

Formation of saw-toothed moraines in front of the Bødalsbreen glacier, western Norway

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Several large end moraines with a distinct 'saw-tooth' form were deposited in front of the Bødalsbreen glacier during the Little Ice Age. It is concluded that the marginal moraines were formed by material being pushed into ridges during glacier advances. The saw-toothed shape of the terminal moraines is caused by the local topography of Bødalen.

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Bødalen is a tributary valley to Lodalen in the inner part of Nordfjorden, western Norway. The Bødalsbreen glacier, a westerly outlet of the Jostedal Ice Cap, is situated in the upper part of the valley. During the Little Ice Age, about A.D. 1750, numerous larger and smaller marginal moraines were deposited on the valley floor, up to 1.6 km from the front of the present glacier.

Several of these terminal moraines have a distinct, 'saw-tooth' shape (Figs. 1 & 2). These particular moraine ridges have previously been discussed by Matthews et al. (1979), Rye et al. (1984) and Lien (1985). The authors have not found this type of end moraine described from other parts of the world.

Morphology and composition of the moraine ridges

The terminal moraine, A in Fig. 1, is smoothly curved like most end moraines in front of other valley glaciers. The end moraine is between 1.5 and 4 m high. Proximal to moraine A are a number of saw-toothed moraines. End moraines B and C and the moraine complex D are the largest, 7–9 m high, while smaller ridges in between are more or less buried by glaciofluvial material deposited by lateral meltwater streams.

Terminal moraines B and C have been analysed morphologically by Matthews et al. (1979). They measured twenty transverse profiles, mainly on moraine C, which is the best developed. The data

show that the ridges at outer apices of the saw-toothed moraines have a height of 4–5 m, with a gently sloping proximal side and a steep distal side. The ridges at the inner apices, pointing towards the Bødalsbreen glacier, have a more symmetrical form and are 7–9 m high (Figs. 3 & 2b).

Smaller moraine ridges (20–30 cm high) are found superimposed on the proximal side of the larger end moraines in the eastern part of C and the moraine complex D. The lateral moraines are smaller than the end moraines (1–1.5 m high) and often consist of boulder material only (Fig. 4). They are rarely continuous for more than 200–300 m and have a distinct ridge form. In some of the ridges the boulder size increases towards the glacier.

Grain-size distribution has been determined in till from the terminal moraines. This has also been done on the glaciofluvial material deposited between the moraine ridges (Figs. 1 & 5) (Lien 1985). Most of the morainic samples show a grain-size distribution similar to that found in till in other parts of the country (Jørgensen 1977; Voren 1977). A smaller moraine ridge on the distal side of moraine complex D (Figs. 1 & 5, sample 18) differs from the others, as it consists of well-sorted sand and silt.

Lateral meltwater drainage along the glacier front took place throughout the Little Ice Age (Fig. 1). Lateral meltwater streams directed towards the middle of the valley floor by previous formed terminal moraines, have deposited debris and thus buried several smaller moraine ridges.

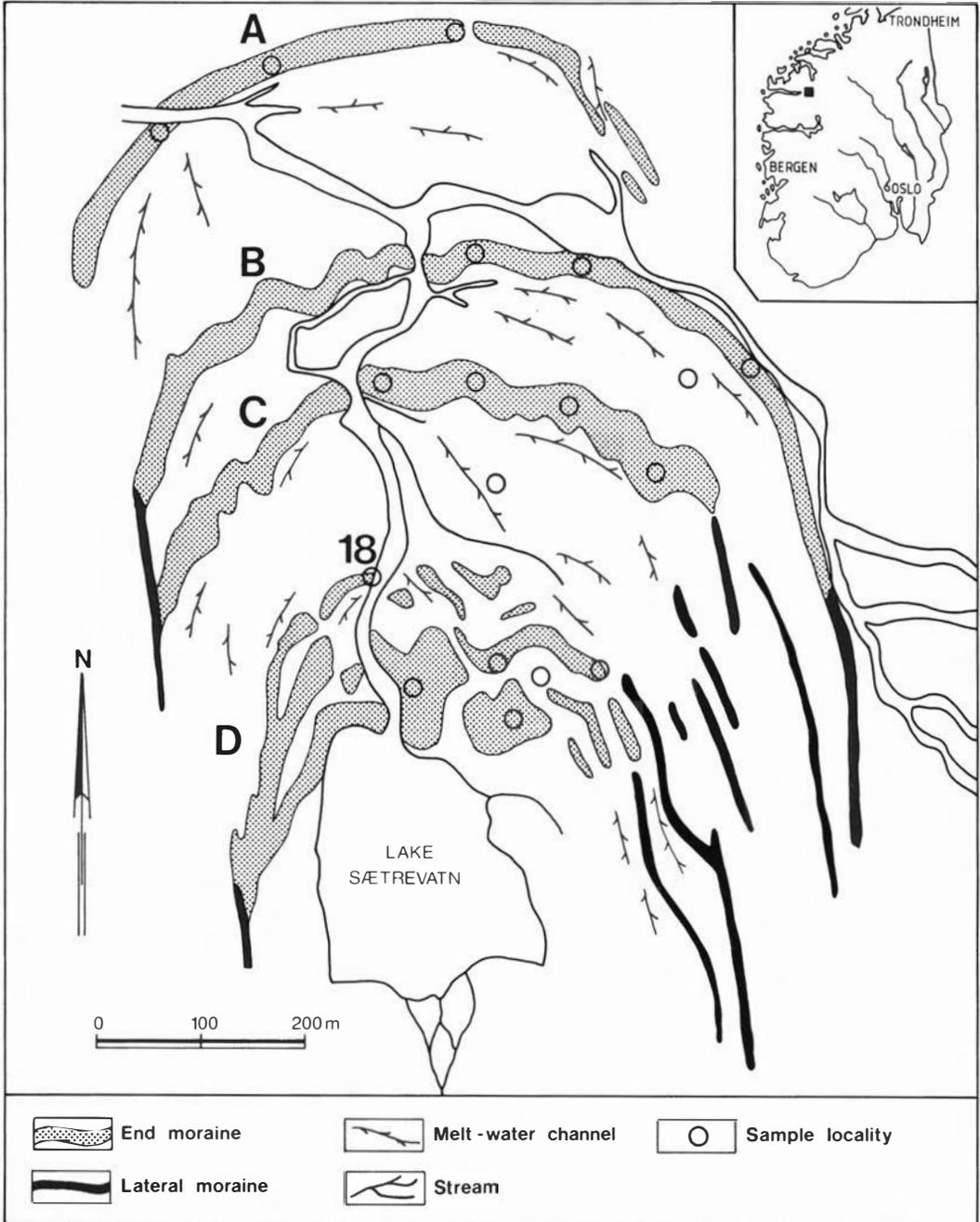


Fig. 1. Little Ice Age moraines in front of the Bødalsbreen glacier, western Norway.

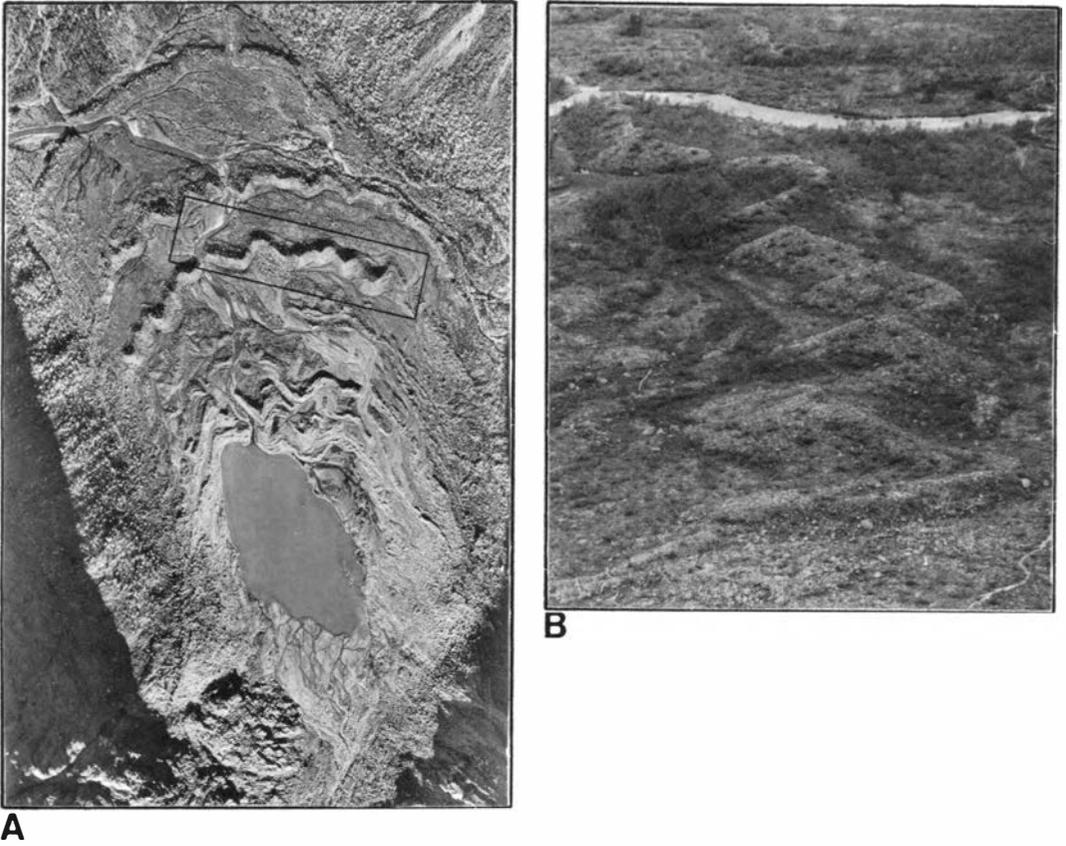


Fig. 2. (a) Saw-toothed moraines in front of the Bødalsbreen glacier. Photo: Fjellanger-Widerøe. (b) Framed part of (a).

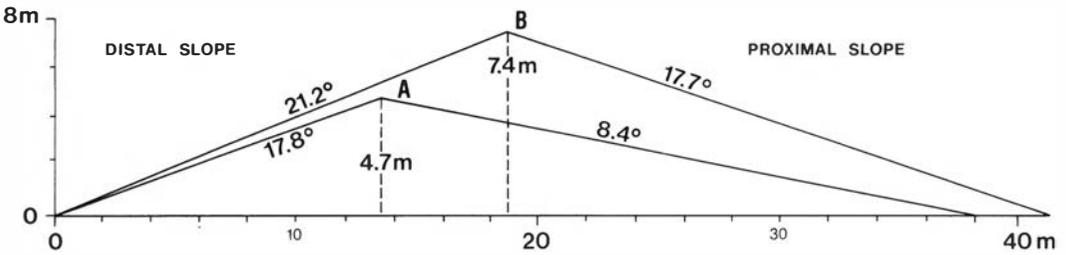


Fig. 3. Schematic outline of the cross-sections in the saw-toothed moraines measured by Matthews et al. (1979) showing average dimensions of ridges at their outer (A) and inner (B) apices.



Fig. 4. Boulder-rich lateral moraine. The ridge is 1–1.5 m high.

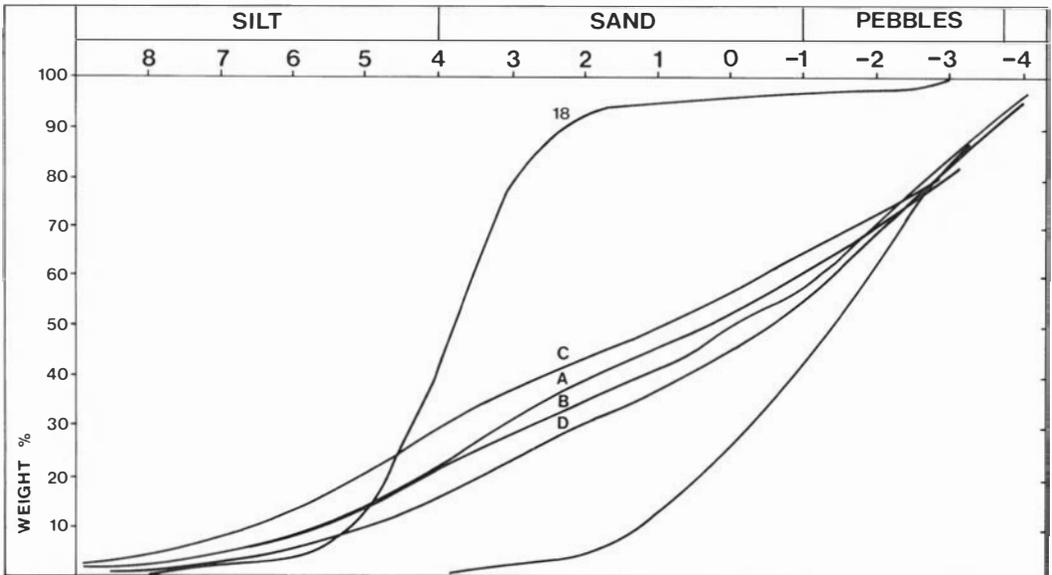


Fig. 5. Some typical grain-size distribution curves (material < 16 mm). The lowermost curve shows grain-size distribution of glaciofluvial material. The letters refer to the end moraines.

Chronology

Lichenometric measurements on the marginal moraines made by Matthews et al. (1979) indicate that moraine A was formed during the maximum of the Little Ice Age, during the period A.D. 1740–1750. A description of the position of the glacier front by Seue (1870) and a photograph taken by Knudsen (1872, Fig. 6) show that terminal moraines A–C had already been formed at that time.

Measurements of frontal fluctuations of the Bødalsbreen glacier during the period 1900–1947 (Fægri 1950) and photographs by Rekstad (Photo Archive, Norges geol. unders.) indicate that two terminal moraines of the moraine complex D were formed in 1912 and 1930, respectively.

The lichenometric measurements made by Matthews et al. (1979) support this, and indicate that the terminal moraines B and C may have been formed at about 1770 and 1820, respectively (Fig. 7).

Process of formation of the end moraines

Terminal moraines can be formed through: (a) glacier advances pushing up material in front of the glacier, (b) melt-out and flow till deposited at the glacier front, and (c) water-soaked till being squeezed into ridges by the weight of overlying ice.

Terminal moraines deposited during glacial advances are usually large and form distinct ridges. The other processes generally result in small or poorly marked ridge forms.

Goldthwait (1951) and Bishop (1957) have described marginal moraines formed by till melting out at the glacier front. Through this process the fine material may be washed out by glacial meltwater (Goldthwait 1951), even though this does not always happen. At the Bødalsbreen glacier this sorting of the material has not taken place, and the terminal moraines here are very rich in fine material.



Fig. 6. Bødalsbreen glacier in 1872. The picture shows that end moraines A, B and C have been formed. The glacier front is heavily indented by several longitudinal crevasses. Photo: K. Knudsen. Photo Archive, University Library of Bergen.

It takes ice rich in englacial material to create terminal moraines of some size by ablation at the glacier front. Bishop and Goldthwait carried out their research on polar glaciers, which are generally rich in englacial debris. Goldthwait (1951) concluded that parts of the Barnes Ice Cap, rich in englacial debris, needed 25 years to supply material sufficient to form a 4–5 m high marginal moraine. Temperate glaciers like the Norwegian ones usually carry only small amounts of englacial material (Hoppe 1952; Okko 1955; Lewis 1960; Boulton 1970). The Bødalsbreen glacier of today is almost devoid of englacial debris, and the photographs taken by Knudsen (Figs. 6 & 8) and Rekstad (Photo Archive, Norges geol. unders.) show that also in earlier times the glacier carried very little englacial material. Thus the ice-front must have been stagnant for a very long time in order to deposit material sufficient to form moraine ridges between 1 and 5 m high by the

melt-out process. The ice-front of the Bødalsbreen glacier is not likely to have been stagnant for such a long period of time (Fig. 7).

Material needed to form ablation moraines may also be transported to the glacier by debris avalanches from the valley sides (Tarr & Martin 1914; Loomis 1970; Reid 1970), but such moraine ridges are normally quite small and contain little fine material. Due to ablation at the glacier front, the glacier flow-lines will have a radial pattern from the centre-line of the glacier, and most of the debris will be deposited laterally (Boulton & Eyles 1979). This is not the case at the Bødalsbreen glacier, where most of the material is deposited in front as end moraines, not as lateral moraines. The material in the moraine ridges is regularly distributed. A discontinuous input of avalanche debris would cause an irregular distribution. Besides, there are no source areas in the valley sides for avalanches with sufficient debris.

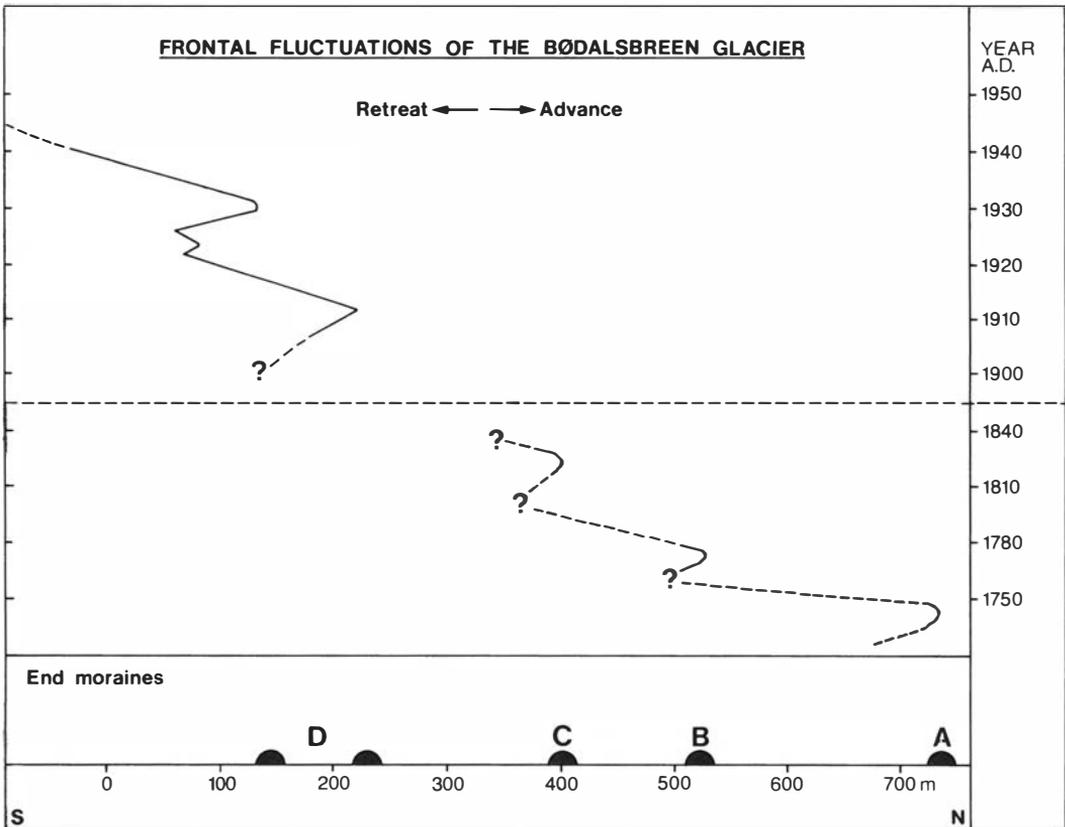


Fig. 7. Time-distance diagram showing the frontal fluctuations of the Bødalsbreen glacier during the Little Ice Age. The diagram is based on lichenometry for the period before A.D. 1900, and measurements of the glacier front after A.D. 1900.

Goldthwait (1951) describes the ablation moraines as low and non-distinct ridge forms, while the end moraines in front of the Bødalsbreen glacier are high and distinct ridge forms. Ablation material from the glacier front cannot explain the contrast between the large end moraines and the small boulder-rich lateral moraines.

Terminal moraines can also be formed by water-soaked material being forced upwards at the glacier margin, due to the weight of the overlying glacier (Hoppe 1952; Price 1970). Matthews et al. (1979) claimed that the end moraines in Bødalen cannot have been formed in this way, because they contain very little fine material. On the other hand Price (1970) mentions moraine ridges 1–2 m high in Iceland, concluding that they have been created by water-soaked till being squeezed up at the glacier front. The till of these moraine ridges contains less than 9% silt/clay (<0.05 mm). In Bødalen almost all till samples contain more than 15–16% silt/clay (<0.063 mm, Fig. 5). If Price's (1970) conclusion is correct, it should be possible to form terminal moraines by squeezing up water-soaked material in front of the Bødalsbreen glacier as well. It is not likely, however, that the Bødalsbreen glacier was thick or heavy enough to squeeze out terminal moraines up to 9 m high. This theory does not explain the contrast between the large terminal moraines and the small lateral moraines; nor does it explain the genesis of the bouldery lateral moraines. In fact, some of the lateral moraines have been deposited on bedrock.

There are several features which indicate that the saw-toothed moraines in front of the Bødalsbreen glacier were formed by a push mechanism. The well-sorted material in the end moraine distal to moraine complex D is interpreted to be glaciofluvial material that has been pushed into a ridge form. The glaciofluvial material must have been deposited in front of the glacier by lateral meltwater streams prior to glacier advance. The bouldery lateral moraines have a very distinct ridge form and the boulders must have been pushed up in front of an advancing glacier. The boulders probably formed an erosion residual (lag deposit) on the bottom of lateral meltwater streams prior to advances of the glacier.

On the terminal moraines some large boulders with diameters up to 2–3 m seem to have been pushed into position. If they had melted out of the ice front, one would also expect to find single boulders between the terminal moraines,

but this is not the case. The contrast between the large terminal moraines and the small lateral moraines indicates that the process of formation was more active longitudinally.

Smaller ridges superimposed upon the proximal side of the larger end moraines, as found on moraines C and D, are commonly said to indicate that the terminal moraines were formed during several advances (Cowan 1968; Mottershead & Collin 1976). The numerous small lateral moraines connected to moraines C and D suggest the same. The historical data and the lichenometric measurements suggest that the two terminal moraines of complex D were formed during glacier advances up to 1912 and 1930, respectively (Fig. 8). The glacier front stayed at these positions for a period of 3–5 years. This supports the opinion that the moraines were formed over several years, e.g. by glacier advances during winter time (Worsley 1974; Birnie 1977; Boulton & Eyles 1979; Rabassa et al. 1979; Rogerson & Batterson 1982).

Numerous large terminal moraines in front of other outlets of the Jostedal Ice Cap have been formed during glacier advances (Rekstad 1900, 1901; Andersen & Sollid 1971; Embleton & King 1975; Mottershead & Collin 1976). During the years A.D. 1930–1960 there was a period of general glacier retreat and terminal moraines were usually not formed in this period.

Terminal push-moraines which are formed in areas with permafrost can have vast dimensions. Usually they also have inner structures indicating that they consist of thrust sheets of frozen material (Gripp 1938; Rutten 1960; Kälin 1971; Ahmad 1979). Such structures have not been found in the unsorted material of the terminal moraines in front of the Bødalsbreen glacier. There is therefore no reason to suggest that the material in front of the glacier was frozen prior to the glacier advances. Frozen material would also have prevented the development of the distinct saw-toothed form of these end moraines.

Seue (1870) described a highly crevassed ice front (Fig. 6). During advances the material in front of the glacier will accumulate in the crevasses and create moraine ridges of variable height.

On the basis of the field observations, old photographs, measurements of the fluctuations of the glacier front and the lichenometric measurements, it is concluded that the marginal moraines in front of the Bødalsbreen glacier were formed



Fig. 8. The Bødalsbreen glacier forming a saw-toothed moraine. Material is concentrated in a crevasse. The protruding parts of the glacier are overriding parts of the end moraine. Photo: K. Knudsen, 1872. Photo Archive, University Library of Bergen.

by a push mechanism during glacier advances. This is supported by the historical data from other parts of the Jostedal Ice Cap.

End moraines often have a complex genesis, and the process of ablation or squeezing cannot be totally excluded in forming the end moraines in front of the Bødalsbreen glacier. Nevertheless, old descriptions and photographs show that Norwegian glaciers carry very little englacial material, which is necessary to build a marginal moraine by the melt-out process. The Bødalsbreen glacier, and Norwegian glaciers in general, are carrying very little englacial material today. The melt-out process is therefore regarded as very insignificant in building the marginal moraines in front of the Bødalsbreen. The process of squeezing up material in front of the glacier may have taken part in building up the end moraines, but the glacier front was hardly so thick/heavy that it could result in 7–9 m high ridges. As mentioned earlier in the text, the blocky lateral

moraines of which several rests on bedrock, can hardly have been built up by other processes than pushing by an advancing glacier. Even though the squeezing process may have been active in the end moraine part, the building of the marginal moraines as a whole is clearly dominated by the process of pushing by an advancing glacier.

Grain-size distribution of the material composing the end moraines is similar to that found in till from other parts of Bødalen (Lien 1985) and the country (Jørgensen 1977; Vorren 1977). Clast roundness analyses show no difference between till and glaciofluvial material due to the short transportation length (Lien 1985). In the western part of the valley bottom, distally to moraine A, the ground is covered by till, while the rest of the valley bottom and the areas between the end moraines are covered by glaciofluvial deposits. The small end moraine distally to moraine complex D and some of the bouldery lateral moraines are interpreted to be composed

of earlier deposited glaciofluvial material. The extensive outflow of glacial meltwater and deposition of glaciofluvial material between the end moraines taken into account, it seems reasonable that the large end moraines are at least partly composed of glaciofluvial material. The grain-size distribution analysis indicates that till material dominates in the end moraines.

The shape of the end moraines

During the Little Ice Age the Bødalsbreen glacier advanced down to the more level part of Bødalen. At the present glacial lake the valley becomes wider and the glacier front could spread out when it reached this position. This lateral extension led to the development of numerous longitudinal, wedge-shaped crevasses which gave the front of the Bødalsbreen glacier a saw-toothed appearance. During forward pushes the material in front of the glacier was bulldozed and collected into the crevasses, thus creating the unusual moraine forms in Bødalen (Fig. 8).

The protruding parts of the ice front advanced upon and levelled out parts of the moraine ridges, so that these parts are lower than those at the crevasses. All in all there has been an inward concentration of material in the wedge-shaped crevasses, and an outward spreading at the protruding parts. In this way the local topography has caused the unique saw-toothed form of some of the end moraines in front of the Bødalsbreen glacier. During the formation of moraine A the glacier filled the entire valley floor, and the crevasses were closed. Thus moraine A has the smoothly curved form normally found in terminal moraines in front of other valley glaciers.

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