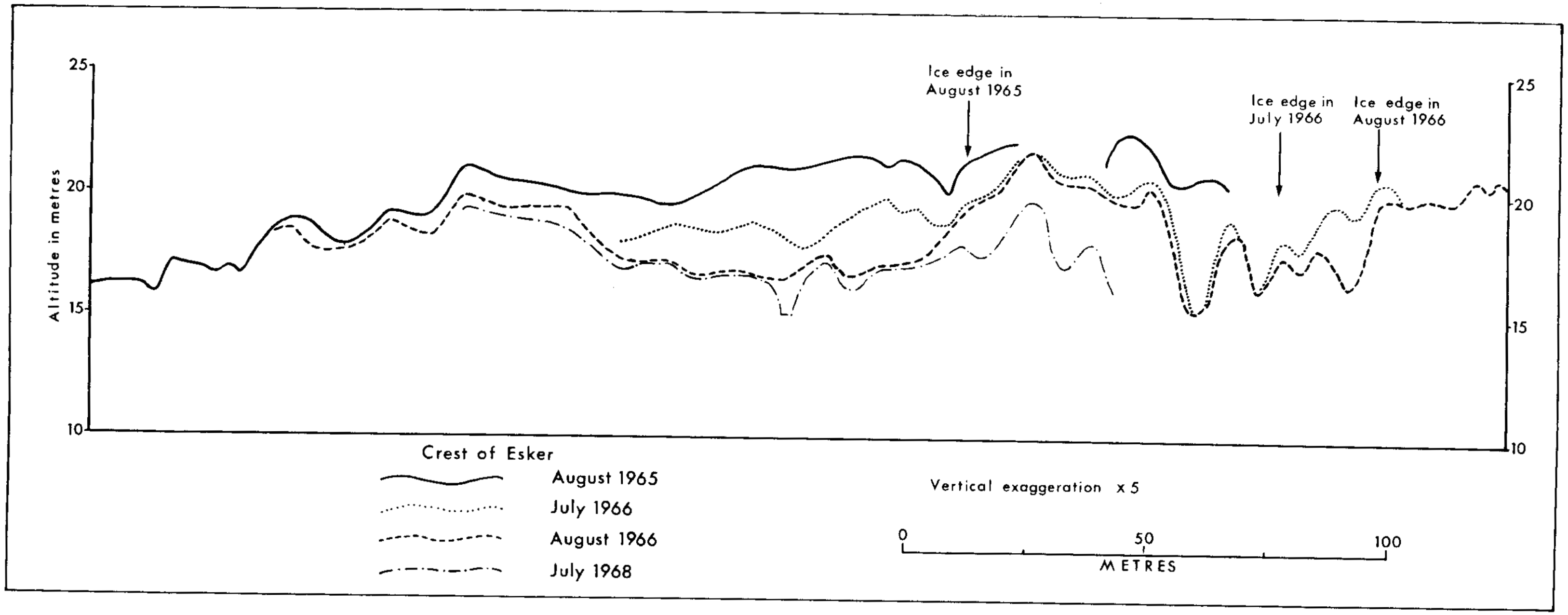

FIGURE 7. Height changes on the crest of Esker 2 between 1965 and 1968.

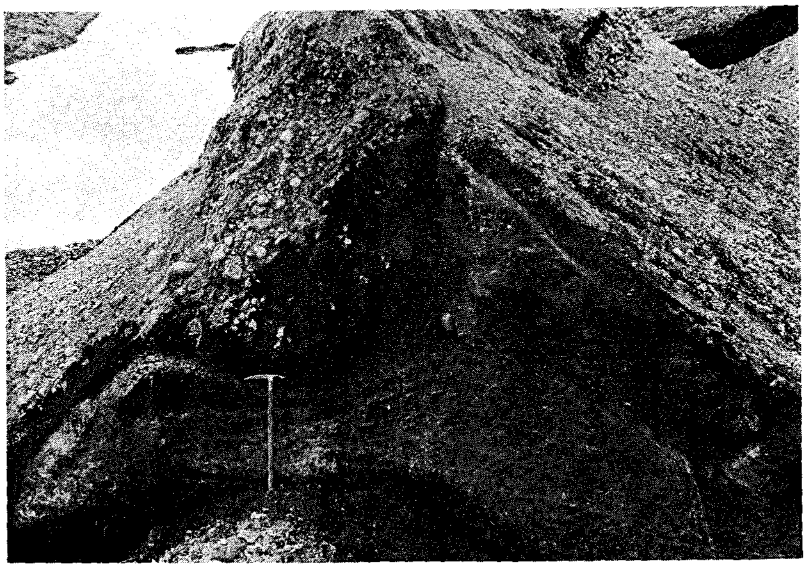

FIGURE 8. Cross section 4 in Esker 2. The ice which formed the side of the tunnel on the left or south east side of the esker has melted. Note the ice underlying the core of the esker indicating its englacial origin. The glacier is to the right of the photograph.

35° (Figures 8 and 9). The band connected with the base of the esker and gave every appearance of being a shear plane. Looking into the ice, the strike of the band could be seen running parallel with the crest of the esker ridge. A fabric analysis carried out in the band showed a preferred orientation at right angles to the strike of the shear plane, suggesting that the gravels had been carried into the shear plane from the base of the glacier.

In the lower 20 cm of the esker it was found that the gravels were surrounded by ice. This was much clearer and less granular than the normal glacier ice, and it is suggested that this ice within the esker was refrozen meltwater.

In 1966, Cross Section 5 was dug in a part of the esker running at right angles to the ice edge (Figure 10). In this case, the form of the ice/esker contact was entirely different when compared with Cross Section 4. In Cross Section 5 the esker occupied a semicircular hollow in the glacier. At the bottom of the hollow the ice dipped steeply downwards to form a narrow funnel extending to the subglacial surface. Again the gravels in the bottom of the esker were surrounded by refrozen meltwater.

In the frontal zone of Breidamerkurjökull, crevasses are developed at right angles to the ice edge as the glacier spreads out in the proglacial area. It is possible that the funnel-shaped hollow at the base of Cross Section 5 represents the bottoms of a crevasse or line of weakness in which the tunnel has been formed.

STRUCTURAL CONTROL OF THE ESKER

It has already been pointed out that parts of the esker run parallel with the ice edge, while other parts are at right angles to the ice edge. From the preliminary observations of the esker it was concluded that this regular layout of the different sections of the esker as they melt out of the glacier "suggests that the structure of the ice exerts a control on the plan of the esker" (Howarth, 1966, p. 9). Recent work by Stenborg (1968) lends support to this suggestion in that he has shown that meltwater streams both on and below the surface of the glacier are primarily controlled by ice structures. At Breidamerkurjökull, it appears probable that shear planes and crevasses are the two main factors providing structural control, parallel with and at right angles to the ice edge respectively.

The importance of structural control is further emphasized by the fact that within the glacier the shape of the tunnel in which the glaciofluvial material has been deposited appears to depend on whether the esker is running parallel with or at right angles to the ice edge. Three cross sections dug where the esker was parallel with the ice edge showed that the shape of the tunnel was in the form of a parallelogram, with both sides of the tunnel dipping up-glacier at a steep angle. In the other two cross sections, however, where the esker was at right angles to the ice edge, the tunnel was rounded in cross section.

What effects ice movement may have are not

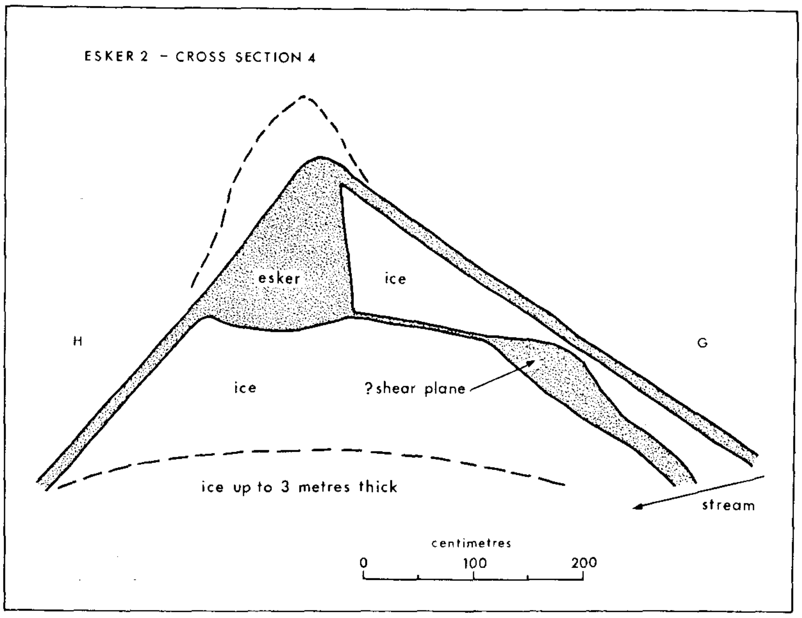

FIGURE 9. Cross section 4 in Esker 2.

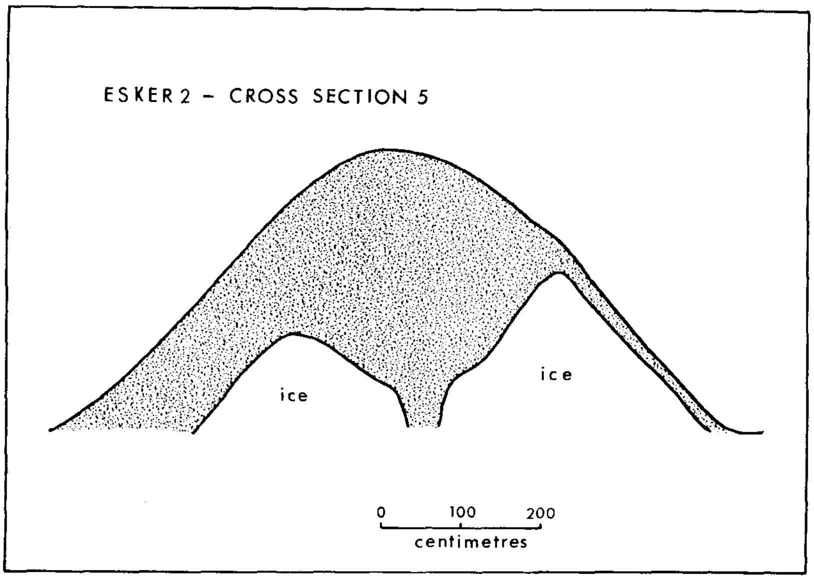

FIGURE 10. Cross section 5 in Esker 2.

known. In 1966 a line of stakes was placed behind the esker extending up-glacier and at right angles to the ice edge. Although no ice movement was recorded 40 m from the ice edge, over a period of 51 days total ice movement of 40 cm was recorded at 175 m from the ice edge. It is thus apparent that a glacier does not have to be stagnant for the effective development of eskers to take place.

THE DEVELOPMENT OF THE ESKER RIDGE

In areas close to the ice edge the sides of the esker consist of a layer of gravels, only a few centimetres thick, overlaying ice. When the esker melts out of the glacier, the upper parts of the esker are comparatively stable and stand out as a ridge. The surrounding glacier ice continues to melt. As the esker ridge dries out and the finer particles in the gravels lose their cohesion, the ridge becomes unstable. Wind erosion and rain add to the instability and sands and gravels from the ridge start to slump down onto the clean ice surrounding the esker. The sands and gravels then greatly reduce the rate of melting of the underlying ice. Beyond the limit of the slumped material the glacier ice continues to melt away, but all the time material is continuing to fall from the esker and move down the slope of the already protected ice. In this way, the extent of the slumped material gradually increases to cover more and more of the clean glacier ice and to inhibit its rate of melting. By the time that all surrounding glacier ice has melted away from the area, an esker with ice underlying its slopes of slumped gravel has been formed and a condition of comparative stability is established.

It must be emphasized, however, that the amount of material falling from the crest of the esker is comparatively small compared with the total volume of sand and gravel within the esker. The slumped material on the slopes of the esker is only a few centimeters thick and has an angle of rest on the ice of approximately 30 to 35°. As the ice core continues to melt, the main body of the esker is gradually lowered on to the ground surface. Thus a single esker ridge is formed which still maintains a stratified internal structure, because the rate of melting of the ice core is more rapid than the slumping of the sands and gravels from the crest of the esker.

It is suggested that a similar sequence of events will occur whether the esker is formed subglacially, englacially, or supraglacially. Only two conditions are necessary. First, the glacier surface at the ice edge must have a comparatively low gradient so that the esker is able to melt out on to the surface of the glacier. Second, as the esker melts out of the glacier its sides must be in contact with the ice so that material falling from the crest of the esker will bury the surrounding glacier ice. Thus the presence of ice at the sides of an esker does not necessarily indicate an ice core beneath the whole of the esker.

DISCUSSION

Esker 1 may be classified as a proglacial esker in that its development took place in the proglacial environment after the retreat of the ice edge. Other suggested mechanisms for the development of proglacial eskers, however, involve direct deposition of glaciofluvial material by streams flowing out from the ice edge (Flint, 1957). It could be argued that Esker 1 is not a true esker because its form is dependent upon the melting out of buried ice from areas surrounding the ridge. In some areas of kame and kettle topography or in extensively pitted sandur it is possible to have series of sinuous ridges produced as remnants by the melting out of ice to form kettle holes. This type of topography has been described by Price (1969) at western Breidamerkurjökull, and on Baffin Island, King and Buckley (1969) have described esker-like ridges near Eqe Bay which are thought to have developed from accumulations of sediment between blocks of dead ice. At eastern Breidamerkurjökull, however, the main ridge stands well above the surrounding kettle topography to form a distinct feature. In addition, it does not occur as the side of a kettle hole, as would be the case if it had developed as an integral part of a pitted sandur or general area of dead ice topography. The area was originally developed as a sandur so that the whole ridge almost certainly consists of stratified deposits, although it was not possible to study the internal composition in great detail. Thus from its form and general stratified nature it would seem valid to classify the ridge as an esker.

Doubts were expressed by Crosby (1902) and more recently by Jewtuchowicz (1965) that englacial or supraglacial eskers could be lowered to the proglacial surface to form single ridges. Observations by Price (1966) at the Casement Glacier as well as observations of Esker 2 reported in this paper have shown that this is possible. Price (1966, p. 124) shows in diagrammatic form how this can happen and he suggests that if rapid lowering takes place a single ridge will form, but if the ice core only melts slowly it is likely that two ridges will be developed by the slumping of debris to either side from the crest of the esker. It is interesting to note that at eastern Breidamerkurjökull, where the ice core is very much thinner than that observed at the Casement Glacier, the reverse occurs. Under normal conditions of slow melting the single esker ridge is lowered slowly to the proglacial surface, while rapid collapse of the ice core (usually due to streams penetrating beneath the ice core and causing an increase in ablation) leads to the development of a number of small ridges.

SUMMARY

The investigations of two esker ridges at eastern Breidamerkurjökull have shown two different ways in which esker ridges may develop. The ridge forming Esker 1 has been produced in the proglacial area by the melting out of buried ice, on either side of the ridge, from beneath what was originally a sandur surface. Initial deposition of the gravels forming the esker appears to have occurred beneath the ice in a subglacial stream course. Esker 2 was in part formed in an englacial tunnel, the plan shape of the tunnel being controlled by structures within the ice. Upon melting out of the glacier, the major part of the esker has been lowered to the proglacial surface as a single ridge.

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