Frost weathering and rock platform erosion on periglacial lake shorelines: a test of a hypothesis

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Matthews et al. (1986) hypothesised that rock platforms around a short-lived ice-dammed lake margin in Jotunheimen, southern Norway, had been rapidly eroded mainly through frost weathering associated with lake-ice development. They proposed a general model accounting for the development of the rock platforms in terms of deep penetration of the annual freeze-thaw cycle, the movement of unfrozen lake water towards the freezing plane, and the growth of segregation ice in bedrock fissures below lake level. This paper presents a test of this hypothesis by observations of the shoreline of the present-day lake, which has been maintained at a lower, stable level since about A.D. 1826 when the ice dam was removed. The presence of cliff and platform development at the present lake shore supports and improves the hypothesis. For the modern platform, width measurements (mean 3.6 m, range 1.5–5.75 m) are similar to those for the relict platform, whereas calculated erosion rates (mean 2.2 cm/year, range 0.9–3.6 cm/year) are overall slightly lower. The depth of water (0.9 m) at the cliff–platform junction suggested for the formation of the relict platform is modified to 0.6 m in the light of the present results. Implications of the results for the formation of the Norwegian strandflat are discussed.

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It has recently been hypothesised by Matthews et al. (1986) that fossil rock platforms around the margins of a former short-lived ice-dammed lake (Bøverbrevatnet) in Jotunheimen, southern Norway were rapidly eroded primarily through frost weathering (frost shattering, frost wedging, frost riving or macro-gelivation) below lake level in association with lake-ice. Preliminary observations of the margins of a number of other lakes at similar altitudes in the neighbouring Sognefjell area have revealed well-developed cliffs and associated planated platforms up to 15 m wide, but since these lakes have probably been at about their present levels since deglaciation in the Preboreal Chronozone, they provide unsuitable sites for assessing the validity of the high rates of platform extension by frost weathering (up to 7.1 cm/year) attributed to the relict lake shoreline by Matthews et al. (1986). Lichenometry, however, indicates that the modern Bøverbrevatnet has been at its present lower, stable level for only about 160 years, a sufficiently brief existence for testing the validity of the frost weathering hypothesis. The present shoreline of Bøverbrevatnet encounters bedrock in restricted areas on the northern and southern shores, and initial inspection showed that here the bedrock had indeed been distinctly notched. Furthermore, cross-profiles measured perpendicular to the shore confirmed the presence of a distinct platform below lake level. The purpose of the present study was therefore to test the details of the semi-quantitative model developed by Matthews et al. (1986) from the original frost weathering hypothesis, and in particular to compare the modern and relict shorelines in terms of four aspects: (1) width of the platform; depth below lake level at (2) the cliff–platform junction, and at (3) the outer edge of the platform; and (4) the rates of platform extension.

Setting

Bøverbreen (8°05′E; 61°33′N) forms the western outlet of the Smørstabbreen ice cap (Fig. 1a). Bøverbrevatnet lies c. 1 km from the glacier snout at an altitude of 1374 m. Meteorological data from nearby Fanaråken (2062 m) allow estimates to be made of mean annual temperature (1.2°C) and

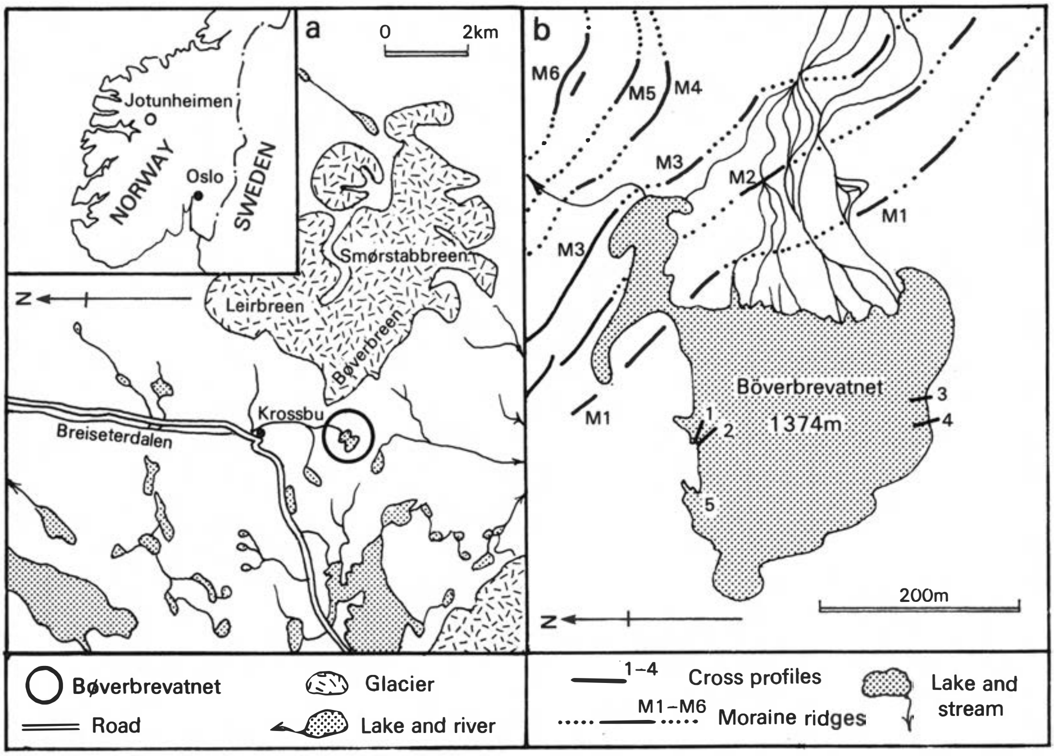

Fig. 1. (A) Location of Bøverbrevatnet, western Jotunheimen, Southern Norway. (B) Map of Bøverbrevatnet, the end moraine sequence and measurement sites (see text).

mean annual precipitation (ca. 1000 mm) at the site. The bedrock comprises partly mylonitised gabbros of the north-west boundary fault zone of the Jotunheimen massif (Battey & Brynhi 1981; Gibbs & Banham 1979).

During the 'Little Ice Age', Bøverbreen advanced into Bøverbrevatnet, with the glacial maximum being reached about A.D. 1750 and marked by the outermost (Ml in Fig. 1b) of a series of moraines. This advance dammed the lake such that its level rose by ca. 3 m and was controlled by an overflow col on the north-western side of the lake. Following retreat of the glacier beyond moraine M3 in Fig. 1b, the lake level lowered and has subsequently been controlled by an outlet via this moraine.

Previous work at ice-dammed Bøverbrevatnet

Whilst in Matthews et al. (1986) consideration was given to a range of lake-shore phenomena together with changes in ice marginal drainage during glacial retreat, the main focus of interest was the lake-shore rock platform, its dimensions and rate of extension. Here, a brief summary of results relevant to this paper only is given, and the reader is referred to Matthews et al. (1986) for more detailed information, particularly on methodological and dating problems. Lichenometry was carried out above and below the relict lake shoreline and on the moraines (Matthews et al. 1986). With reference to lichenometric curves previously published for Storbreen ca. 10 km to the east (Matthews 1974), the lichen size data from the shoreline gave predicted dates for the drainage of the lake ranging from A.D. 1822 to A.D. 1830 with a mean predicted data of A.D. 1826. A similar date for lake drainage is indicated by lichen sizes for moraine M3 (the youngest moraine in which the relict shoreline is eroded) and moraine M2, with mean predicted dates of A.D. 1817 and A.D. 1830 respectively. ^{14}C dating of organic material above and below lacustrine silts indicated that only during a short period in the 'Little Ice Age' could the level of Bøverbrevatnet have reached the height of the relict shoreline. Combined with the available historical evidence of glacier variations in southern Norway, these data indicate that glacier retreat from M1 to M3 took ca. 75 years whereas the previous glacier advance over the same ground was probably more rapid (cf. Hoel & Werenskiold 1972; Østrem et al. 1976). Hence 50 years was considered a reasonable period for glacier advance. It was therefore concluded that ice-dammed Bøverbrevatnet existed for between a minimum of 75 and a maximum of 125 years.

Along the north-western and south-western former shores of the ice-dammed lake clear notches had been produced giving rise to small cliffs and platforms (1.7–5.3 m in width). The latter mostly comprise *in situ* shattered bedrock and are mantled for the most part with angular rock fragments (Fig. 2) which were inferred to have been produced by the frost shattering process and subsequently moved by lake-ice pushing and pulling to form 'pavements'. Calculated rates of erosion indicated that platform extension occurred at a mean rate of 2.6–4.4 cm/year (maximum 4.2–7.1 cm/year), the ranges corresponding to calculations based on whether a 75 or 125 year period for the existence of the lake was assumed. A semi-quantitative model of rock platform development by frost shattering at the interface between lake-ice and bedrock was formulated with planation occurring over a relatively narrow height interval defined by optimal moisture and temperature conditions for frost shat-

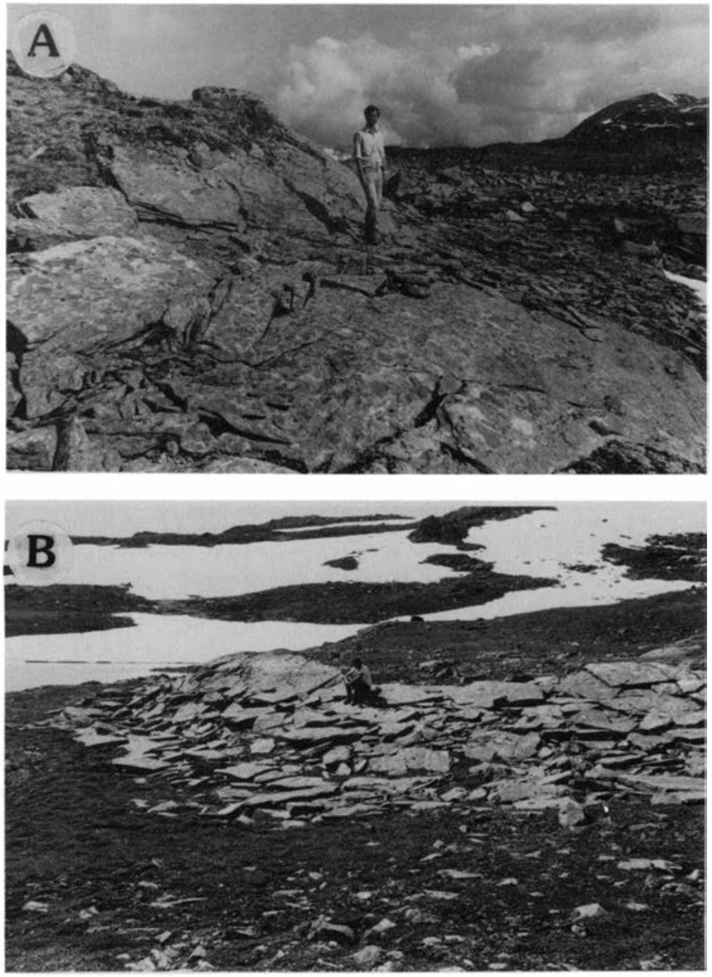

Fig. 2. (A) The relict cliff and platform developed at the former ice-dammed margin of Bøverbrevatnet. Note the frost-shattered bedrock (foreground), the cliff (behind the figure) and the mantle of angular debris on the platform in the background. (B) Large angular slabs produced by lake-ice frost-weathering on the former ice-dammed margin of Bøverbrevatnet. Figure is seated at approximately the former lake level. Note the level of the modern lake (left).

tering. Maximum predicted ice thickness was calculated using the Stephan formula (Harris 1981) at 1.4 m for estimated 'Little Ice Age' temperatures and, assuming this to correspond to the depth of the outer (offshore) edge of the platform, the inner edge of the platform (cliff-platform junction) was calculated to lie about 0.9 m (range 0.6–1.2 m) below the surface of the lake. Cliff height averaged 1.3 m (range 1.1–1.6 m), which indicated that the whole of the platform, the majority of the cliff and the locus of frost weathering lay below the surface of the lake.

The previous work also led to the suggestion that lake shoreline frost shattering may be viewed as an analogue for the erosion of coastal rock platform in modern polar seas and during the Late Glacial and earlier Pleistocene in mid-latitude areas (Dawson et al. 1987). It may therefore be viewed as relevant to the problem of the strandflat, the most recent review of which places considerable emphasis on the role of frost action (Larsen & Holtedahl 1985).

Cliff–platform development along the modern shore

Four sites were selected for measuring cliff–platform development on the northern and southern bedrock shorelines, cross-profiles being measured

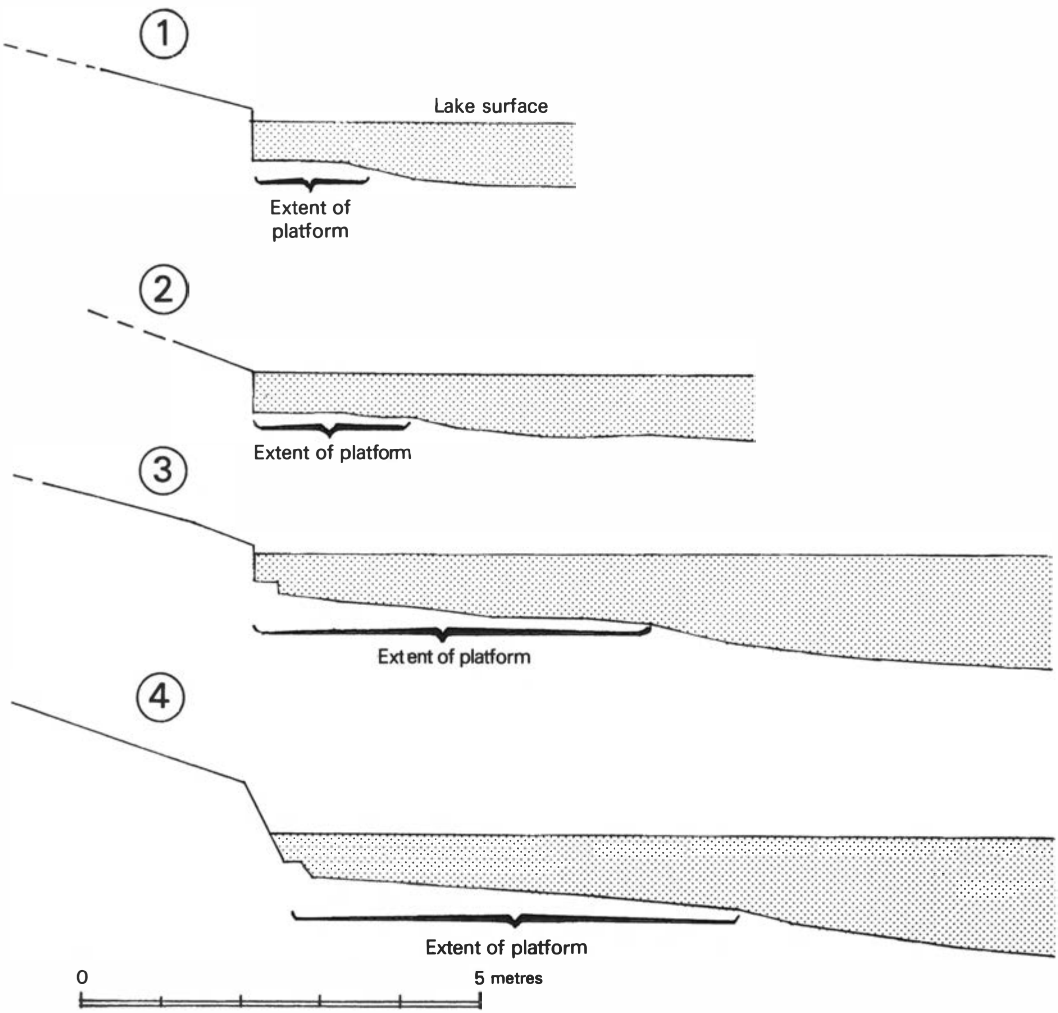

Fig. 3. Cross profiles of the present lake shoreline of Bøverbrevatnet. No vertical exaggeration.

to breaks of slope above lake level and at 0.5 m intervals below lake level by a simple bathymetric survey from a small inflatable dinghy (Figs. 3 and 4). The validity of the original hypothesis is tested by comparing the modern and relict shore platforms in terms of platform width, lake depth at the cliff-platform junction and at the outer edge of the platform, and the rates of platform extension.

The range in width of the modern rock platform (Table 1) (measured from cliff–platform junction to outer edge) differs little from that of the relict platform (mean 3.3 m, range 1.7–5.3 m). On the other hand, depth below lake level of the modern cliff–platform junction is consistently rather low by comparison with the estimated 0.9 m for its relict counterpart. This greater depth was supported for the latter by other measures regarded as indicative of the former lake level (i.e. upper limit of 'lichen kill' and lower limit of large lichens). Depths below lake level of the outer edge of the modern platform are similarly low when taking account of a calculated maximum depth of lake ice of 1.2 m at present day temperatures using the Stephan formula. These discrepancies may be explained in terms of one or more of the following points. First, the predicted 0.9 m depth for the cliff–platform junction was recognised as a maximum estimate and explicitly identified as a possible overestimate by Matthews et al. (1986). Second, the lichen limits recognised on the relict shoreline could well have been affected by factors operating above lake level, such as abrasion by expanding lake-ice, late snow-lie at the lake margin or rock flour deposition through wave action. Third, the level of the lake between freeze-up and break-up, when frost-weathering

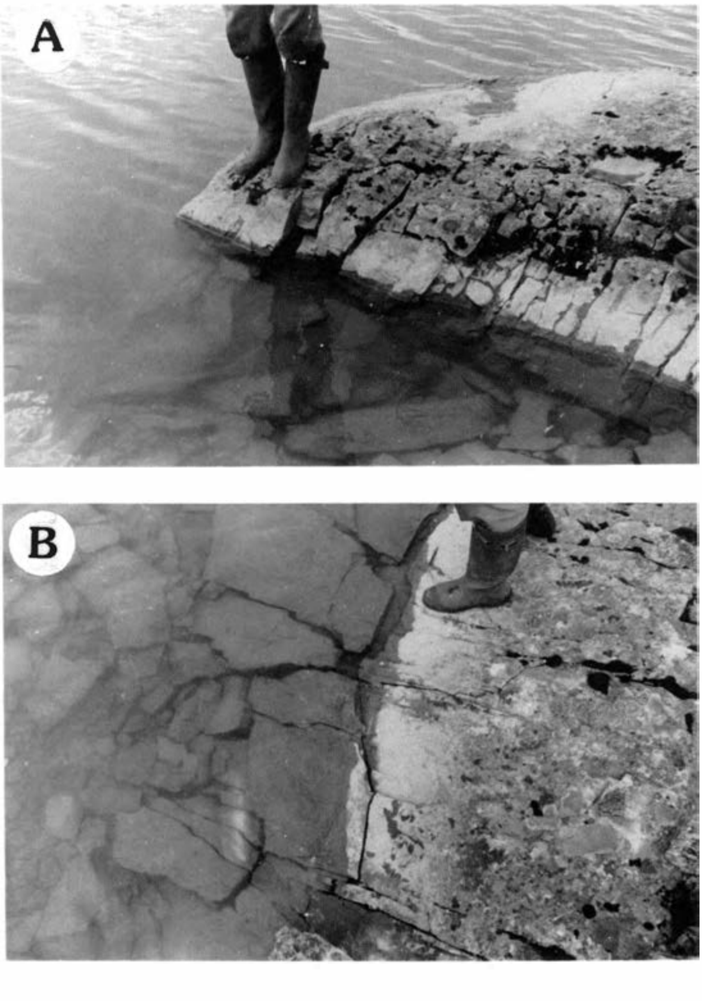

Fig. 4. (A) Cliff formation at present lake level with angular slabs below lake level, both resulting from frost-weathering. Note that the cliff appears to be in the process of being undercut by frost weathering. (B) *In situ* shattered bedrock at the present day lake margin. Note the relatively unaffected nature of the bedrock above lake level.

Table 1. Measurements and estimated erosion rates for the modern rock platform, Bøverbrevatnet.

Profile	Platform width (m)	Depth at cliff-platform junction (m)	Depth at outer edge of platform (m)	Erosion rate (cm/year)
1	1.5	0.62	0.69	0.94
2	2.0	0.51	0.64	1.25
3	5.0	0.52	0.88	3.12
4	5.75	0.56	0.88	3.59
$\bar{x}$	3.6	0.55	0.77	2.23

would have occurred, may well have been lower than the lake level controlling the lichen limits, a possibility which is supported by the presence of a 'lichen-free' zone at the margin of the present lake at periods of abnormally low water in summer (cf. Fig. 4). Fourth, the turbidity of the lake water prevented establishment of the nature of the platform beyond a short distance from the cliff, whether intact bedrock, *in situ* frost-shattered rock or mantled with angular debris. Certainly, near the cliff at all four sites, angular debris covered the platform beneath. In view of the nature of the limited extent of the relict shoreline and observations of other lakes in the area, the platform, with the exception of the near-cliff zone where water depths to bedrock were established, could well lie at a greater depth than that depicted in Fig. 3.

Little can be deduced from a comparison of the depths below lake level of the outer edges of the relict and present day platforms in view of the probable mantling of frost-shattered debris on the latter whereas any such mantle could be avoided when analysing the former. Indeed the shallower angles on the present day (2–5°) compared with the relict (5–12°) platform suggest that there may well be a mantle of debris on the outer edges of the modern platform.

Erosion rates for the present day platforms tend to be rather less than those for the relict platform (means 2.6 and 4.4 cm/year, range 1.4 to 7.1 cm/year) especially when compared with the higher values which relate to the minimum (75 years) duration estimated for the existence of the former ice-dammed lake. One explanation for these low rates is that they are influenced by certain differences in the nature of the bedrock shorelines, which may include the density and dip of bedrock joints and the angle of the bedrock shore. This explanation is supported by the existence of a particularly broad expanse of shattered rock just below lake level at site 5 (Fig. 1), where there is no cliff development as a result of the shallow angle of the bedrock shore, but the rock has clearly been shattered across a width in excess of 8 m. Another explanation concerns what are possibly critical temperature differences affecting the ice-dammed and modern lakes. Not only were mean annual temperatures on average about 1–2°C lower during the 'Little Ice Age' (Matthews 1976, 1977), but also at this time glacial meltwater would have been flowing directly into Bøverbrevatnet from the ice front, leading to lower lake temperatures. Alternatively, the ice-dammed lake may have existed for longer than originally thought or the modern lake level may not have been maintained throughout the suggested 160 years.

Conclusions

The test indicates that cliffs and platforms have been formed around the modern margin of Bøverbrevatnet, supporting the original hypothesis which stressed the efficacy of lake-ice frost-shattering on bedrock shores. Erosion rates are at the lower end of, or slightly below the range calculated on the basis of the relict platform. Although the modern lake level has probably been maintained for longer than that of the fossil lake, the efficacy of the frost weathering process may have been reduced by the marginally less severe post- 'Little Ice Age' climate. The erosion rates are nevertheless sufficiently close not to necessitate any modification to the original hypothesis. However, water level on the fossil ice-dammed lake had been calculated from indirect indicators and, in the light of the measurements presented here, the original model would seem to require a small adjustment. Whilst a certain water depth would seem to be necessary for the slow growth of sufficient segregation ice for frost-shattering, the original 0.9 m depth at the cliff-platform junction suggested for the model now seems too high and needs to be replaced by a somewhat lower figure of ca. 0.6 m. The most likely explanations for this lower figure are that the level of the lake surface is relatively low in winter and that the lake-ice thickness does not reach the maximum possible value calculated from meteorological data.

Preliminary observations in the area suggest that exposed parts of other high altitude lake shorelines not susceptible to snow accumulation and resulting protection from frost-shattering are particularly favourable for platform development. The extent of penetration of and the effectiveness of the annual freeze-thaw cycle are perhaps the critical factors promoting the process and this will depend not only on macro-, meso- and micro-climate but also on the nature and direction of lines of weakness in the bedrock in relation to the shore profile and water supply. Further work is planned on the distribution and extent of lake-shore rock platforms in the Sognefjell area in order to understand the environmental controls on their development.

The Bøverbrevatnet results presented here add further weight to the argument put forward previously (Matthews et al. 1986; Dawson et al. in press) concerning the possible importance of the annual freeze-thaw cycle in the rapid development of coastal bedrock platforms in periglacial areas. Although the effects of, for example, seawater as opposed to freshwater on freeze-thaw action and of an 'ice-foot' on platform erosion cannot be deduced from these results, the less complicated nature of shore processes and their known periods of duration at both the relict and present day lake margins allow an unusual opportunity both to isolate frost weathering effects and to determine the resulting rates of erosion. Whilst Larsen & Holtedahl (1985) have recently advocated frost-shattering in conjunction with sea-ice erosion as the main processes leading to the formation of the strandflat, they lacked a specific modern analogue for the process and had also to consider other processes acting at the coast including wave abrasion and cirque glaciation. The high rates of erosion at the relict (1.4–7.1 cm/year) and present day lake margins (0.9–3.6 cm/year) of Bøverbrevatnet are close to the 4 cm/year erosion quoted by Larsen & Holtedahl (1985) who, following Rasmussen (1981), thought it would have resulted from a combination of frost-shattering and sea-ice erosion. Our results indicate that frost-shattering alone could produce this rate of rock break-up and hence platform formation at the coast. Thus, although sea-ice and waves appear to be responsible for the removal of debris and are necessary to account for some detailed surface forms, frost weathering should perhaps be regarded as the most important diagnostic process in strandflat formation.

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References

Battey, M. H. & Bryhni, I. 1981: Berggrunnen og Landeskapet. *In* Garmo, T. T. & Marker, E. (eds.): *Jotunheimen. Norges Nasjonalparker 10*, 21–33. Oslo.

Dawson, A. G., Matthews, J. A. & Shakesby, R. A. 1987: Rock platform erosion on periglacial shores: a modern analogue for Pleistocene rock platforms in Britain. *In* Boardman, J. (ed.): *Periglacial processes and landforms in Britain and Ireland.* Cambridge University Press, Cambridge 173–182.

Gibbs, A. D. & Banham, P. H. 1979: *Sygnefjell.* Berggrunnsgeologisk Kart, 1518 III, 1:50,000. Foreløpig utgave. *Norges geologiske undersøkelse.*

Harris, C. 1981: *Periglacial mass-wasting: a review of research* (British Geomorphological Research Group, Research Monograph No. 4). Geo Abstracts, Norwich. 204 pp.

Hoel, A. & Werenskiold, W. 1962: Glaciers and snowfields in Norway. *Norsk Polarinstitutt Skrifter 114*, 1–291.

Larsen, E. & Holtedahl, H. 1985: The Norwegian strandflat: a reconsideration of its age and origin. *Norsk Geologisk Tidsskrift 65*, 247–254.

Matthews, J. A. 1974: Families of lichenometric dating curves from the Storbreen gletschervorfeld, Jotunheimen, Norway. *Norsk Geografisk Tidsskrift 28*, 215–235.

Matthews, J. A. 1976: 'Little Ice Age' palaeotemperatures from high altitude tree-growth in S. Norway. *Nature 264*, 243–245.

Matthews, J. A. 1977: Glacier and climatic fluctuations inferred from tree-growth variations over the last 250 years, central southern Norway. *Boreas 6*, 1–24.

Matthews, J. A., Dawson, A. G. & Shakesby, R. A. 1986: Lake shoreline development, frost weathering and rock platform erosion in an alpine periglacial environment. *Boreas 15*, 33–50.

Østrem, G., Liestøl, O. & Wold, B. 1976: Glaciological investigations at Nigardsbreen, Norway. *Norsk Geografisk Tidsskrift 30*, 187–209.

Rasmussen, A. 1981: The deglaciation of the coastal area N.W. of Svartisen, Northern Norway. *Norges geologisk undersøkelse 369*, 1–31.