Late Quaternary, cryoplanation of rock surfaces in lacustrine environments in the Bergen area, Norway

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Relatively horizontal and smooth rock surfaces bordering lakes 65-150 m a.s.l. in the relatively mountainous Bergen area are described. The surfaces, 1- 4 km^2 in size and up to 1.5 km wide are developed in strongly foliated metamorphic Proterozoic and Paleozoic bedrock ranging in composition from granitic to gabbroic. The detailed topography of the bog-covered rock surfaces has been mapped by various methods: map surveys, probing and levelling, profiling with seismic refraction and ground penetrating radar (GPR) as well as direct levelling of the rock platforms around the lakes.

The formation of the rock surfaces is compared to the recent formation of an up to 20 m wide rock platform along one of the lakes. Alternating air temperature inversions in the lake basin and heavy precipitation during milder periods (NAO) are thought to be responsible for frequent freeze/thaw fluctuations as well as an oscillating lake level facilitating frost weathering. The rock surfaces are thought to have formed during Weichselian interstadials by frost weathering (cryoplanation) along the shores of former lakes and rivers. Implications for the formation of the 30 km wide Norwegian strandflat in similar rocks just north of this area are discussed.

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Introduction

Smooth, relatively horizontal rock surfaces are found in a variety of geological environments and may be the result of subaerial erosional processes operating for millions of years. They may be structurally controlled by flat-lying sedimentary sequences or may transect the bedrock structures. They may also represent exhumed erosion surfaces, thus representing a hiatus. In some areas, however, they make up the present rock surface over a larger area such as the much debated Norwegian strandflat along the coast of Norway (Reusch 1894, Nansen 1904, 1922; Ahlman 1919; Larsen & Holtedahl 1985; Holtedahl 1998). Even if many processes have been ascribed to the formation of the strandflat there has been no dispute as to its close association with sea level at the time of formation. The strandflat around Bergen lies at a general elevation of 30-50 m a.s.l. (Holtedahl, 1998). Apart from unpublished work by Maisey (1968) from the Flesland area (Fig. 1), little attention has been paid to the relationship between these landforms and the lithology and structures of the bedrock.

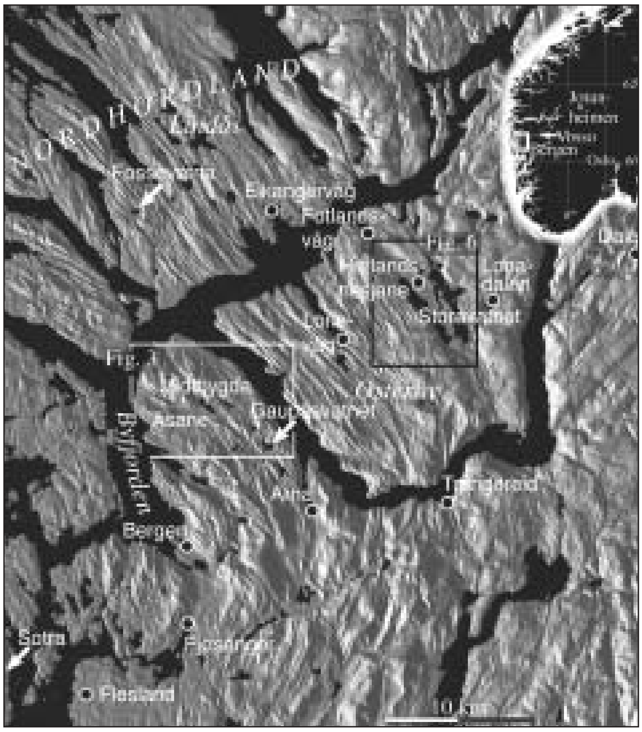

Fig. 1. Map of the Bergen area. Note the strike-parallel "ridge and valley" topography developed on the rocks belonging to the Bergen Arc System. Inset map shows location of area in Norway.

Descriptions of relatively level rock surfaces in lacustrine environments are rare. Relatively narrow rock platforms bordering glacial or alpine lakes are, however, described from both Scotland and the Jotunheimen mountains of the central part of Norway (Fig. 1) (Sissons 1978; Matthews et al. 1986). In both glacial and alpine regions the formation of such platforms is considered to be rapid with frost weathering along the lake shores being the main process (Dawson 1980; Shakesby & Matthews 1987). In keeping with this general impression, a recently discovered rock platform, up to 20 m wide around Storavatnet on the island of Osterøy (Fig. 1) is thought to have formed by frost weathering processes in the latter half of the Holocene (Aarseth & Fossen 2004).

Several wider, sub-horizontal rock surfaces in relation to lakes, have recently been discovered in the Bergen area. This paper describes four locations where relatively level rock surfaces are formed at low altitudes in and around the city of Bergen. They are developed on different rock types in clear association with lakes or rivers. The mode and time of formation of these rock surfaces are discussed.

The term cryoplanation, used in the title of this paper is the most adequate one for the process believed to be the main cause for the formation of the landforms described below. The term is normally used synonymously with altiplanation, which describes the planation of terraces at high altitudes in a periglacial climate, usually in connection with snowfields (Washburn 1973). The word itself, however, only refers to frost as being responsible for making planar surfaces which is the case here.

Location

The four areas that will be described here are less than 20 km apart: The Fossevatna lakes in Lindås, Storavatnet on Osterøy island, Midtbygda, and the area around Gaupåsvatnet, Bergen (Fig. 1). They are located at 60.5° N, just inside the coast of western Norway, and north of the centre of Bergen. This region is dissected by up to 645 m-deep fjords and surrounded by mountains 500-800 m high. Fossevatna, (90 m a.s.l.) and Gaupåsvatnet (65 m a.s.l.), will be described briefly at the end, whilst Storavatnet (160-170 m a.s.l.) will be discussed in relation to the rock platform around the lake (Aarseth & Fossen 2004). Midtbygda at 90 m a.s.l., where most quantitative data have been gathered, will be described in greater detail.

Climatic conditions

This region is currently influenced by a west coast climate as described from Bergen by Spinnangr (1942). The precipitation is both orographic and frontal being most intense during the fall and winter months, and least in May. A total mean annual precipitation of 2250 mm for the period 1961-1990 is reported by the Meteorological Station in Bergen. The other two areas (Storavatnet and Fossevatna) differ only slightly from this value (Meteorologisk Institutt 2003).

The winter climate in the Bergen area is very unstable, and the winter precipitation in western Norway correlates well with the oscillating NAO index (Nesje et al. 2000; Nesje & Dahl 2003). Stable, cold weather conditions very seldom last more than 8-10 days near sea level. During such periods temperature inversions prevail, resulting in up to 10°C lower temperatures in the basin than 50 m higher up on the hillsides in Midtbygda (Fig. 1). Here 25 % of the days between November and March normally experience inversion conditions (Tangen 1976). Similar situations are presumed for Storavatnet (Aarseth & Fossen 2004), Fossevatna and Gaupåsvatnet after lake ice has formed. Under such conditions lake levels will oscillate and frequent freeze/thaw cycles will operate during winter months.

A brief history of the Weichselian and Holocene in the area

The history of the Weichselian glaciation in western Norway is quite well known due to many finds of sediments below Weichselian till or in isostatically rebound marine caves (Mangerud 1991). The most continuous Eemian and Early Weichselian stratigraphies are at Fjøsanger, 6 km south of the centre of Bergen (Mangerud et al. 1981) (Fig. 1). Together with findings farther south and north along the coast (Larsen & Sejrup 1990, Mangerud 1991), at least five interstadials are identified for the Weichselian glaciation. During these interstadials the fjord districts are considered to have been free of glaciers. This must also have been the case for the areas investigated here. Late Weichselian sub-till sediments containing marine molluscs have been dated and are evidence of open fjords during the Allerød interstadial. Such findings are reported both at Eikangervåg and Trengereid along the fjords surrounding Osterøy (Mangerud 1977) (Fig. 1). During the latter half of the Younger Dryas stadial fjord glaciers advanced to a position 20-30 km west of the actual sites and formed the distinct Herdla Moraines (Aarseth & Mangerud 1974).

According to Aarseth & Mangerud (1974), the direction of the Younger Dryas isobases in this area were very close to N-S. The final deglaciation of the fjords took place at the transition between the Younger Dryas and the Preboreal chronozones (Aa & Mangerud 1981). The gradient of the marine shoreline in Younger Dryas is 1.3 m/km just north of Bergen (Aarseth & Mangerud 1974). At the time of deglaciation the gradient had decreased to 1 m/km according to diagrams by Aa & Mangerud (1981). This gradient rapidly decreased to

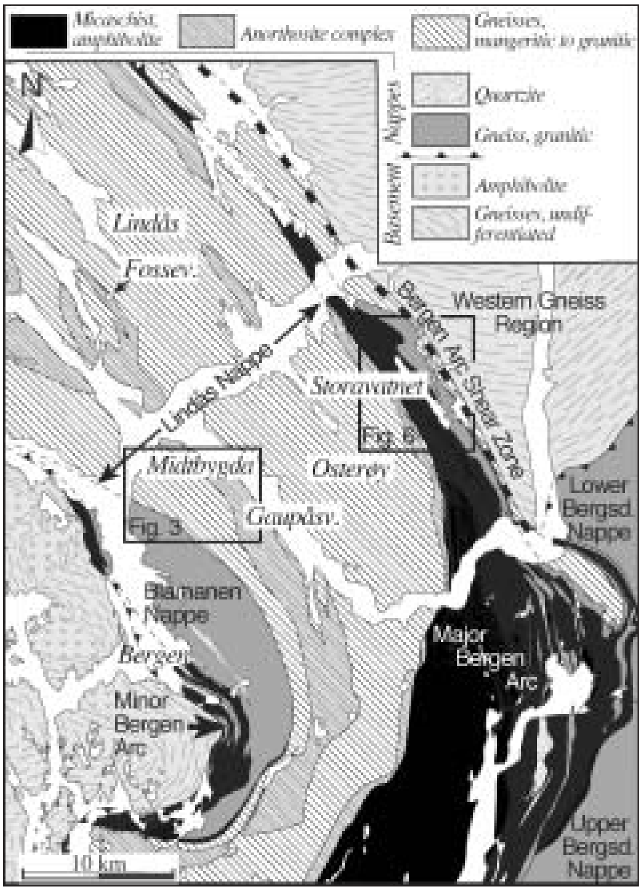

Fig. 2. Bedrock map of the Bergen area. Based on Ragnhildstveit & Helliksen (1997).

about 0.53 m/km at 9400 BP (Krzywinski & Stabell 1984) and 0.18 and 0.12 m/km at 5900 and 5300 BP, respectively. The isobases are believed to have had a constant ~N-S orientation since the Younger Dryas (Kaland 1984).

Methods

The main methods for studying the rock surfaces have been map analyses in combination with field reconnaissance and levelling. The maps used are at a scale of 1:5000 with a 5 m C.I. (contour interval) for Fossevatna, Gaupåsvatnet and Osterøy, and at a scale of both 1:5000 and 1:2000 with a 5 m and 1 m C.I., respectively, for Midtbygda. In addition, levelling of the bedrock surface was carried out along chosen profiles by probing with a thin steel rod down to bedrock, in combination with an automatic level mounted on a tripod, and using local benchmarks for calibration. The heights of rock surfaces along the largest lakes in Midtbygda, Langavatnet and Liavatnet, were also levelled at several points, using local benchmarks for calibration.

The depth of Storavatnet was measured using a high frequency recording echosounder (Simrad EY, 70 kHz), while data from public archives were used to obtain the depths of the lakes in Midtbygda.

Two profiles on Herlandsnesjane at Storavatnet and eight profiles in Midtbygda have been investigated using ground-penetrating radar (RAMAC/GPR) with a 100-MHz antenna with 1 m separation and 0.1 m trace spacing. Calibration of the signals to bog thickness was by probing. The bog surface was later levelled with the automatic leveller.

Data from geotechnical surveys carried out in 1920 and 1971 were used for the Midtbygda area. They comprise probing, levelling and refraction seismic profiling. In 1920 the bedrock surface and sediment thickness along the Daleelva river were levelled continuously over a length of 3.75 km, in connection with a plan to lower the groundwater table by making a new canal to drain the boggy area. Probing and levelling were also done in connection with plans to build a light railway from Midtbygda to Bergen. Here, the rock surface was measured at 20 m intervals along three parallel profiles 550 m long and 10 m apart. Seismic profiling was completed along parts of the line for a new motorway as well as for parts of the planned light railway line. For Midtbygda aerial photographs at a scale of 1:15 000 from both 1950 and 1970 were used to study areas around the lakes before and after lowering of lake levels in 1960.

Bedrock geology

The study areas lie within the Bergen Arcs or along its northeastern margin (Fig. 2). The Bergen Arc System (Kolderup & Kolderup 1940; Sturt & Thon 1978) consists of arcuate belts of allochthonous Proterozoic and Paleozoic rocks that have undergone Caledonian deformation and metamorphism to various degrees. The Paleozoic rocks are dominated by gabbro, greenstone, amphibolite and micaschist, and occur both in the Major and Minor Bergen Arcs. Between these two arcs is a variety of Proterozoic intrusive rocks and gneisses as well as subordinate zones of quartzite rocks, all belonging to the Blåmanen and Lindås Nappes, (Ragnhildstveit & Helliksen 1997). Marginal to the arc system is the Western Gneiss Region, which is considered to be part of the Baltican basement, although heterogeneously deformed and metamorphosed during the Caledonian orogeny and the succeeding Devonian extensional phase (Milnes & Wennberg 1997).

Fossevatna

The Fossevatna area is located mainly in a zone of anorthosite in the Lindås Nappe, but extends to the east into surrounding foliated mangeritic rocks. Anorthositic rocks are dominated by white saussuritized plagio-

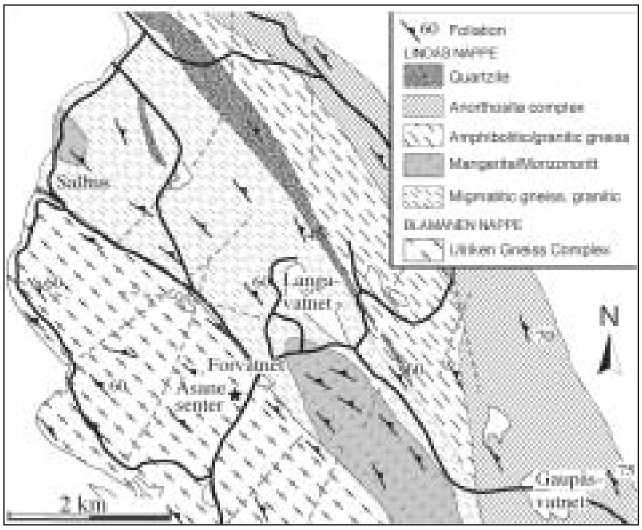

Fig. 3. Bedrock map of the Åsane area, Bergen. For location, see Figs. 1 and 2. Based on Fossen & Ragnhildstveit (1997).

Fig. 4. Rock platform at Melingen (location area C on Fig. 12). Bands of amphibolite or amphibolitic gneiss are found within the migmatitic rocks.

Fig. 5. Exfoliated gneiss, 200 m west of Flatevad (Fig. 12) with sub-horizontal jointing.

clase and carry pods or bands mainly of pyroxene. The foliation in the anorthosite and mangerite dips around 60° to the northeast.

Gaupåsvatnet

Gaupåsvatnet lies in the same zone of anorthositic rocks in the Lindås Nappe as the Fossevatna area (Fig. 3). The foliation in the Gaupåsvatnet area dips steeply to the ENE, and this dip reflects the local intensity of the Caledonian reworking. In general, ridges and hills are of fairly massive anorthosite, whereas the valleys follow zones of more sheared versions of the same lithology.

Midtbygda

The bedrock geology in the Midtbygda area (Fig. 3) is composed of moderately sheared migmatitic gneisses of the Ulriken Gneiss Complex (Blåmanen Nappe) in its western part, and rocks of the Lindås Nappe in its eastern part. The contact between the two nappe units is not clear, but has been interpreted to follow a high-strain zone that crosses the lake Forvatnet. The area to the east of this contact is dominated by fairly massive migmatitic gneiss and mangeritic to syenitic plutonic rocks. Bands of amphibolite or amphibolitic gneiss are found within the migmatitic gneiss (Fig. 4), the latter gneiss showing a steep Proterozoic foliation that has been heterogeneously reworked by Caledonian deformation. This foliation is conformable with the variously sheared plutonic rocks. As elsewhere in the Lindås Nappe, ridges consist of the most massive and least foliated rocks.

In some of the flat areas of Midtbygda, particularly in its western parts, horizontal exfoliation of the migmatitic gneiss has produced a weakness that may have enhanced the frost-driven erosion suggested below (Fig. 5). The exfoliation is a result of the lithostatic pressure release after the Neogene domal uplift and subsequent erosion of Scandinavia (Riis & Fjeldskaar 1992; Doré 1992). Well-foliated amphibolitic gneisses with some bands of quartzite occur in the area east of Langavatnet.

Storavatnet

The flat areas around Storavatnet on Osterøy are composed of Cambro-Silurian amphibolite and micaschists of the Major Bergen Arc and the neighbouring anorthositic gneisses of the Kvalsida gneiss (Fig. 6). The platform is also carved into more massive granitic to tonalitic gneisses, locally with layers of amphibolite and quartzite in the eastern part of Storavatnet (Henriksen 1979).

Area description

First, the relatively level rock surface around Storavatnet on Osterøy will be described. The relationship with the younger rock platform around this lake, as descri-

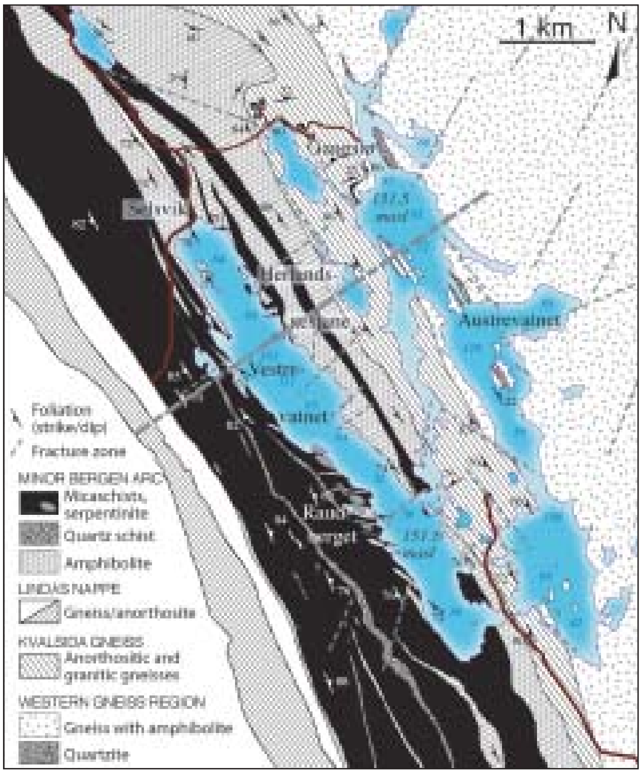

Fig. 6. Bedrock map of the Storavatnet area, Osterøy. See Figs. 1 and 2 for location. Based on Henriksen (1979).

bed by Aarseth & Fossen (2004), will be dealt with in the discussion.

Storavatnet, Osterøy island

On Osterøy, a relatively smooth rock surface is found at several places around Storavatnet (Figs. 7, 8 and 9). The lake, with a natural level of 151.5 m a.s.l. prior to 1920, is centrally located on the island. It consists of two connected elongated basins, Vestrevatnet and Austrevatnet, 5 and 7 km long with a total area of 10.0 km^2 and depths of 111 m and 128 m, respectively (Aarseth & Fossen 2004). The topography around parts of the lake is strikingly different from the landscape on the rest of the island (Figs. 7 and 8). The western part of the island, with rocks belonging to the Bergen Arc System has a pronounced "ridge and valley" topography which is parallel to the strike of the Caledonian bedrock (Fig. 1). The eastern part lies within the Western Gneiss Region and features steep mountain sides rising to an undulating plateau at 500-700 m, with some higher mountains reaching a maximum height of 868 m a.s.l.

The largest, relatively flat areas are found on both sides of the northern part of Vestrevatnet at Herlandsnesjane and Myking (Figs. 7, 8 and 9). The area at Herlandsnesjane is from 0.5 to 1.5 km in width and up to 4 km long, and has a general elevation of 158-165 m a.s.l. A few hills rise 10-20 m above this surface. In the Myking area the plain is somewhat higher, from 165 to 170 m a.s.l. (Fig. 9). The topography here is more dependent on bedrock strike with some narrow bands of quartz schist and amphibolite making up small ridges between elongated depressions. The height of the Myking flats corresponds to the elevation of the saddle point in a wide depression crossing the direction of the foliation, leading down towards Lonevåg to the southwest (Fig.1).

At the southern end of the lake only smaller areas with relatively level surfaces are found. On both sides of the sound connecting the two parts of the lake the flat areas are smaller, with plateaus reaching 170 m a.s.l. All relatively flat areas around the lake are covered with bogs of various thickness, and may also host smaller bog-lakes.

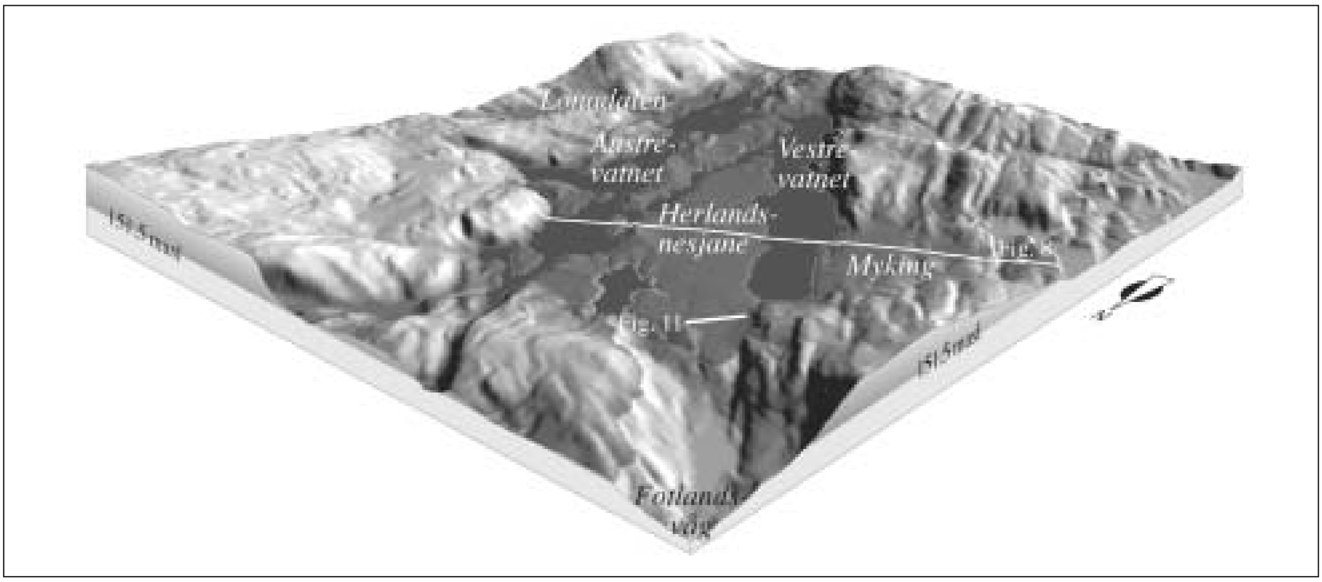

Fig. 7. Topographic model of the Storavatnet area, Osterøy. Scale: Length of profile line Fig. 8 is 5.2 km and length of Austrevatnet is 7 km.

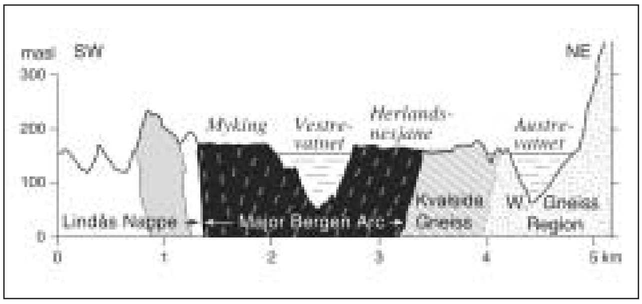

Fig. 8. Topographic profile across the Storavatnet area. Location given on Fig. 7. Bedrock geology indicated.

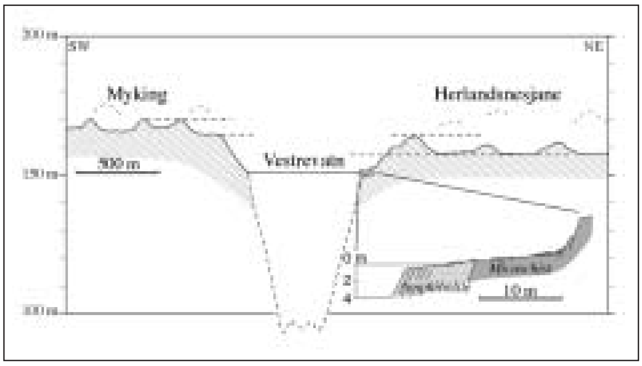

Fig. 9. Profile sketch across Lake Vestrevatnet showing the relationship between the general heights of the bog covered and glacially modified terrain at Myking and Herlandsnesjane and the sub-recent rock platform along the lake (Aarseth & Fossen 2004). Location: central part of Fig. 8.

Fig. 10. GPR measuring for profile 1, Fig. 11 on the snow-covered bogs at Herlandsnesjane. Location: westernmost point on profile 1, Fig. 11.

Two GPR profiles from the northern part of Herlandsnesjane (Fig. 10), of which profile 1 is shown in Fig. 11, show that the bedrock surface below the bogs has a few depressions up to 12 m deep along the 426 m long profile, while other parts have a relatively level rock surface at 158-165 m a.s.l.

Bedrock in the eastern part of Herlandsnesjane belongs to the Kvalsida Gneiss, containing anorthositic and granitic gneisses. We have no GPR profiles from this area, but the surface appears more uneven with several hills rising above the general plateau surface. In the Western Gneiss Region, east of Austrevatnet, small areas with a level surface at 160-165 m are found only in two places; near the northern and southern ends of the lake (Fig. 7). Bodies of non-foliated serpentinite on the southwest side of the lake (Fig. 6) (Henriksen, 1979), have neither rock platform (Aarseth & Fossen 2004) nor level rock surfaces.

Midtbygda, Åsane

The Midtbygda area comprises a topographic depression with a nearly horizontal basin floor covering an area of 4 km^2, and having a narrow outlet for the Daleelva river at Flatevad ('Flatford'), where the rock threshold was lowered from 86.0 to 84.5 m a.s.l. in 1960 (Figs. 12 and 13). The general height of the basin floor is 87-90 m, surrounded by hills with heights of 300-486 m. The Daleelva river flows through four small lakes: Langavatnet, Banntjørna, Liavatnet and Forvatnet (Fig. 12) with a natural height difference of less than 1 m (before 1960). The lakes have water depths of 54 m, 12 m, 34 m and 16 m, respectively. The total drainage area of the river NE of Flatevad is 14.2 km^2. During a survey in 1920 maximum flood stages of 0.35-0.47 m were reported in November in the four lakes.

The area around the largest lake (Langavatnet, 1.5 km long) has an abrupt transition from the lakeside plains to steep hillsides on three sides (Figs. 12 and 13). East of Liavatnet there is also a sharp transition from a bedrock platform along the lake to a steep hillside, while the two smaller lakes are on the plain. The nearly horizontal path along the canal connecting Liavatnet and Forvatnet gives a good view of the flatlying bedrock surface on both sides of the canal where the parking lot pavement covers the almost horizontal natural rock surface.

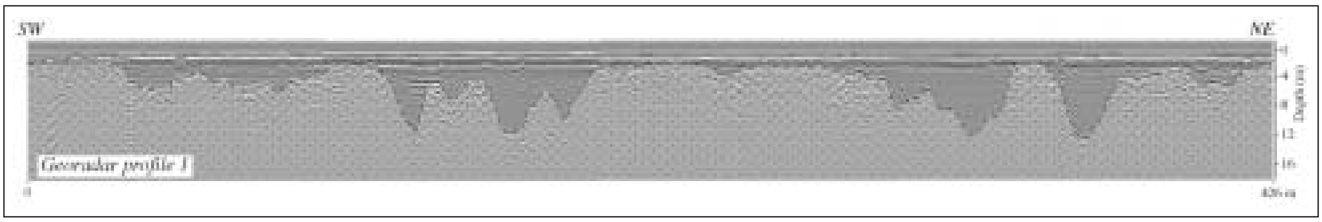

Fig. 11. GPR profile 1 across northern part of Herlandsnesjane. Location: Fig. 7.

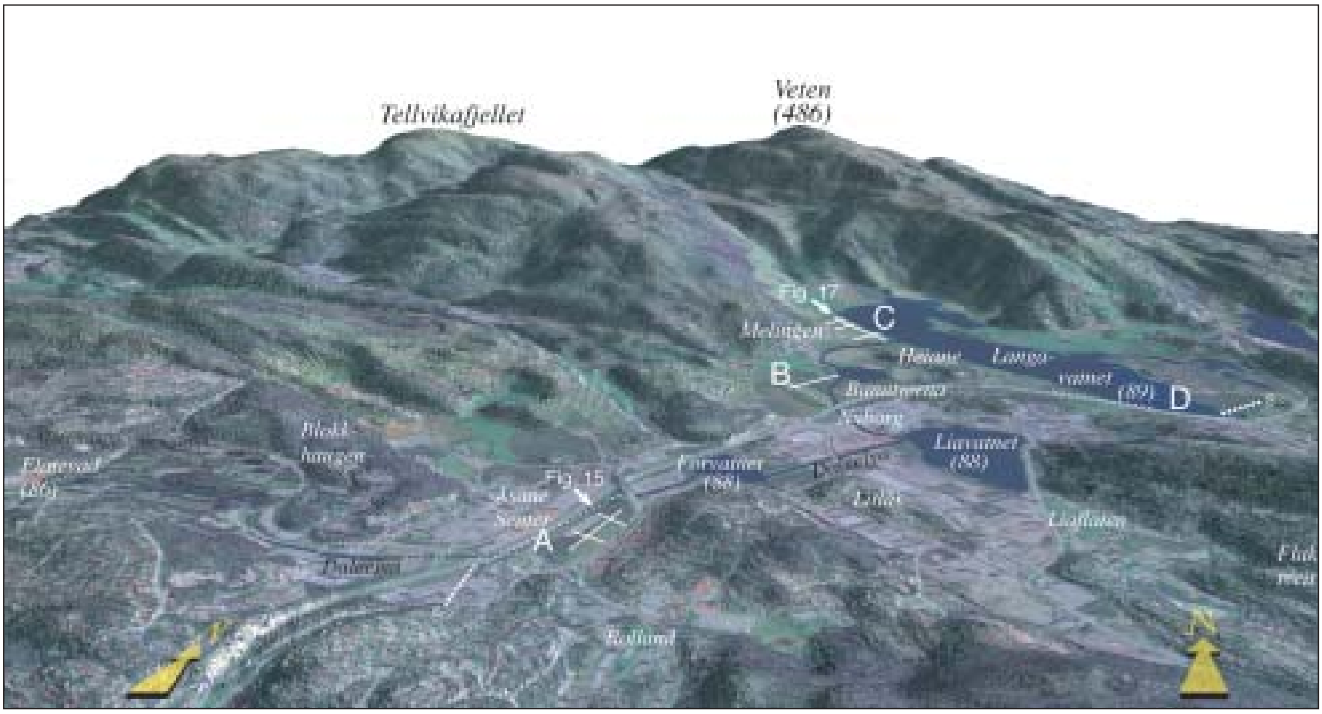

Fig. 12. Digital elevation model with aerial photo of Midtbygda, Åsane with the four lakes and Daleelva river canal. Lake levels 1920 in m a.s.l Profiles are indicated for GPR (lines) at A, B and C, refraction seismic (dotted and with S) and probing (stippled lines). Looking towards north-northwest with an avarage width of 3 km.

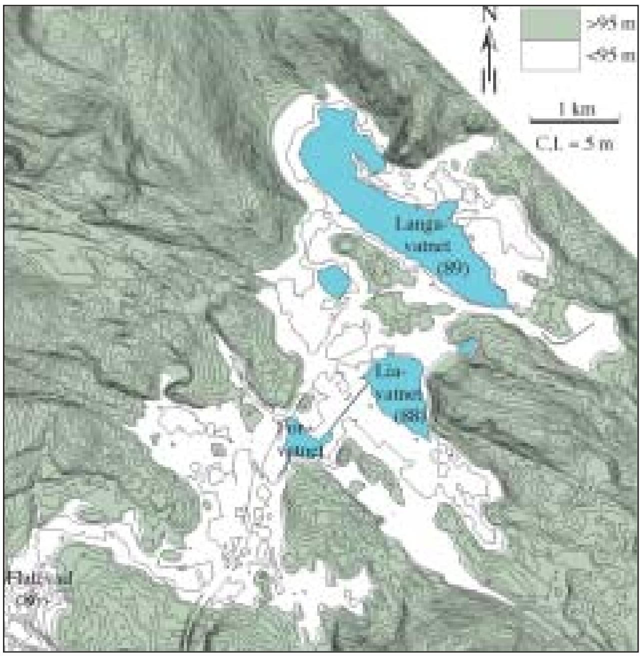

Fig. 13. Contour map of Midtbygda, Åsane showing areas 95-85 m a.s.l. Lake levels as in 1920.

Similar level rock surfaces can be viewed along the canal south and west of Åsane Senter. At both places along the canal, bedrock sections reveal joints parallel to the bedrock surface. The joints clearly represent sheeting (exfoliation) due to pressure release during and after Cenozoic uplift and erosion (Riis & Fjeldskaar 1992).

In the early 1970's farmers at Melingen (Fig. 12) transported surplus soil removed from the development work at Åsane Senter to the fields along Langavatnet. Before this time flat bedrock areas nearest to the lake had only a thin soil cover or no soil cover at all. These areas were flooded even after the river canal was constructed.

A few isolated hills rise above the basin floor, the two highest, Heiane and Litlås, (Fig.12) reach 25 m above the plain while the others are considerably lower. The plain has extensions along small valleys parallel to the strike of the rocks, for example, at Liaflaten and Rolland. Several bedrock ridges emerge above the plain level, such as Blokkhaugen, a hill west of Åsane Senter (Fig. 12). Many of these ridges are less foliated and thus more resistant to weathering than the surrounding gneiss.

Quantitative measurements of the rock surface in Midtbygda.

The 3.75 km long profile along the planned canal for the Daleelva River gives a good picture of the flat bedrock surface, the lake basins, and a few other rock basins (Fig. 14). The curvature of the canal is rather gentle compared to the original course of the river. Thus, the profile in Fig. 14 does not follow the exact path of the natural river, but crosses it at several places. This means that the profile may be up to 50 m from the centre line of the original river. This is expressed on the

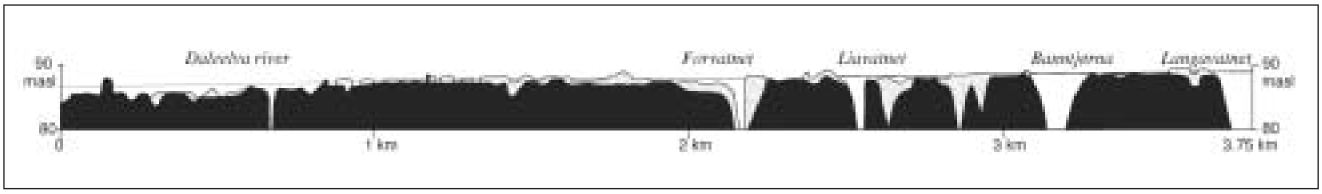

Fig. 14. Profile from 1920 along the projected Daleelva river canal from Langavatnet to Flatevad. Bedrock (black), sediments (dotted) and lakes and river (white) are shown. The Daleelva river is shown in Fig. 12.

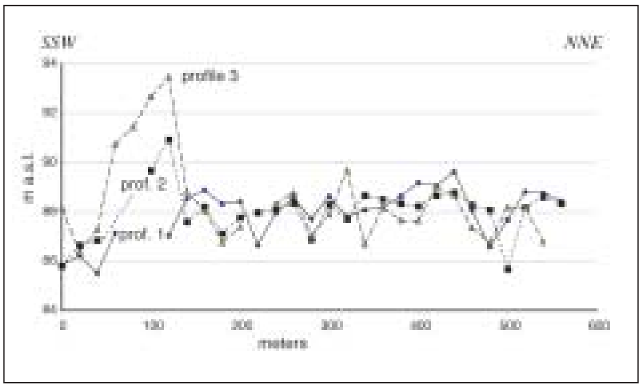

Fig. 15. Rock surface heights along three 550 m long S-N profiles based on probing. Profiles 1, 2 and 3 are10 m apart and located near Åsane Senter (area A in Fig. 12).

Fig. 16. View towards Midtbygda, Åsane, looking south. Melingen is located on the flats just across the nearest lake (Langavatnet). Banntjørna and Nyborg to the left and Åsane Senter in the distance to the right.

profile by intermittent bog mounds and river courses, especially around 1.2 km (Fig. 14). Therefore, the profile records not only the rock surface along the original river bottom, but also that on both sides of it at many places. The rock mound close to the left end of the profile is where the canal intersects a sharp river bend around higher terrain.

By plotting heights of the rock surface at the most level parts of the original profile from 1920, the profile can be divided into three sections according to changes in the slope of the rock surface. The upper 2.5 km, containing the lakes, has a mean gradient of 0.6 m/km whereas the section from 1.25 km to 0.8 km is 10 times steeper (6 m/km) and the lowermost section has a mean gradient of 1.4 m/km.

The three 550 m-long parallel profiles, based on probing close to the river canal and from approximately 1.5 – 2.0 km along the river profile (area A, Fig. 12), also reveal a nearly level rock surface except that it intersects a small hill at the southern end (Fig. 15). At the northern end, one point on the middle profile is lower than the rest because it intersects the bottom of the blasted out river canal. Other probe-based profiles west of the southern end of Langavatnet (area D, Fig. 12) reveal a similar level rock surface. Here, a 200 m-long, also probe-based profile along a nearly horizontal bog show depths of 0-1.7 m to bedrock at 89-90 m a.s.l.

The relatively short seismic profiles, both south of Åsane Senter (area A, Fig. 12) and southeast of Langavatnet (area D) farther N, reflect the same level rock surface under a bog cover of 1-3 m. The velocities of the P-waves in these rocks vary from 3800 ms^{-1} to 5300 ms^{-1}. There are no detectable relationships between the velocity variations and any irregularities in the heights of the rock surface. On a 140 m-long profile with a geophone distance of 10 m in area A, Fig. 12, the bedrock relief was less than 1 meter.

The GPR profiles provide additional data about the smooth rock surfaces in three areas: near Melingen west of Langavatnet (area C), south of Banntjørna, area B, and east of the Åsane Senter, area A (Fig. 12). The most level ground was found near Melingen (Fig. 16). Here, the rock surface was extremely flat except for an up to 14 m-deep bog-filled channel, most likely due to glacial erosion, that was detected nearest to the hillside on the two northernmost transverse profiles. The relative relief in the remaining profiles was of the order of 1 m at approximately 89-90 m a.s.l. (Fig. 17).

The most detailed measurements were done by levelling the rock surfaces at eight locations around each of the two largest lakes, Langavatnet and Liavatnet. A representative rock surface elevation was levelled at each location around Langavatnet (Fig. 4), and the highest and lowest points within a small area of the rock platform were levelled around Liavatnet (Fig. 18). All heights were plotted on a map and later projected on to

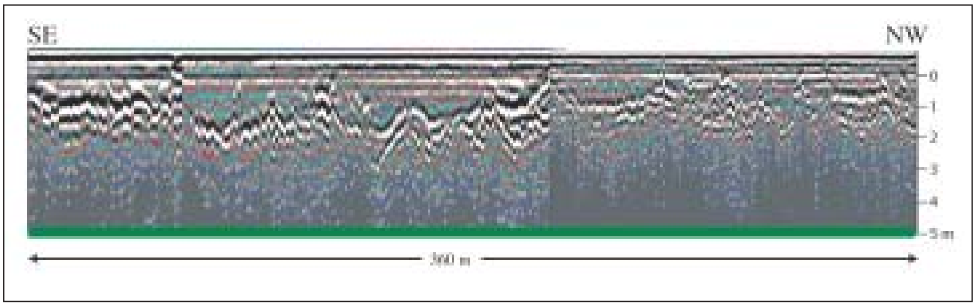

Fig. 17. GPR profile 5 along the fields just SW of Langavatnet. The profile runs along the flats in the foreground on Fig. 16 and in area C on Fig. 12.

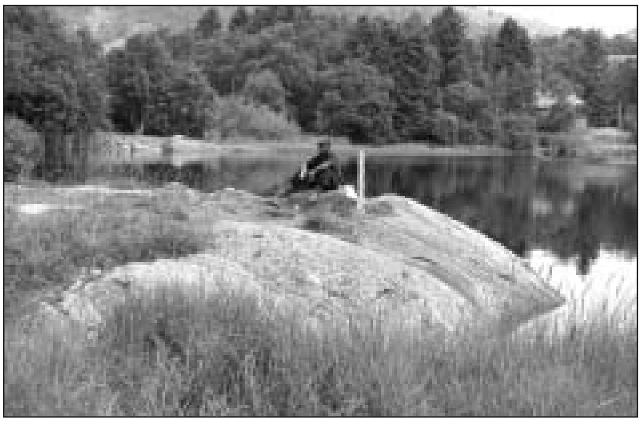

Fig. 18. The rock platform on the western side of Liavatnet with glacial polishing under the natural (1920) lake level.

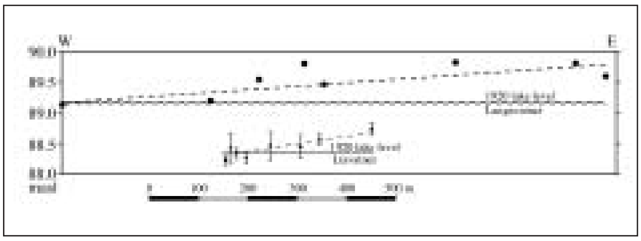

Fig. 19. Heights of rock platforms along Langavatnet (dots) and Liavatnet projected on to a W-E profile, perpendicular to the Late Weichselian isobases.

Fig. 20. View towards the northwest of the Fossevatna area from Vassberget. Storavatnet to the right and Litlavatnet farther down.

a W-E profile, perpendicular to the direction of the Late Weichselian and Early Holocene isobases (Fig. 19). Although the lakes are small, and the rock surfaces not completely level, the profiles reflect a probable tilting of the rock surface.

A regression line through the rock surface elevations around Liavatnet reveals a gradient of 1.3 m/km and 0.12 m as a maximum vertical distance between the mean value and the regression line. The profile from Langavatnet is more irregular because the rock platform here is more uneven, especially around the southern end of the lake. The gradient here is only 0.6m/km and the maximum distance from the regression line 0.3 m. Both lakes have their present outlets in their western parts. This agrees well with the western rock levels being close to the 1920 lake levels, and levels further east at somewhat higher elevations (Fig. 19).

Fossevatna, Lindås

From the topographical maps of the area around Bergen, Fossevatna area, 14 km north of Midtbygda, was chosen for further reconnaissance. Two neighbouring lakes, Storavatnet and Litlavatnet, 0.5 and 0.3 km long, respectively, and both 90 m a.s.l. are here situated on the northwest side of a steep hillside leading up to the 288 m-high hill, Vassberget.

A rock platform just above lake level is found at several places around the lakes, and numerous small flat, grass-covered islands with a rock platform are grouped in the western part of Storavatnet (Fig. 20). The size of the basin area here is 1 km^2. The river outlet from the basin is narrow and the river flows down to a narrow, uneven ledge of the strandflat at 40-50 m a.s.l., before entering a narrow sound. The Fossevatna basin has the shape of a glacial cirque facing NW.

Discussion

Storavatnet, Osterøy.

The relatively level rock surface around Storavatnet, Osterøy is developed across several bedrock types, although the widest surfaces are found at Herlandsnesjane and Myking in older Paleozoic mica-schists and amphibolites. A strong relationship to bedrock lithology and structures was also found for the rock platform around the lake described by Aarseth & Fossen (2004). A 2-2.5 m higher, undulating rock bench with glacial grooves was found at a few places in the same area and is thought to have been formed at a higher lake level during the Allerød interstadial, the grooves representing the Younger Dryas glacial readvance. Both these rock platforms are explained as due to frost weathering in combination with mass movement and lake ice push transport at lake level during frequent freeze/thaw cycles in wintertime (Aarseth & Fossen in print).

The rock surfaces described here are some 7-14 m higher than the Holocene rock platform and much more rugged. This makes it difficult to relate them specifically to former horizontal or tilted lake shorelines. Still, they differ radically from the rest of the topography on the island (Fig. 8). Their appearance, and nearness to a similar, but narrower rock platform makes a relationship to former lake levels most likely. Glacial erosion as well as subaerial weathering may have contributed to the rugged surface. Glacial erosion in this area has, however, been selective, creating the two very deep lake basins in addition to smaller basins now filled by bogs and bog-lakes.

The present lake drains towards Fotlandsvåg to the NW. There is a possibility that the low area around Storavatnet was part of a larger valley system crossing the island before glacial erosion cut the deep fjords. The largest river in this part of the country, the Vosso river system, now reaches sea level in a fjord east of Osterøy. A preglacial drainage path through Dale and Lonadalen (pass point 240 m a.s.l.), and further on over the Myking flats towards Lonevåg (Figs. 1 and 7), is straighter and perhaps more likely than the winding path outlined by the present fjords in this area. The saddle point fits well with the Myking flats west of the lake. The final modelling of the relatively level rock surface, however, is believed to result from frost weathering along the lakes with an outlet either on the Myking side or towards Fotlandsvåg to the NW (Fig. 1).

Midtbygda, Åsane.

Lakes are found only in the northeastern half of Midtbygda. The rock surface here is smoother than at Herlandsnesjane on Osterøy. Although rock basins are found in Midtbygda as well, the rock surface nearest to the lakes Langavatnet and Liavatnet (Figs. 4 and 18) has similarities to the Holocene rock platform around lake Storavatnet on Osterøy (Aarseth & Fossen 2004). This implies that lake levels have played an important role during its formation also here. By observing the mean gradient of the rock surface along the lakes it can be concluded that the Midtbygda area was subjected to an oblique isostatic depression during the formation of the level rock surfaces (Fig. 19). Judging from the height difference between the two regression lines of the rock platforms around the lakes, the two lake levels must have played important roles during the formation of the rock surfaces in their respective surroundings.

Frost weathering along the lake shores is therefore thought to be responsible for the formation of rock platforms as described from Storavatnet on Osterøy (Aarseth & Fossen 2004). In contrast to the more severe environment responsible for rock platform formation in the alpinic Jotunheimen region (Fig. 1) (Matthews et al. 1986; Shakeby & Matthews 1987), freeze/thaw cycles are frequent during wintertime in Midtbygda. In addition, the coastal climate has probably prevented the development of a stable lake level as well as an even ice thickness on the lakes. These fluctuations can be compared to a tidal effect, but with a lower frequency. In periods between the mild and often windy weather conditions, high-pressure situations in combination with temperature inversions would cause freezing at the contact between the lake ice and the rock platform. Thus, freezing probably took place while the lake levels were still relatively high, and the first to freeze would be the contact between the lower part of the cliffs and the lake ice, making this area most susceptible to frequent frost wedging. This process would cause lateral expansion of the even rock surfaces as described for the formation of the Holocene rock platforms on Osterøy (Aarseth & Fossen in 2004). At Åsane Senter the rock surface along the canal has a steeper gradient until the river turns west. Here, it levels out and eventually turns south, leaving the Midtbygda area through some rapids. The steeper gradient near Åsane Senter cannot be related to isostatic rebound alone. The same frost weathering process (cryoplanation) acting along the lake margins is believed to be responsible for frost weathering along the river. The cryoplanation process in the whole area southwest of Liavatnet is enhanced by strong sheeting of the gneissic bedrock expressed as sub-horizontal joints (Fig. 5) that facilitate frost weathering along the river.

The level rock surface gets narrower towards the outlet of the basin at Flatevad. The Blokkhaugen ridge (Fig. 12) forms a natural barrier for cold air trapped in the basin during temperature inversion periods. Farther west temperatures are less extreme due to shorter periods with temperature inversion and nearness to Byfjorden (Fig. 1).

Fossevatna

The easternmost lake (Storavatnet) is close to a steep, 200-m high mountain slope facing north and northwest. The amphitheatre-like form probably represents a cirque. Glacial erosion has subsequently created Litlavatnet (Fig. 20), and frost weathering along the shores of the two lakes may have been responsible for the even level rock surface in this area.

Gaupåsvatnet

Gaupåsvatnet (Fig. 1) presently 65 m a.s.l. and 5 km SE of Midtbygda, is also partly surrounded by a rock platform. It has a few small, flat-topped rocky islands visible during low lake stands. This area has not been studied in detail, but is known as one where strong temperature inversion occurs (map in Utaaker 1995). Further upstream, several lakes are surrounded by flat areas, although it is possible that flat bogs may conceal deeper rock basins here.

Time of formation of the rock surfaces

Erosion surfaces are difficult to date. We have so far obtained no absolute dates for the rock surfaces discussed here. From the discussion it is obvious, however, that the formation of the smooth rock surfaces must post-date formation of the lakes, which are all the result of glacial erosion. Some of the lakes may have originated as glacial cirque tarns. Cirques with tarns at relatively low altitudes are described from the coastal areas both in and near Bergen (Ahlman 1919, Genes 1978, Larsen & Mangerud 1981). As soon as the lakes were formed, suitable basins would be subject to temperature inversions, resulting in active frost weathering. As shown from Storavatnet on Osterøy, the process of rock platform formation does not require a periglacial environment (Aarseth & Fossen in 2004). The most important factors are oscillating lake levels, temperature inversions and rock structures suitable for intensified disintegration by frost.

Glacial erosion in western Norway has been selective and concentrated mainly in the fjords where glacier confluence intensifies erosion (Holtedahl 1967; 1975). On coastal islands on the level strandflat erosion has only modified the undulating rock surfaces by scouring small valleys and lake basins along zones of weakness. This seems also to be the case on the flat rock surfaces discussed here.

To determine the time taken for a given surface to form, it is necessary to know the rate of the process concerned. Rasmussen (1981) investigated marine rock platforms in northern Norway formed during the Younger Dryas stadial. He found a widening of these platforms to be 0.04 m/y. From lacustrine alpine environments Matthews et al. (1986) estimated rates to be up to 0.071 m/y during the Little Ice Age.

The freshness of rock ledges nearest to the lakes, with no signs of glacial striae above the outer edge of the rock platform (Fig. 18), points to a Holocene age, or at least to rejuvenation of the rock surfaces closest to the lakes. The lakes were too small, however, to accumulate all the weathered material from the complete cryoplanation of the rock surfaces. It is, therefore, necessary to have several periods of frost weathering interspersed with glacial stages during which weathered material was removed. During the Weichselian glaciation at least five such periods have occurred (Mangerud 1991). The last interstadial, Allerød, is considered too short, but frost weathering at the locations in question may have been active for up to 1200 years during this interstadial. The Ålesund interstadial, which lasted from around 40 000 to 30 000 years ago (Mangerud 1991), is the next alternative, but with only two stadials to follow, it is more likely that the process of rock surface cryoplanation started in the Eemian or in one of the early interstadials during the Weichselian or even earlier.

The thresholds at river outlets control lake levels, which again control the levels of the rock surfaces described. This means that even very minor glacial erosion at the thresholds will have an impact on the rock surface elevations. In contrast to the Saalian glaciation, glacial erosion during Weichselian is believed to have been relatively modest along the west coast of Norway because relatively undisturbed Eemian and early Weichselian sediments are found at several locations (Mangerud 1991). Thus, we postulate that the formation of the rock surfaces occurred during interstadials in the Late Quaternary. A more precise dating is impossible at the present time.

Implications for the formation of the Norwegian strandflat

Even though the formation of the Norwegian strandflat has been discussed in depth for more than a century (Reusch 1894; Holtedahl 1998), little attention has been paid to how its formation relates to bedrock. Maisey (1968), however, found that the width of the strandflat was different on opposite sides of the fjord SW of Flesland airport (Fig. 1). He attributed this to differences in bedrock lithology. The bedrock around the airport is predominantly anorthositic gneiss belonging to the Bergen Arc System and with a foliation normal to the long axis of the fjord (Kolderup & Kolderup, 1940), whereas the island of Sotra, west of the fjord, has felsic and more gently dipping gneisses with a foliation parallel to the fjord.

The strandflat on the islands and mainland in the western part of Nordhordland, north of Bergen (Fig. 1), is up to 30 km wide and thus much wider than farther south. The bedrock types are the same as in the four areas discussed here. At Osterøy the rock platform around Storavatnet is widest in well-foliated Paleozoic rocks and lacking in bodies of massive serpentinite. The Nordhordland area has mostly the same rocks with steeply dipping foliations. As frost weathering around sea level is now considered to be the main process responsible for the formation of the strandflat (Holtedahl 1998), these observations demonstrate that foliated and easily disintegrated rocks are more susceptible to frost weathering, and as a result one of the widest parts of the Norwegian strandflat along the coast occurs here.

Conclusions

The almost horizontal and smooth rock surfaces in several rock basins in the Bergen area, Norway, are considered to have formed by frost weathering along lakes and rivers during Late Quaternary time. The formation began with the devlopment of rock platforms bordering the lakes during ice-free interstadials. Frost weathering was enhanced by frequent freeze/thaw cycles and oscillations of lake levels due to unstable winter weather conditions, with temperature inversions interrupted by mild weather and heavy precipitation. The weathering was further enhanced by the structure of the rocks which is strongly foliated and steeply dipping metamorphic rocks of Proterozoic and Older Paleozoic age. In parts of Åsane strong horizontal exfoliation of the gneissic rocks must also have facilitated weathering. The different mineralogy of the rocks does not seem to have had a direct influence on the width of the rock surface which ultimately developed here.

On Osterøy the relationship between the formation of a recent rock platform (Aarseth & Fossen 2004) and the 7-14 m higher, rougher rock surface, is clear. On both Osterøy and in Midtbygda the rock surface is believed to be multicyclic, i.e. it was probably formed during several Weichselian interstadials. The weathered debris formed during an interstadial is believed to have been transported to the lake basins by drifting lake ice during ice breakup. The basins were then emptied by glacial transport during a subsequent stadial. The freshness of rock surfaces close to the lakes in Midtbygda indicates some weathering during the Holocene.

These conclusions have a direct implication for the extension of the Norwegian strandflat in the area. The widest part of the strandflat in western Norway is in Nordhordland (Fig. 1), just north of this area and with the same kinds of bedrock. Here, the surface of the strongly foliated and steeply dipping rocks belonging to the Bergen Arcs were levelled out to form a nearly 30 km wide strandflat on the islands as well as the mainland.

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References

Aa, A.R. & Mangerud, J. 1981: Glacialgeologi og vegetasjonsinnvandring i Indre Nordhordland, Vest-Norge. *Norges geologiske undersøkelse 369,* 33-75.

Aarseth, I. & Mangerud, J. 1974: Younger Dryas end moraines between Hardangerfjorden and Sognefjorden, western Norway. *Boreas 3,* 3-22.

Aarseth, I. & Fossen, H. 2004: A Holocene lacustrine rock platform around Lake Storavatnet, Osterøy, western Norway. *The Holocene 14,* 599-606.

Ahlman, H.W:son 1919: Geomorphological studies in Norway. *Geografiska Annaler 1,* Stockholm.

Doré, A. 1992: The base Tertiary surface of southern Norway and the northern North Sea. *Norsk Geologisk Tidsskrift 72,* 259-265.

Dawson, A.G. 1980: Shore erosion by frost: an example from the Scottish Lateglacial. In Lowe, J.J., Gray, J.M. & Robinson, J.E., (eds.): *Studies in the lateglacial of northwest Europe.* Oxford Pergamon Press, 205 pp.

Fossen, H. & Ragnhildstveit, J. 1997. Berggrunnskart Bergen 1115 I, M 1:50 000. *Norges geologiske undersøkelse.*

Genes, A.N. 1978: Glacial geology of the island Stord, West Norway. *Norsk Geologisk Tidsskrift 58,* 33-49.

Henriksen, H. 1979: Structural geology and metamorphism on northern Osterøy. Unpublished thesis, University of Bergen, 478 pp.

Holtedahl, H. 1967: Notes on the formation of fjords and fjord valleys. *Geografiska Annaler 49A,* 188-203.

Holtedahl, H. 1975: The geology of the Hardangerfjord, West Norway. *Norges geologiske undersøkelse 323,* 1-87.

Holtedahl, H. 1998: The Norwegian strandflat. A geomorphological puzzle. *Norsk Geologisk Tidsskrift 78,* 47-66.

Kaland, P.E. 1984: Holocene shore displacement and shorelines in Hordaland, western Norway. *Boreas 13,* 203-242.

Kolderup, C.F. & Kolderup, N.-H. 1940: Geology of the Bergen Arc System. *Bergen Museums Skrifter 20,* 137pp.

Krzywinski, K. & Stabell, B. 1984: Late Weichselian sea level changes at Sotra, Hordaland, western Norway. *Boreas 13,* 159-202.

Larsen, E. & Mangerud, J. 1981: Erosion rate of a Younger Dryas cirque glacier at Kråkenes, western Norway. *Annals of Glaciology 2,* 153-158.

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

Larsen, E. & Sejrup, H.P. 1990: Weichselian land-ice interactions: western Norway-Norwegian Sea. *Quaternary Science Review 9:* 85-97.

Maisey, G.H. 1968: Geologiske og maringeologiske studier i og rundt Raunefjorden, Hordaland. Unpublished thesis, University of Bergen.

Mangerud, J. 1977: Late Weichselian marine sediments containing shells, foraminifera, and pollen, at Ågotnes, western Norway. *Norsk Geologisk Tidsskrift 57,* 23-54.

Mangerud, J. 1991: The last ice age in Scandinavia. *Striae 34,* 15-30.

Mangerud, J., Sønstegaard, E., Sejrup, H.P., & Haldorsen, S. 1981: A continuous Eemian and Early Weichselian sequence containing pollen and marine fossils at Fjøsanger, western Norway. *Boreas 10,* 137-208.

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

Meteorologisk Institutt 2003: Precipitation statistics on the web: <http://www.met.no/>

Milnes, A.G. & Wennberg, O.P. 1997: Tektonisk utvikling av Bergensområdet. *Geonytt 1,* 6-9.

Nansen, F. 1904: The bathymetrical features of the north-polar seas. *Scientific Results Norwegian North Polar Expedition 1893-1896. 4,13,* 1-232.

Nansen, F. 1922: The strandflat and isostasy. *Skrifter Vid. Selsk.Mat.-Nat. Kl. 1921,11,* 1-313.

Nesje, A., Lie, O. & Dahl, S.O. 2000: Is the North Atlantic Oscillation reflected in Scandinavian glacier mass balance records? *Journal of Quaternary Science 15,* 587-601.

Nesje, A. & Dahl, S.O. 2003: The "Little Ice age" – only temperature? *The Holocene 13,* 139-145.

Ragnhildstveit, J. and Helliksen, D. 1997: Geologisk kart over Norge, berggrunnskart Bergen – M 1:250.000. *Norges Geologiske Undersøkelse.*

Rasmussen, A. 1981: The deglaciation of the Coastal Area NW of Svartisen, Northern Norway. *Norges geologiske undersøkelse 369,* 1-31.

Riis, F. & Fjeldskaar, W. 1992: On the magnitude of the Late Tertiary and Quaternary erosion and its significance for the uplift of Scandinavia and the Barents sea. In: Larsen, R.M., Brekke, B.T., Larsen, B.T. & Talleraas, E. (eds.) *Structural and tectonic modelling and its application to petroleum geology. 1.* NPF Special Publication, Elsevier, Amsterdam, 163-185.

Reusch, H. 1894: Strandfladen, et nyt træk i Norges geografi. *Norges geologiske undersøkelse 14,* 1-12.

Shakesby, R.A. & Matthews, J.A. 1987: Frost weathering and rock platform erosion on periglacial lake shorelines: a test of a hypothesis. *Norsk Geologisk Tidsskrift 67,* 197-203.

Sissons, J.B. 1978: The parallel roads of Glen Roy and adjacent glens, Scotland. *Boreas 7,* 229-244.

Spinnangr, F. 1942: Temperature and precipitation in and around Bergen. *Bergen Museum Årbok 9.*

Sturt, B. & Thon, A. 1978: Caledonides of Southern Norway. *IGCP Project 27, Caledonian-Appalacian orogen of the Atlantic region.* Geological Survey Canada Pap. 78-13, 39-47.

Tangen, P.O. 1976: *Kartlegging og analyse av vind og temperaturklima i BOB's utbyggingsområde Lid/Flaktveit i Åsane.* Report University of Bergen, Department of Geophysics. 31 pp.

Utaaker, K. 1995: Energi i arealplanleggingen – Lokalklima i Bergen. *Meteorological report series,1–1995.* University of Bergen. 45 pp.

Washburn, A. L. 1973: *Periglacial processes and environments.* St. Martin's Press, New York. 320 pp.