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"SAW-TOOTH" MORAINES IN FRONT OF BØDALSBREEN, SOUTHERN NORWAY

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ABSTRACT. A series of end moraines, with a remarkable saw-tooth pattern, is reported from the glacier foreland of Bødalsbreen, a northern outlet of the ice cap Jostedalsbreen. The three-dimensional morphology of the moraines is described and analysed. Historical records and lichenometric measurements indicate that they were deposited after the "Little Ice Age" glacier maximum of the mid-eighteenth century. It is inferred that the local topography of Bødalen was conducive to the formation of a heavily crevassed pecten at the snout of Bødalsbreen, which produced the end moraines by a push mechanism during minor glacier advances. The observations suggest that pushing may be an underestimated mechanism in moraine ridge formation generally.

RÉSUMÉ. *Moraines en "dents de scie" sur le front du Bødalsbreen en Norvège du sud.* On décrit une série de moraines terminales qui présentent une disposition en "dents de scie" remarquable, dans la zone proglaciaire de Bødalsbreen, un émissaire septentrional de la calotte glaciaire de Jostedalsbreen. La morphologie en trois dimensions des moraines est décrite et analysée. Des relations historiques et des mesures lichénométriques indiquent qu'elles ont été déposées après le "petit âge glaciaire", le maximum glaciaire du milieu du dix-huitième siècle. On en conclut que la topographie locale de Bødalen était favorable à la formation d'un "peigne" profondément crevassé à la langue de Bødalsbreen, qui produisit la moraine terminale par un mécanisme de poussée au cours de petites avancées du glacier. Les observations suggèrent que la poussée peut être un mécanisme sous-estimé dans la formation des reliefs morainiques en général.

ZUSAMMENFASSUNG. *"Sägezahn"-Moränen vor dem Bødalsbreen, Süd-Norwegen.* Es wird über eine Serie von Endmoränen mit bemerkenswertem Sägezahn-Muster aus dem Vorfeld des Bødalsbreen, einem nördlichen Ausflussgletscher des Jostedalsbreen berichtet. Die dreidimensionale Morphologie der Moränen wird beschrieben und analysiert. Historische Berichte und lichenometrische Messungen deuten auf ihre Ablagerung nach dem Maximum der "kleinen Eiszeit" in der Mitte des 18. Jahrhunderts. Es wird vermutet, dass die lokale Topographie des Bødalen die Bildung eines stark zerspaltenen Spatels an der Front des Bødalsbreen gefördert hat, der die Endmoränen während kleinerer Gletschervorstösse aufwarf. Die Beobachtungen lassen darauf schliessen, dass Schubvorgänge bei der Bildung von Moränenrücken bisher allgemein in ihrer Bedeutung unterschätzt wurden.

INTRODUCTION

A series of prominent end-moraine ridges occurs in front of Bødalsbreen (long. 7° 07′ E., lat. 61° 46′ N.), a northern outlet glacier of the ice cap Jostedalsbreen in southern Norway. The "saw-tooth" pattern of most of the moraines, strikingly apparent on vertical aerial photographs, is unlike any previously reported in the literature. This paper summarizes our investigations of these unique forms, and discusses possible alternative modes of formation.

LOCAL SETTING AND MORAINE COMPOSITION

At present Bødalsbreen occupies a relatively narrow valley with bedrock (granite gneiss) exposed on the eastern slope and with till and scree mantling the western slope (Fig. 1). Northwards, the valley broadens considerably and decreases in gradient where it is floored by extensive fluvio-glacial outwash deposits. Prominent moraine ridges, occurring in this

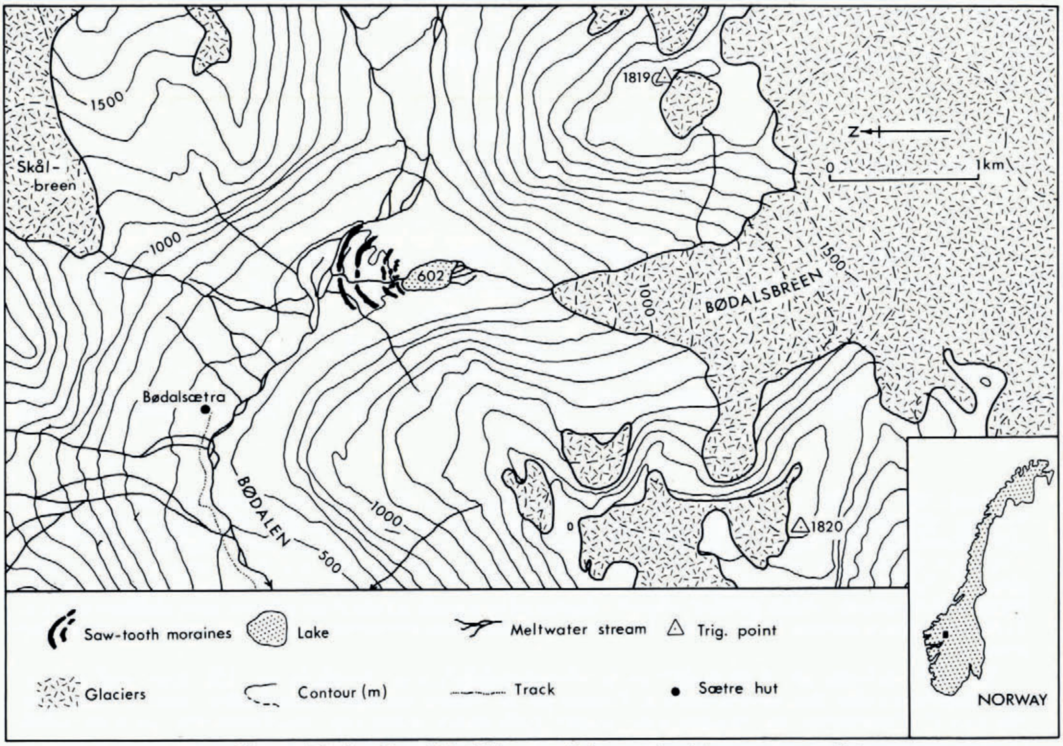

Fig. 1. The location of Bødalsbreen and the moraine-ridge sequence studied.

lower part of the valley, have been mapped in the field (Figs 2 and 3). The outermost moraine (A in Fig. 3) is a typical arcuate end moraine, in contrast to parts of moraines B and C, which display the impressively regular saw-tooth form, and to parts of moraine complex D, which consist of at least two, apparently superimposed, saw-tooth ridges. Significantly, moraine A abuts against the valley side for most of its length, whereas the saw-tooth forms occur as gently curving terminal sections of moraines B–D on the valley floor. On both flanks of the glacier foreland, terminal sections of all the moraine ridges continue as smaller lateral moraines. Where the valley is broad, the gradient of each lateral moraine is gently sloping (*c.* 1 : 13), but farther up-valley the gradient increases significantly (*c.* 1 : 1.6) with the lateral moraines ascending to considerable heights on the valley sides.

Exposures made by outwash streams through the terminal moraines reveal derived fluvio-glacial deposits, which comprise a matrix of sands and silts with many larger well-rounded clasts up to cobble size and occasional large boulders. The lateral ridges are of very different composition, being almost devoid of fines and in places represented merely by lines of boulders.

Morphological analysis

Twenty cross-profiles, aligned perpendicular to the moraine crests, have been examined in detail on the saw-tooth sections of moraines B and C (Figs 3 and 4). Slope angles were recorded for measured slope segments, using an Abney level and tape, at the tips of "teeth" (portions of moraine pointing down-valley) and at the back of "notches" or "recesses" (portions of moraine pointing up-valley). Consistently low slope angles (1–3°) were recorded

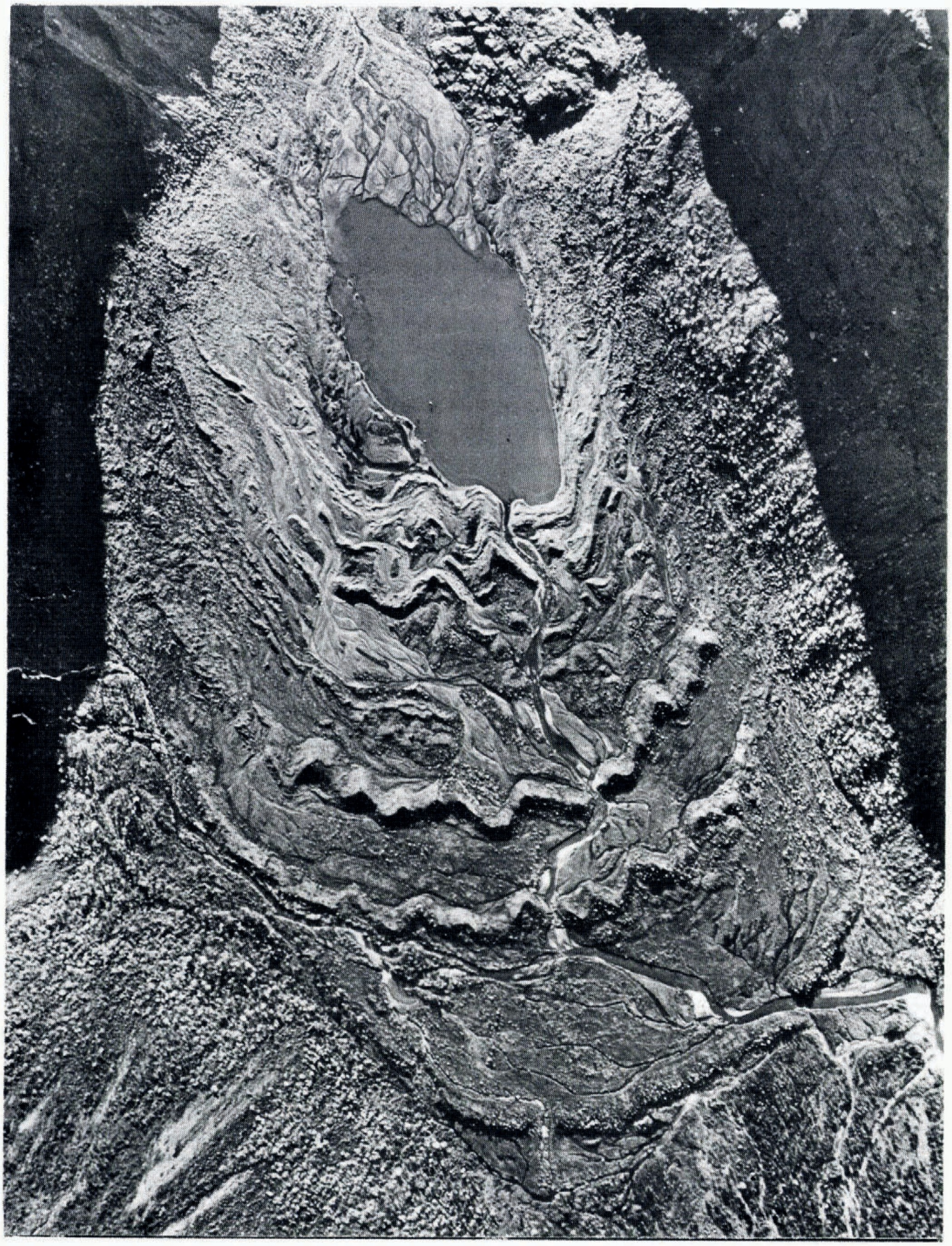

Fig. 2. Vertical aerial photograph of the Bødalsbre glacier foreland showing the saw-tooth moraines. (Photograph by Fjellanger-Widerøe, Oslo, 1962.)

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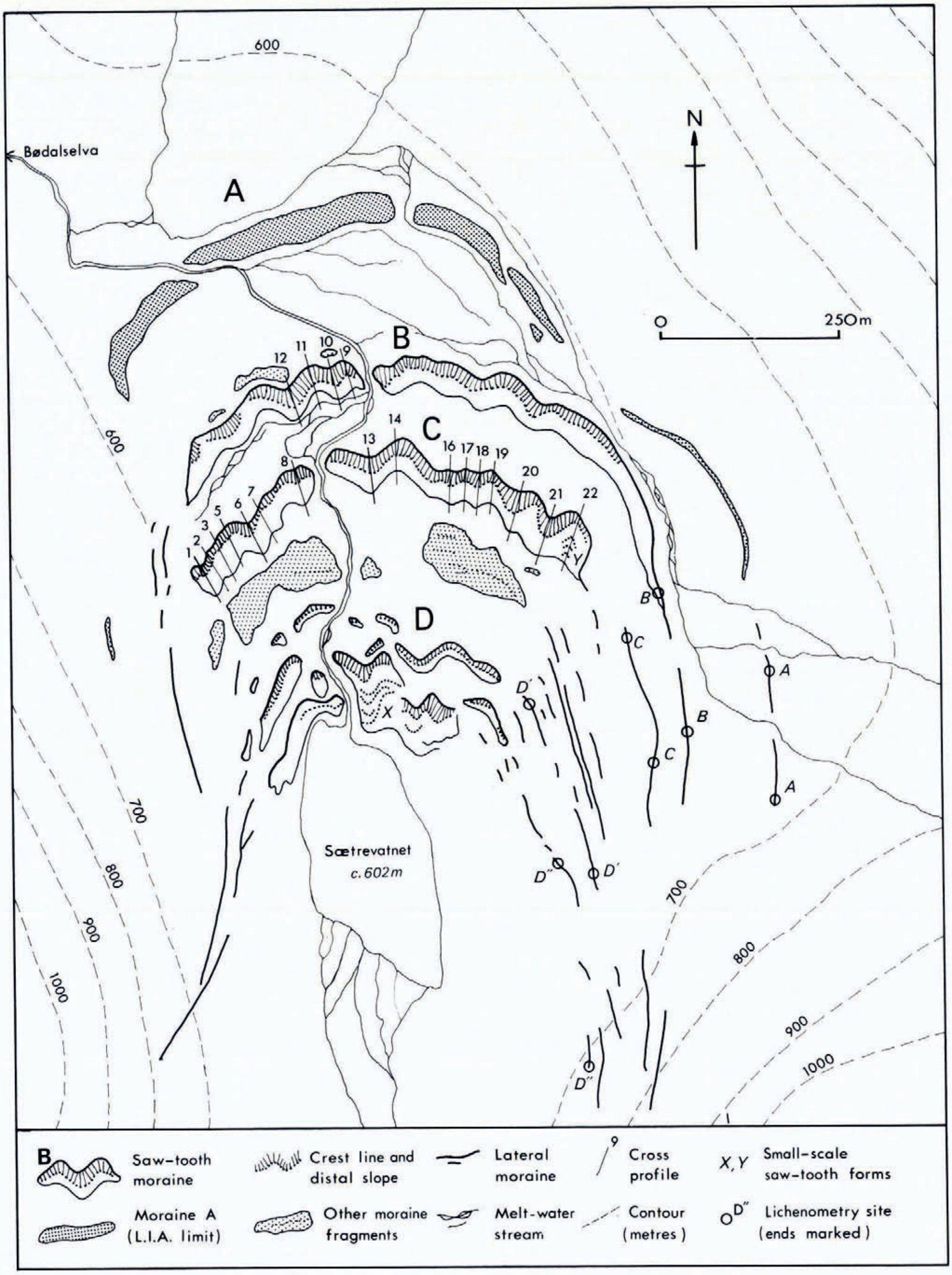

Fig. 3. A morphological map of the Bødalsbre glacier foreland showing the moraines, measured profiles, and lichenometry sites.

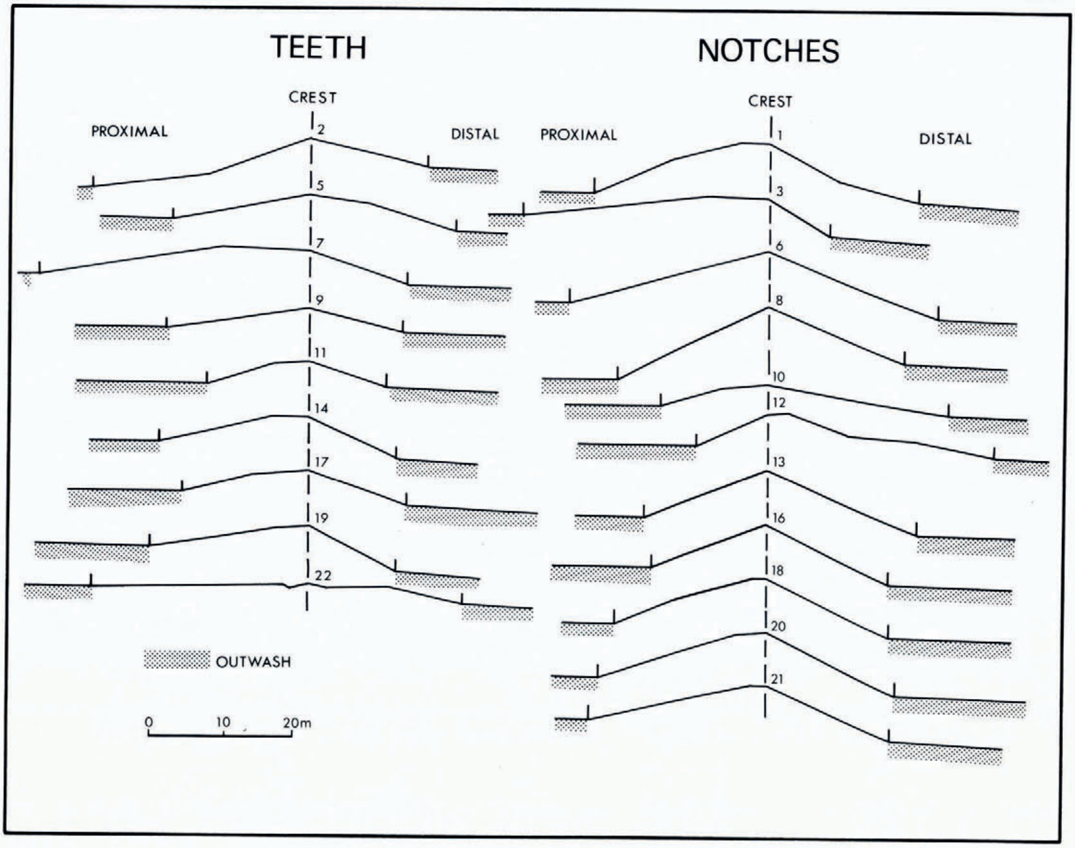

Fig. 4. Measured cross-profiles of saw-tooth moraines in Bødalen.

on the fluvio-glacial outwash deposits between the moraines. Sections of moraine that had been obviously modified by melt water were avoided.

A general picture of the three-dimensional morphology of these moraines can be obtained from the size and shape of teeth and notches, summarized and compared in Table I. The results of both a parametric *t*-test of the difference between two independent means (Blalock, 1960) and the non-parametric Mann–Whitney *U*-test of the difference between two independent sample distributions (Siegel, 1956) are given. From the statistical analyses, and from Figs 2–5, it is clear that there are systematic differences in the form of teeth and notches,

TABLE I. SOME ASPECTS OF THE MORPHOLOGY OF TEETH AND NOTCHES. THE SIGNIFICANCE OF DIFFERENCES IS ASSESSED USING STATISTICAL TESTS APPROPRIATE FOR INDEPENDENT DATA SETS

	Sample size		*Mean*		*Standard deviation*		*Significance of differences*	
Aspect considered	*Teeth*	*Notches*	*Teeth*	*Notches*	*Teeth*	*Notches*	t	U
Height h	9	11	4.7 m	7.4 m	1.4 m	1.7 m	<0.01	<0.01
Proximal slope angle θ_p	9	11	8.4°	17.7°	3.5°	6.7°	<0.01	<0.001
Distal slope angle θ_d	9	11	17.8°	21.2°	6.2°	5.9°	ns	ns
Width w	9	11	37.9 m	41.2 m	9.5 m	4.5 m	ns	ns
Asymmetry A ($= h/w \tan \theta_p$)	9	11	0.60	0.51	0.08	0.14	ns	<0.02

ns = not statistically significant ($p > 0.05$).

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Fig. 5. Saw-tooth moraine C on the Bødalsbre glacier foreland showing teeth and notches and a corresponding undulating crest line. The photograph is taken from the western valley side, towards the north-east.

which are an integral part of the overall morphology of saw-tooth moraines. Notches are higher than teeth, resulting in an undulating moraine crest-line (Fig. 5). Notches also have steeper proximal slope angles, but they do not differ significantly from teeth in their distal slope angles. An index of asymmetry A, which quantifies the centrality of the crest line with respect to the moraine base along each cross-profile (defined in Table I), indicates that teeth are relatively asymmetrical (an index of 0.5 indicates perfect symmetry). At least two characteristics are common to both teeth and notches: these are the steep distal slope and a constant width.

In order to investigate asymmetry further, the powerful parametric t-test of the difference between two *dependent* means (Blalock, 1960) and the non-parametric Wilcoxon matched-pairs signed-ranks T-test (Siegel, 1956) were applied to the differences between matched pairs of proximal and distal slope angles (Table II). These tests confirm the asymmetrical nature of teeth and the symmetry of notches.

Table II. Differences between proximal and distal slope angles for individual profiles. The significance of differences is assessed using statistical tests appropriate for matched pairs of data

Location of profiles	*Sample size*	*Mean difference* deg	*Standard deviation of the differences* deg	*Significance of differences* t	T
Teeth	9	9.4	5.90	<0.01	<0.01
Notches	11	3.5	10.65	ns	ns

ns = not statistically significant ($p > 0.05$).

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One other typical, though small-scale, morphological feature of these moraines is worthy of mention. Small channels, up to about 2 m deep, are found incised into the crests of teeth. These are interpreted as the routes followed by glacier melt water through the moraine at a time when glacier ice was in contact with or close to the moraine (the tips of teeth being the lowest points of the moraine barrier across which melt water could escape).

Moraine chronology

Annual measurements of the position of the glacier snout margin, begun in A.D. 1900 (Fægri, [1950]), indicate that most of the moraine complex D was formed during glacier advances in the first three decades of the present century. The inner ridge of the complex (moraine D″) probably dates from 1932 when a major retreat began. Older records are not available for this glacier, but other outlet glaciers of Jostedalsbreen (e.g. Nigardsbreen) are known to have reached their "Little Ice Age" maxima about A.D. 1750 and to have undergone an intermittent retreat since that time (Fægri, [1950]; Eide, 1955; Hoel and Werenskiold, 1962).

Lichenometric measurements were made on moraine ridges A–D in order to supplement the historical data. Because of insufficient boulder habitats for lichen growth on the saw-tooth sections of moraines B and C, the lichen measurements were made on the lowest parts of the equivalent boulder laterals on the eastern side of the glacier foreland (Fig. 3). The long axes of the largest specimens of *Rhizocarpon geographicum* agg. were measured proximal to the ridge-crest of each moraine (Table III). Moraine A was partly overgrown by birch trees, so that the lichen sizes given for this moraine should be regarded as minimum figures. Measurements relating to the moraine complex D were made on the outer (D′) and inner (D″) ridges of the complex.

Although local conditions for lichen growth appear to be less favourable at Nigardsbreen, data from moraines of known age at that glacier (Rekstad, 1901; Fægri, 1933; Andersen and Sollid, 1971; Østrem and others, 1976) clarify the approximate ages of the Bødalsbre moraines (Table III). A twentieth century date is confirmed for most, if not all, of the moraine complex D. The best-developed saw-tooth moraines (moraines B and C) are shown by lichenometry to be distinctly older, probably dating from the late-eighteenth and early-nineteenth centuries, respectively. Moraine A appears to date from about A.D. 1750.

Table III. Lichen sizes on Bødalsbre moraines and comparable measurements on moraines of known age at Nigardsbreen. The mean of the five largest lichens includes a separate lichen from each of five 25 m lengths of moraine. At Bødalsbreen 250 m were searched on each moraine (summer 1978); at Nigardsbreen 400 m were searched (summer 1975)

Moraine	*Single largest lichen* mm	*Five largest lichens* mm
Bødalsbreen		
A	128	125
B	129	120
C	112	104
D′	60	54
D″	38	37
Nigardsbreen		
A.D. 1750	122	115
A.D. 1873	73	69
A.D. 1909	49	48
A.D. 1930	41	40

MECHANISMS OF MORAINE-RIDGE FORMATION

The extensive literature dealing with the formation of terminal moraines suggests at least five possible alternative mechanisms for their development. These will be considered individually with reference to the saw-tooth moraines.

Formation of moraine ridges by the squeezing of water-soaked till from beneath a glacier snout has been suggested (Gravenor and Kupsch, 1959; Stalker, 1960; Price, 1970). This hypothesis is rejected for the Bødalsbre moraines, because of their scale (up to 9 m in height) in relation to ice thickness at the time of their formation. The position and gradient of lateral moraines associated with saw-tooth moraine B, indicates that ice thickness at the former glacier snout was not very different from its thickness at the present snout of *c.* 15 m (Fig. 6). Further, the regular plan and composition of the saw-tooth moraines suggests that the requirement of a semi-plastic state for the debris is unlikely to have been met.

Rockfalls from valley-side slopes, spurs, and head walls provide material for supraglacial transport of debris, which on reaching a near stationary margin may eventually accumulate to form a ridge (Tarr and Martin, 1914; Loomis, 1970; Reid, 1970; Johnson, 1971). Almost no supraglacial debris is found on Bødalsbreen at present, suitable source areas are lacking, and moraines produced in this manner are unlikely to be of the scale of the Bødalsbre moraines

Fig. 6. The present snout of Bødalsbreen showing the formation of a moraine ridge by pushing of debris in front of the advancing glacier. Note the presence of radial crevasses at the snout. The largest boulders are about 2 m long.

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because stationary phases of a suitable duration are unknown for valley glaciers in southern Norway during the retreat from their "Little Ice Age" maxima.

Shearing, or simply surface melting, at a glacier snout may bring to the ice surface debris bands which may be subsequently deposited as ridges. Formation of the Bødalsbre moraines by this mechanism would require the transference of large quantities of fluvio-glacial debris from the base of the glacier to its terminal zone. It is difficult to envisage this mechanism operating at the required scale, owing to the temperate nature of this glacier. The basal freezing-on concept, developed by Weertman (1961) and applied by Andersen and Sollid (1971) to Nigardsbreen, is more appropriate to polar or sub-polar glaciers, and these are well documented as carrying considerable quantities of englacial debris derived from the glacier bed (Goldthwait, 1951; Bishop, 1957; Donner and West, 1957; Boulton, 1970; Hooke, 1970). Hoppe (1952), Okko (1955) and Boulton (1970) have noted that temperate glaciers generally carry very little basally-derived englacial material, and Lewis (1960) has drawn attention to this point with respect to Norwegian glaciers in particular. These observations are corroborated by those of the present authors at Bødalsbreen, which shows no sign of debris bands or shear planes even though the glacier is currently advancing. Furthermore, there is no evidence to suggest that Bødalsbreen was a less "clean" glacier in the past, in terms of either englacial or supraglacial debris.

Surging of Bødalsbreen provides a fourth hypothesis for consideration, because contorted or convoluted moraines have been associated with surging glaciers (Washburn, 1935; Sharp, 1958; Thorarinsson, 1964; Hattersley-Smith, 1969; Meier and Post, 1969; Rutter, 1969; Clapperton, 1975). Four points indicate that this mechanism did not contribute to the formation of the saw-tooth moraines. First, no surges have been reported for the glaciers of southern Norway, despite the well documented nature of glacier fluctuations in this region and the tendency for surging glaciers to occur together in limited areas. Secondly, there is much evidence to show that the contorted moraines of surging glaciers are en- or supraglacial rather than terminal features. Thirdly, the chaotic assemblage of crevasses often reported for surging glaciers does not accord with the regular pattern of the Bødalsbre moraines. Lastly, preservation of a whole sequence of "Little Ice Age" moraines of varying age would require a series of small-scale surges of decreasing magnitude, which is an unreasonably complex explanation.

The fifth hypothesis suggests that during an advance a glacier can act as a bulldozer and push material into a ridge (Gwynne, 1942; Dyson, 1952; Okko, 1955; Rutten, 1960; Hewitt, 1967; Dahl, 1967; Kälin, 1971). The following reasons, added to the arguments given above in connection with the alternative mechanisms, have led the present authors to accept a push mechanism.

(1) The continuity of the moraine ridges across the valley floor suggests a regular or "controlled" process of formation that was equally effective across the whole width of Bødalen. This aspect of the gross morphology of the features does not conform with the other hypotheses considered above but is compatible with a push mechanism.

(2) The repetition of tooth and notch forms is readily explained by a radial pattern of crevasses at a glacier snout. Bødalen possesses a local topography that is conducive to the formation of a pecten (with associated radial crevasses) over the range of locations in the valley where the saw-tooth forms occur (see below). No mechanism other than pushing is likely to produce such a clear imprint of the ice margin in end moraine form.

(3) The small-scale morphology of teeth and notches supports a push mechanism. In particular, the greater height of notches reflects the accumulation of bulldozed debris in the recesses formed by radial crevasses at the glacier snout, while the lower height of teeth may be explained in terms of debris spreading around the advancing projections of ice between crevasses.

(4) Asymmetrical moraine cross-profiles, with relatively steep distal slopes (characteristic of teeth on the saw-tooth moraines), have been attributed by many writers to a push mechanism, although pushing is not the only mechanism capable of producing asymmetry. The low-angle proximal slopes of teeth are explained here by ice mounting the moraine barrier during formation and/or by processes operative during retreat of ice from the proximal slopes.

(5) The presence of micro-scale saw-tooth forms encountered on some moraine slopes, which mirror the larger forms and parallel their crest-line, is difficult to explain other than by pushing during minor oscillations of the ice margin. Examples of these features are found on the proximal slope of moraine C at its easternmost extremity (Y in Fig. 3), and on the proximal slope of one of the ridges in complex D (X in Fig. 3) where the delicate superimposition of four micro-ridges is preserved.

(6) Embleton and King (1975) noted that the constituent material of push moraines commonly exhibits evidence of tectonic disturbance in the form of faulting and thrusting. A number of exposures in the Bødalsbre moraines showed no signs of such structures. However, the formation and preservation of these structures requires cohesion of the pushed material, which could be produced by a frozen state or by a high content of fines. Neither condition is satisfied at Bødalsbreen, where the climate was not cold enough over a prolonged time period to produce deep freezing, and the fluvio-glacial material was not of a suitable composition. The absence of tectonic structures is thus in accord with a push origin in this instance.

(7) The well-documented records of "Little Ice Age" glacier fluctuations elsewhere in southern Norway indicate that the formation of end moraines has been associated with minor advances during an overall retreat from the "Little Ice Age" limit. This evidence does not preclude some other mechanisms but is in agreement with the push mechanism postulated here.

(8) Bødalsbreen is at present advancing and the western portion of the glacier snout is pushing large boulders into a moraine ridge (Fig. 6). This observation adds weight to the idea of an origin by pushing for moraines B–D, but sheds no further light on the cause of their saw-tooth form because of the present shrunken state of the glacier with consequent differences in snout form and material availability.

(9) Finally, a simple laboratory experiment confirms that pushing can produce analogous saw-tooth forms. Using gentle pressure, an inclined corrugated sheet of hardboard in the form of a wedge was pushed along a tray containing a mixture of fine dry sand and silt. A small saw-tooth ridge with an undulating crest line and a steep distal slope was produced, the cross-sectional form of the model varying according to the manner in which the wedge was advanced and retracted.

Conclusion

It is considered that the saw-tooth moraines in Bødalen were formed in the following way. On advancing into the wider part of the valley, Bødalsbreen fanned out, thinned, and flowed across the gently sloping outwash plain. Fluvio-glacial deposits were pushed up at the limit of the "Little Ice Age" advance (moraine A). During subsequent retreat, lateral tension, combined with the relative thinness of the ice, caused the development of radial crevasses at the glacier snout, and hence the formation of a pecten. The pecten persisted during minor advances between the late-eighteenth and early-twentieth centuries, when the fluvio-glacial deposits were pushed up into the saw-tooth ridges (moraines B–D). The pecten form of the glacier snout is thus essential for the production of such an unusual morphology.

This schema explains the distinct morphological differences between moraine A and the remaining moraines, and between the terminal and lateral sections of moraines B–D. Where the saw-tooth pattern is not developed, the moraines are in close proximity to valley-side slopes. The constriction of the expanded glacier limited the divergent spreading of the ice during minor advances and the maintenance of radial crevasses.

The Bødalsbre end-moraine sequence is of interest in itself but also has important implications for the study of end moraines elsewhere. For this sequence, many of the recognized possible modes of moraine formation have been eliminated. This has been conditional upon the unique morphology of the moraines and the particular topography of Bødalen. Where moraines are neither unusual nor well-preserved, it may not be possible to infer process from form to such an extent. Failing clear evidence to the contrary, workers studying other moraines have often preferred other mechanisms to pushing. The clear applicability of pushing in front of Bødalsbreen demands that greater consideration be given to this mechanism.

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