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RECENT "ANNUAL" MORAINE RIDGES AT AUSTRE OKSTINDBREEN, OKSTINDAN, NORTH NORWAY*

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Abstract. A series of minor moraine ridges lying on a lodgement till surface in front of the glacier Austre Okstindbreen are described. The available chronological control suggests that from 1957 through to 1970 a new ridge was formed each winter and that this pattern of annual production is probably also applicable to the period back to circa 1950. During the winter months of 1970/71 and 1971/72 the glacier advanced and deformed the ice cover of a marginal lake which now isolates the till areas from the ice margin. It is concluded that the ridges are true "annual" moraines formed primarily by ice push although the operation of a squeeze process during their genesis is not rejected.

Résumé. *Recentes moraines "annuelles" à Austre Okstindbreen, Okstindan, Norvège du Nord.* On décrit une série de petites rides morainiques reposant sur une surface de till de plâtrage à l'aval du glacier Austre Okstindbreen. Les chronologies disponibles suggèrent que de 1957 à 1970 une nouvelle ride fut formée chaque hiver et que ce processus de production annuelle s'applique également à une période remontant à 1950 environ. Pendant les mois d'hiver 1970/71 et 1971/72, le glacier avança et déforma la couverture de glace d'un lac bordier qui isole maintenant la surface de till du bord de la glace. On en conclut que les rides sont de véritables moraines "annuelles" formées principalement par la simple poussée de la glace, bien que l'action d'un processus de compression pendant leur formation ne soit pas rejeté.

Zusammenfassung. *Rezente "Jahrliche" Moränenrücken am Austre Okstindbreen, Okstindan, Nord-Norwegen.* Eine Reihe kleiner Moränenrücken, die auf der Oberfläche einer Grundmoräne vor dem Austre-Okstindbreen liegen, wird beschrieben. Die verfügbare chronologische Kontrolle lässt vermuten, dass von 1952 bis 1970 jeden Winter ein neuer Rücken entstand und dass dieser Vorgang sich wahrscheinlich schon seit 1950 wiederholt hat. Während der Wintermonate 1970/71 und 1971/72 hat sich der Gletscher vorgeschoben und dabei die Eisdecke eines Randsees verformt, der nun das Gebiet der Grundmoräne vom Eisrand trennt. Es wird gefolgert, dass die Rücken wahre "jährliche" Moränen sind, die hauptsächlich durch Eisschub entstanden sind, obwohl Druckvorgänge während ihrer Entstehung nicht ausgeschlossen sind.

1. Introduction

"Annual", washboard, and minor moraine ridges have now been investigated for over a century. The literature on the subject has been well summarized by Elson (1968), and the reader is referred to this work for a recent succinct background review of the wide diversity of physical characteristics and interpretations associated with these landforms. Despite their reported widespread occurrence in areas of former glaciation, on the subjective basis of published descriptions it would seem that they are relatively rare features at the margins of contemporary glaciers. However, it is recognized that perhaps most of the examples which have been included under the previously noted names may have been created sub-aqueously and therefore their observation in the process of formation will not be an easy task. This contribution to the topic is largely restricted to a consideration of those sub-aerial members of this landform group which have been formed in ice marginal environments related to modern temperate glaciers.

Seldom has it been possible to attribute the designation "annual" to moraine ridges with any degree of certainty since unambiguous chronological control has not been available and consequently, at the best, only tentative dating could be attempted. In the occurrence to be described it is thought that the evidence is sufficiently consistent to warrant the name "annual", although it is not absolute, hence the usage of quotation marks will be retained. In order to avoid any possible confusion which may arise out of using the unqualified term moraine which has, unfortunately, both lithological and morphological connotations in the literature, the landforms will be termed moraine ridges and the work of others has been adapted where necessary to maintain consistency in this respect.

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The object of this paper is to describe and discuss a recently formed example of these landforms, produced in association with glacial retreat during the last two decades. The site is located in the immediate proglacial area of the glacier Austre Okstindbreen, in Rana, Nordland Fylke, north Norway. The evidence suggests that periodic re-advance of the ice margin is an important but not necessarily exclusive contributor to the causative process. It is submitted that the positive identification of "annual" moraine ridges is a useful way of establishing general ice marginal behaviour without having recourse to detailed continuous measurements of glacial variation throughout the year. The paucity of comment on annual ice marginal oscillations superimposed upon a longer term trend of marked overall retreat may be explained by the fact that the usual single measurements of annual glacier variation may have failed to detect it. Thus this type of activity may be a more widespread phenomenon than is generally recognized.

2. Austre Okstindbreen

Austre Okstindbreen is an outlet glacier which descends from the eastern half of the Okstindan plateau ice cap, (Fig. 1), the latter having a total area of some 50 km². From the ice cap the outlet glacier initially flows north, but subsequently turns eastwards to terminate in a valley. This valley is about 200 m deep, 0.5 km wide, 2 km long and has a general altitude of 710–30 m a.s.l. During the period of Neoglacial climatic variation the glacier has advanced and retreated within the confines of the valley, and the outermost Neoglacial end moraine just fails to emerge beyond the eastern limits of the valley.

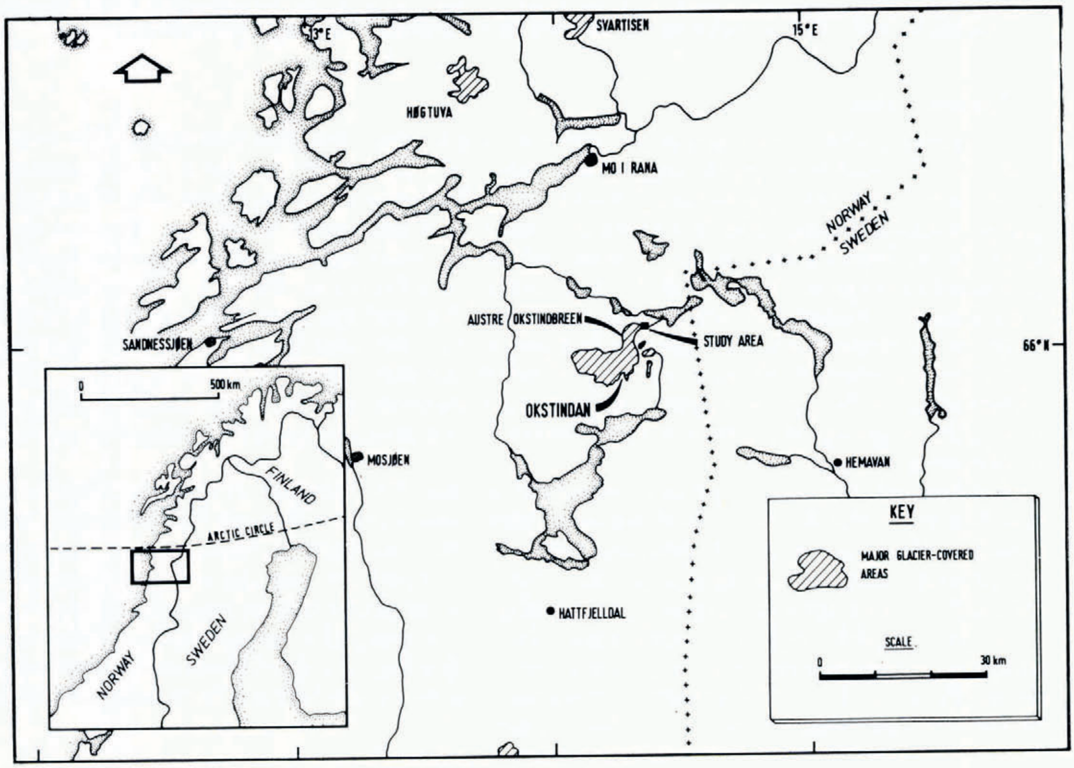

Fig. 1. Location map of Austre Okstindbreen.

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During recent decades the glacier has been in almost continuous retreat. Since about 1950 (all dates will be in years A.D.) until 1969 the glacier snout has in part terminated on the till surface in the valley bottom (Fig. 2). From approximately 1960 onwards, the area of contact between the ice and the till surface has diminished as a frontal melt-water lake has gradually extended along the ice front as retreat progressed until 1970, when the entire snout terminated in the lake. This latter situation has persisted until 1973 and, provided that the recent recessional trend is maintained, it is likely that the lake will become even larger in the near future. Throughout the retreat period the ice tongue has been in contact with the mica schist bedrock walls of the valley along its southern and northern margins, although lateral moraine ridges do occur but are poorly developed. It is on the till surface that the moraine ridges under consideration are located.

Fig. 2. The study area viewed from the tip of the corrie occupied by Skoltbreen on the northern flanks of Oksskolten, 1 August 1963.

The pattern of Neoglacial events associated with Austre Okstindbreen will be fully discussed on another occasion. For the present it can be said in summary that a fairly continuous series of measurements of frontal variation are available for the period 1908–44 (Hoel and Werenskiold 1962), along a standard transect originally established by Adolf Hoel. Thereafter, until the University of Reading observations in 1968, no known measurements were made along the transect. Fortunately, however, on three occasions air photograph sorties have included most of the area under consideration. The latter data, in conjunction with ground measurements from 1968 onwards, constitute the main control against which the hypothesis that the production of the moraine ridges is an annual event is tested.

3. The till surface

In gross morphology the till surface forms a crudely elliptically shaped low mound on the valley floor. To the east it is bordered by a lake which extends across most of the valley bottom and from this lake the ice front withdrew in about 1950. Before and since that time the main melt-water stream has flowed through the lake. To the south, the till area is defined by the melt-water stream, and it would appear that this situation has been maintained whilst the till surface has been progressively revealed as the ice margin has receded. The present ice marginal lake currently separates the till area from the glacier front in the west. The most ill-defined limit is that to the north where a former minor melt-water stream flowed, and is composed of a complex of small lakes and two narrow, linear, stream-lined till land-forms.

The till is typical of that associated with Rana glaciers, being derived primarily from a mica schist bedrock, and having been accreted subglacially by lodgement. The matrix grain size is: 57% sand, 39% silt and 4% clay (average of nine determinations) and the clasts are of variously shaped, locally derived material together with well rounded Swedish granitic material which has obviously been recycled from the sediments deposited by the Weichselian inland ice. At the surface is a scattering of largely angular boulders which for the most part appear to be resting on the till surface. These are interpreted as having been derived from largely supra- and englacial material which has been let down on to the surface of the lodgement till. Almost the entire till surface is moulded into fluted ground moraine, which trends generally parallel with the main valley axis and conformable with the former flow direction of the ice. Across this flute trend the "annual" moraine ridges run roughly at right angles creating a basic grid-iron pattern on the till surface which is clearly visible when viewed from vantage points on the steep confining valley sides.

4. The "annual" moraine ridges

In composition the ridge material is similar to the till forming the immediately adjacent till surface and there appears to be little doubt that the material is derived primarily from the till although inevitably some of the fines have been removed. Although the ridges are prominent when viewed from above, they are often less easy to distinguish on the ground. At the western (glacier) end of the area they are easily identified, but eastwards they become less distinct. This is to be expected, for in an area where the ridges have been produced successively at the ice margin which is in overall retreat for a significant period, the time available for post-deposition degradation by sub-aerial processes, especially mass movement, will naturally increase away from the ice margin. However, even allowing for post-formation erosion, it cannot necessarily be assumed that the dimensional range displayed by the most recent ridges was originally exhibited by the older ones. This is because the recent ridges have been formed in an area where the till surface slopes towards the ice margin. In such a situation it is possible that the ridges were originally larger than those produced where the till surface is horizontal or sloping away from the ice margin. The newest ridges have a height in the range 0.10–1.0 m with an average of about 0.50 m and a width of around 1.0 m, whereas the older ridges, for example in the area exposed by the ice retreat in 1955, have height and widths of 0.25 m and 0.60 m respectively.

During the preliminary examination of the area in 1968, to aid the recognition of the ridge outcrops and provide fixed points for mapping, a series of small cairns were built at approximate 10 m intervals. Once the pattern was established it was possible to relate the ground evidence fairly easily with the area shown on the air photographs, and it was apparent that little modification had occurred since the photography. As the ground evidence became more familiar it became possible to identify degraded ridge features in the eastern part of the area which were not apparent on the air photographs. What were originally interpreted as moraine ridge traces near the eastern lake shore were subsequently re-evaluated as features produced by wave-washing and lake-ice effects related to former higher lake levels. Since the lake outflow is cut in till, the level of the lake is being progressively lowered with time.

In the area of most recent ice marginal recession from the till surface, the ridge pattern becomes more involved. Unfortunately this area was revealed after the date of the most recent air photography and, additionally, within this latter area the till surface relief increases and consequently plane-table mapping becomes more difficult. The final map of the ridges (Fig. 3) has been produced by using all the available evidence, including air and ground photographs, plane-table mapping and levelled traverses. From the map it can be seen that a reasonably consistent pattern of moraine ridges emerges, with each ridge trending roughly north–south and paralleling the others for the most part.

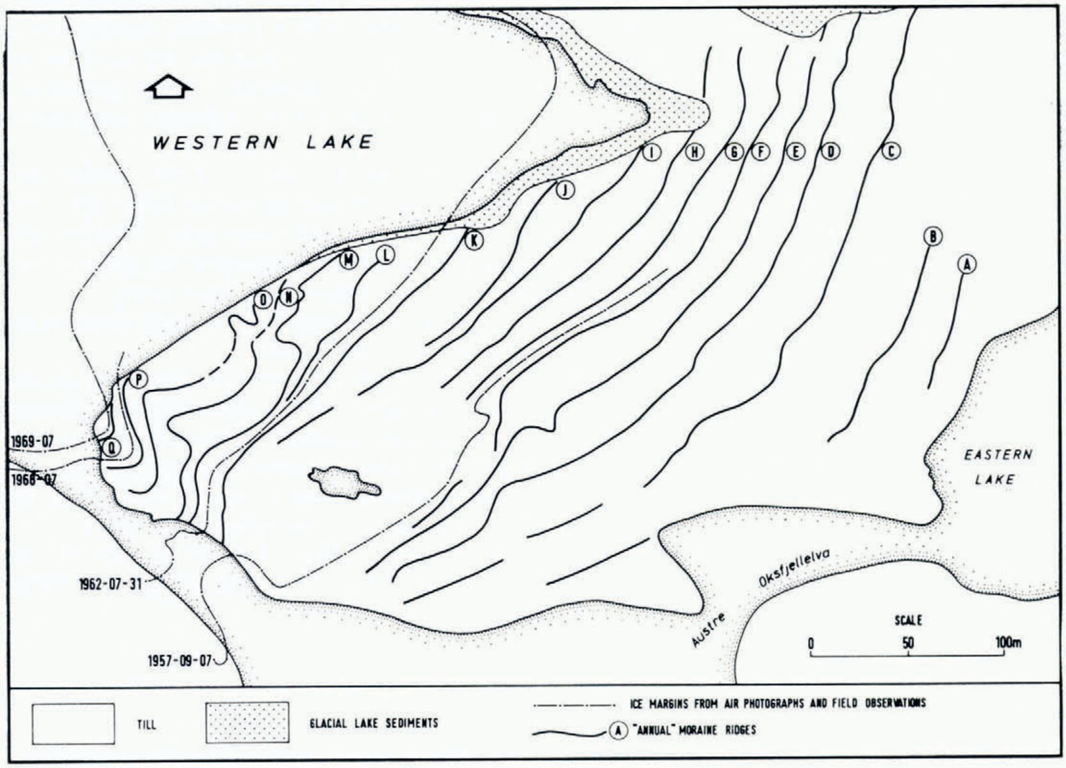

Fig. 3. Map of the "annual" moraine ridges in front of the eastern lobe of Austre Okstindbreen, formed in the period 1950–69.

On the distal side of the eastern melt-water lake is a further till mound which has a well developed fluted surface. On the western facing slope of this latter area, two exceedingly faint ridges could be detected above the former highest shore line of the lake. This area corresponds to that which had just become ice free when the last Norsk Polarinstitutt measurements were made in 1944.

An accurate bottom profile of both of the melt-water lakes would be of potential interest to see if similar ridges could be detected below the water. The more easterly of the lakes was sounded by a weighted line in 1971 where the Hoel transect crosses the lake. The other was subject to sounding by a portable echo sounder in 1969 but the depth values in both cases can only be considered approximate since it proved to be difficult to operate with any degree of accuracy from a small inflatable rubber dinghy and hence minor relief features were impossible to detect.

5. Chronological control

The mapped ridge outcrops may be related to the chronology of glacier retreat as follows:

(i) The two air photograph sorties were flown by Widerøe Flyveselskap A/S for Norges Vassdrags- og Elektrisitetsvesen on 7 September 1957 (sortie 835, prints V2-3) and 31 July 1962 (sortie 1320, prints K10-11). On both occasions the ablation season had progressed sufficiently for the ice margin to be reasonably clearly identified and for the adjacent till surface to be clear of snow. Unfortunately the first sortie only covered the southern two thirds of the ice margin in the area of the till plain and consequently the position of the margin is incomplete in Figure 3. However, the subsequent sortie covered the entire area of interest. From this evidence it is possible, using photographic enlargements made from the original negatives, to plot the ice margins at these two dates on the moraine ridge map with some accuracy. This procedure revealed that the ice margin closely responded to changes in the subglacial topography of the till mound.

(ii) In the summer of 1945, Professor Sten Rudberg, on his way to climb Oksskolten, which rises immediately to the south of the valley containing Austre Okstindbreen, took a photograph of the area which is now the eastern melt-water lake. This reveals that a narrow water body was impounded between the ice margin and the slope of the till mound and appears to have been the embryonic stage of the lake today.

(iii) An oblique air photograph taken by Widerøe Flyveselskap A/S in 1948 shows that the ice margin lay half-way across the eastern melt-water lake.

(iv) In 1965 an unknown observer painted twelve stations on prominent boulders within the area defined by the 1962 and 1968 ice margins. As the date 1965 was found inscribed with the same paint on the rock surface adjacent to the reference cairn built by Koller in 1941, it appears probable that this observer was acquainted with the long term measurement of Austre Okstindbreen and it seems reasonable to assume that the twelve stations are in close proximity to the 1965 ice margin.

(v) From 1968 the ice marginal variations have been a topic of study as part of the University of Reading investigations in the area based on the Okstindsjø Field Station.

6. Genesis

(a) *Summer observations 1968–70*

By 1968 when the writer first visited the area only a small part of the glacier margin remained in contact with the till surface. In late June of that year the ice margin was observed to be in contact with and partially buried by the proximal slope of a small and very fresh-looking ridge of till (Fig. 4). The ridge was very unstable and the adjacent till was of low load-bearing capacity which hampered closer examination. As the summer progressed the ice melted back and when last observed during late August it had retreated 4 m but still remained in contact with the till lying above the lake level. The proximal slope of the ridge was at this time being lowered by slow creep of the saturated surface till. The lake was beginning to encroach on to the residual ice tongue and it was apparent that it would shortly isolate the main glacier from the supra-aquatic till surface.

When the locality was revisited during late June the following year, a new ridge had appeared (Fig. 5) and was located just above the level of the melt-water lake. Behind it was the almost totally submerged outermost part of the glacier tongue partially buried by till which was slumping into the water from off the new ridge. Shortly afterwards the surface of the ice had ablated sufficiently for the lake to completely isolate the glacier from the till ridge.

Fig. 4. The moraine ridge which was in contact with Austre Okstindbreen in July 1968.

Fig. 5. The moraine ridge which was in contact with Austre Okstindbreen in July 1969.

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In June 1970 the ice was found separated by a channel along the southern margin of the till mound and this was the main connection between the melt-water lake to the north and the main melt-water stream to the south of the till mound. A small ridge of till was seen projecting above the water surface in the channel but was being subjected to rapid erosion by the flow of water out of the lake. Within a week this ridge was no longer visible.

In the period of observation during the above three summers no further new ridges were seen to form. This seems to suggest that the process of ridge formation had a yearly period and that they were formed outside the main summer season. Since 1970 the sub-aquatic record is unknown. From the above evidence the use of the descriptive term "annual" seems justified. When the ridge outcrop pattern over the whole till mound is considered in conjunction with the above observations and the chronological control presented in the previous section this annual mechanism seems applicable to the whole area. Thus although the moraine ridges seem to be annual in character, what is not obvious is precisely how this mechanism operates and therefore it is necessary to discuss further the various alternative possibilities.

(b) *Alternative mechanisms*

In studies of glacial landforms there has been a tendency to attribute specific phenomena to a particular process which has produced it. This situation is partly reflected by the conclusions reached by those who have examined "annual" moraines in the wider usage of the term (see Elson, 1968), and there is sometimes a reluctance to admit that a ridge feature might be of a multivariate nature, produced by a combination of processes, or indeed, that different processes might produce similar landforms. Taking the literature as a whole, the possible mechanisms which have been proposed as influencing the creation of "annual" moraine ridges may be summarized as follows:

(i) sub-aerial dumping of debris into transverse crevasses in stagnant ice.
(ii) melt-out of debris bands on the ice surface.
(iii) bottom melting and superimposition of englacial debris on the bed.
(iv) basal lodgement of till in a zone of thrusting inside an outer, stagnant ice margin.
(v) flowage of water-saturated till (squeezing) to the margin under the static loading of glacier ice.
(vi) glacial push (bulldozer action, ploughing) during re-advance.

The first four mechanisms require, either singly or in combination, that the glacier involved possesses the following characteristics:

(a) shear planes extending from the bed to the surface,
(b) a stagnant outer margin,
(c) debris in or on the glacier which, when deposited, will produce a till of the same texture as that exhibited by the moraine ridges, and,
(d) transverse crevasses in the snout area.

With respect to Austre Okstindbreen during the period 1968 onwards, none of these characteristics were apparent near the snout, and photographic interpretation for 1941, 1957 and 1962 suggests a similar conclusion. Indeed, from this evidence the glacier has been, and remains, remarkably "clean", there being little basal and englacial debris. However, it cannot be stated categorically that none of the four mechanisms in question have operated during the substantial periods when no evidence of the glacier behaviour is available.

The photographic evidence and 1968–70 ground observations do show that the moraine ridges are produced marginal to the ice and that their outline reflects the shape of the glacier margin at the time of formation. It has been reported above that recent observations suggest that the timing of ridge building lies outside the summer period and this is supported by the ice margin–innermost ridge relationship on the air photographs. From many contemporary ice marginal environments, irrefutable evidence shows that where the outermost, subglacial conditions are wet-based, the till beneath is unconsolidated and in a saturated hydroplastic state. In such situations it is possible for the static weight of the ice to cause an unstable equilibrium to readjust such that the ice sinks into the till and laterally displaces it to the ice edge where it is extruded in unconfined conditions to produce a moraine ridge. Such moraine ridges can be morphologically identical to those encountered at Austre Okstindbreen. During the ablation period, especially once any seasonally frozen layer has thawed, conditions for the mechanism just described are suitable and there would appear to be no reason why this mechanism should not operate at various periods throughout the ablation period when the degree of saturation will vary as the climatic conditions change. The creation of more than one ridge within a single ablation season has been observed, for instance, at the margin of Breiðamerkurjökull in Iceland (personal communication from J. Rose).

The alternative mechanism to extrusion is one linked to the periodic advance of the ice margin whereby the advancing margin acts like a bulldozer, ploughing into the proglacial till, pushing up a moraine ridge in the process. If this type of behaviour is to repeat itself periodically on an annual basis, the glacier involved would probably have to be in a delicate steady state such that the equilibrium is easily tripped either way. Under conditions of retreat, forward movement and supply of ice to the margin would be exceeded by ablation during the summer. By contrast in the winter the ablation would be at a minimum and the supply of ice would exceed the wastage resulting in a forward movement of the ice margin as the response. It is recognized that this is a simplified generalization and several factors, such as a reduction in the subglacial melt water, seepage and run-off will promote a reduction in the ice flow rates during the winter period, hence the amount of marginal advance is likely to be less than if ablation alone was determining the equilibrium form. Conditions can be visualized where a quasi-equilibrium could produce an essentially static margin over a period of years with minor oscillations related to the seasons, such that over time an increasingly large moraine ridge would be generated by successive increments of till. Where the moraine ridges are of small size, form fairly evenly spaced patterns parallel to the ice margin, and give consistent evidence that the spaces correspond to overall annual recession, then the dominant trend is obviously one of glacier retreat. This trend operating over a period of years must express the average long-term mass balance of the particular glacier.

The latter situation seems to apply at Austre Okstindbreen, and superimposed upon a continuing negative balance there is a weak tendency for advance to occur when the ablation is reduced or is minimal. Data relating to the flow of Austre Okstindbreen is unfortunately unavailable. It should be noted that this particular glacier seems to be wet-based and that around the frontal zone seasonal freezing to the bed is unlikely since a deep drift of snow usually accumulates around the margin and often persists well into the summer. Provided that there is no prolonged period of low temperatures before the first snowfall, the drift will minimize the tendency for the ice to freeze to the bed at the outer margin. That this is the norm in recent years gains support from observations in the numerous subglacial caves which are revealed around the ice–bedrock margins during the summer.

Measurements of ice marginal variation throughout the year do not appear to be common since usually it is only the annual change in the marginal position which is recorded, the observations being made in the early autumn as far as possible. However measurements within one year are available for one Norwegian glacier thanks to the experiment inaugurated by Fægri in 1935. At Nigardsbreen, an outlet glacier from the ice cap Jostedalsbreen, data are available on a monthly basis for the period from 1935–46. During the period of detailed observation Nigardsbreen was in a period of very strong recession and it is consequently not surprising that the results indicate continued retreat throughout the period. The main recession occurred in the period June to September with a minimum rate during February and March. During these latter two months the mean recession rate for the twelve years

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was less than 0.20 m. This low value suggests that should a re-advance occur due solely to a reduction in the ablation rate then it would first become apparent in either February or March. It is felt that these results are valid as a guide as to what might be expected at Austre Okstindbreen since the general climatological environments are similar. The mean monthly values from Nigardsbreen are published by Fægri ([1950], fig. 5).

Although the field evidence presented so far gives support to the "annuality" concept of moraine ridge formation, both the "extrusion" and "push" mechanisms seem compatible with the evidence. Obviously unambiguous data of a winter advance (should it occur), interacting with the ground moraine can only be monitored by personal winter observations or a system of automatic sensors operating through this period. A simple way of demonstrating the existence of re-advance, but not necessarily its timing, would be to carefully stake out the margin along its contact with a till surface at the end of the ablation season and then to record its relationship with the markers at the commencement of the following ablation period. The timing of the latter observations are important since the total amount of advance may be small and this seems likely judging from the relatively minor size of the ridges.

(c) *Re-advance observations*

(1) *Summer evidence*. Since 1968 the margin of Austre Okstindbreen where it abuts against the bedrock wall on the northern side of the valley, has been recorded by painting markers on the bedrock at the ice–rock contact, at the end of the field season, usually during September. In the summers of 1969 and 1970 when the margin became finally exposed after the dissipation of the snow drift, the ice margin was everywhere within the marked border of the previous year. This could be taken to indicate several alternative situations:

(i) continued significant ablation after the field season had been concluded and minor forward movement only,

(ii) frontal recession occurring beneath the snow cover such that when the margin is revealed any evidence of a previous, more advanced position is lost, or

(iii) that on this margin there is simply no re-advance.

The third alternative seems unlikely to have held in 1970, for in early July of that year, after the marginal snow bank had melted, a small moraine ridge was found in contact with the ice margin (Fig. 6). This feature was restricted to a till-covered area lying between bedrock knolls. As the ablation season progressed, a proximal, low-amplitude, fluted till surface was revealed with the flutes trending perpendicular to the ridge crest. These extended down the local slope and when last observed disappeared beneath the glacier margin. These relationships seem to indicate that the glacier had re-advanced and in doing so had pushed up the till-covered slope, deforming the till in the process. Fortunately, in 1971 the snow drift melted early and the glacier margin showed quite clearly that the ice was forward of the painted markers from the previous year by at least 1 m. Hence this margin at least had re-advanced at some period outside the main summer period.

(2) *Winter advance*. A more spectacular demonstration of the re-advance behaviour was forthcoming from observations made during the late winter season of 1971. On 4 April the eastern margin of Austre Okstindbreen, where it ended in the then frozen and snow covered marginal western melt-water lake, was found to be defined by a well developed ridge of lake ice. On the southern shore of the lake by the main exit of the subglacial melt-water stream there was no morphological feature to be seen; a smooth snow drift completely blotted out the irregular bedrock topography. However, as the glacier marginal zone was traced towards the lake centre, imperceptibly, a low-amplitude ridge started to develop in the snow cover (Fig. 7). This snow-covered ridge grew in amplitude until, when it had reached a height of some 2 m, the smooth crest became ruptured, and the jagged edges of fractured lake ice were visible in the ridge core. This produced an essentially triangular-shaped structure in the central part of

Fig. 6. A moraine ridge shortly after formation on the northern margin of the eastern lobe of Austre Okstindbreen, July 1970.

Fig. 7. Strike view of the pushed lake-ice ridge of Austre Okstindbreen shown in Figure 8.

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the lake consisting of two slabs of lake ice (Fig. 8). The reverse sequence was evident towards the northern shore. This feature would seem to be a response to stress exerted on the surficial lake ice and attendant snow cover by a glacier advance, such that where the forward movement exceeded a threshold value, the ice strength was insufficient to allow the ice to deform by folding. Thus when the elastic limit was reached the ice ruptured. A differential movement along the glacier front increasing towards the centre is suggested by this relationship, and the maximum amount of displacement exhibited by advance whilst the lake was still frozen may be estimated from the amount of displacement exhibited by the lake ice. This appears to be of the order of 3 m.

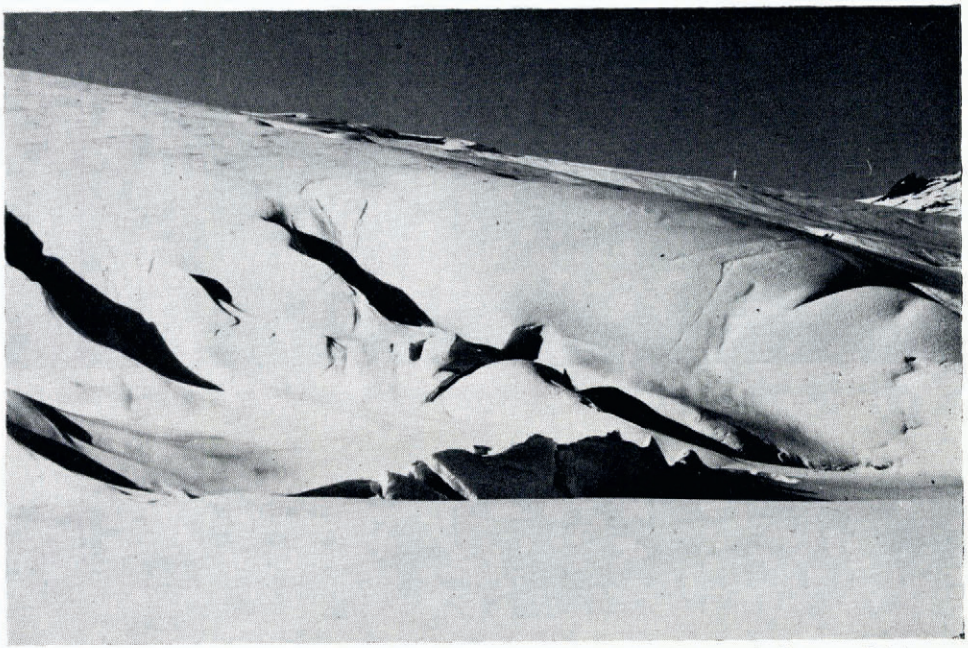

Fig. 8. Ridge of pushed lake ice produced by a winter re-advance of Austre Okstindbreen 4 April 1971. Height c. 2 m.

During late March 1972 the glacier was again observed but no ridge of any kind was apparent along the margin. However, it was evident that there was a much greater accumulation of snow than there had been a year previously and therefore it was possible that a pressure ridge had developed but was concealed by the drift of snow. It may be significant that a very heavy snowfall accompanying a storm had occurred during the week previous to the observations. Confirmation of this suggestion was forthcoming later in the year when the locality was revisited on 16 June. On this latter occasion the snow drift had largely dissipated but the cover of lake ice was still largely intact. Along the glacier margin a structural ridge of folded ice and snow was distinctly observable, suggesting another winter re-advance despite the lack of morphological evidence for it three months previously. From this experience it is clear that the vital evidence for a winter re-advance is at times elusive, and the timing of observations is therefore critical. Accordingly its observation requires a system of continuous measurement or some good fortune with the period of inspection as was the case in 1971 and 1972. Bearing in mind the Nigardsbre findings mentioned previously, it is probable that the re-advance structures are formed in the first quarter of the year. The freshness of the lake-ice ridge in April 1971 is consistent with this proposal.

Speculation on the effects of these two advances into the bottom sediments of the marginal lakes is tempting. The field evidence suggests that the ice cliff remains in contact with the bed and consequently there is likely to be interaction with the sediments lying within the path of the advancing ice. However, to date, as commented previously, precise bottom profiling has not been possible.

7. Summary

The observations reported here strongly suggest that minor moraine ridges developed on till surfaces in front of temperate glaciers may on occasion reflect a slight annual winter advance of the ice margin. It is clear that unambiguous evidence for this mechanism requires either virtually continuous recordings or, as in this instance, a degree of luck in the timing of observations. Thus although the mechanism seems to operate at Austre Okstindbreen, the general applicability remains to be tested. On the other hand it has not been convincingly demonstrated that the squeeze process alone has produced an extensive series of moraine ridges which have no temporal significance. As has often turned out to be the case in the past in controversies over geomorphological processes, the fundamental issue invariably lies in their multivariate nature. Consequently attempts to prove the uniqueness of either the push, debris-band melt-out, or the squeeze hypothesis of ridge formation do not promise to be particularly fruitful. Obviously more long-term observations are required from areas where ridges are under construction. For the immediate future it is unfortunate that predictions for Austre Okstindbreen indicate that further sub-aerially produced forms are unlikely and only sub-aqueous moraine ridges will be produced.

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