Dynamics of the last glaciation in eastern Svalbard as inferred from glacier-movement indicators

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Glacial striae and other ice movement indicators such as roche moutonnées, glacial erratics, till fabric and glaciotectonic deformation have been used to reconstruct the Late Weichselian ice movements in the region of eastern Svalbard and the northern Barents Sea. The ice movement pattern may be divided into three main phases: (1) a maximum phase when ice flowed out of a centre east or southeast of Kong Karls Land. At this time the southern part of Spitsbergen was overrun by glacial ice from the Barents Sea; (2) the phase of deglaciation of the Barents Sea Ice Sheet, when an ice cap was centred between Kong Karls Land and Nordaustlandet. At the same time ice flowed southwards along Storfjorden; and (3) the last phase of the Late Weichselian glaciation in eastern Svalbard is represented by local ice caps on Spitsbergen, Nordaustlandet, Barentsøya and Edgeøya.

The reconstructed ice flow pattern during maximum glaciation is compatible with a centre of uplift in the northern Barents Sea as shown by isobase reconstructions and suggested by isostatic modelling.

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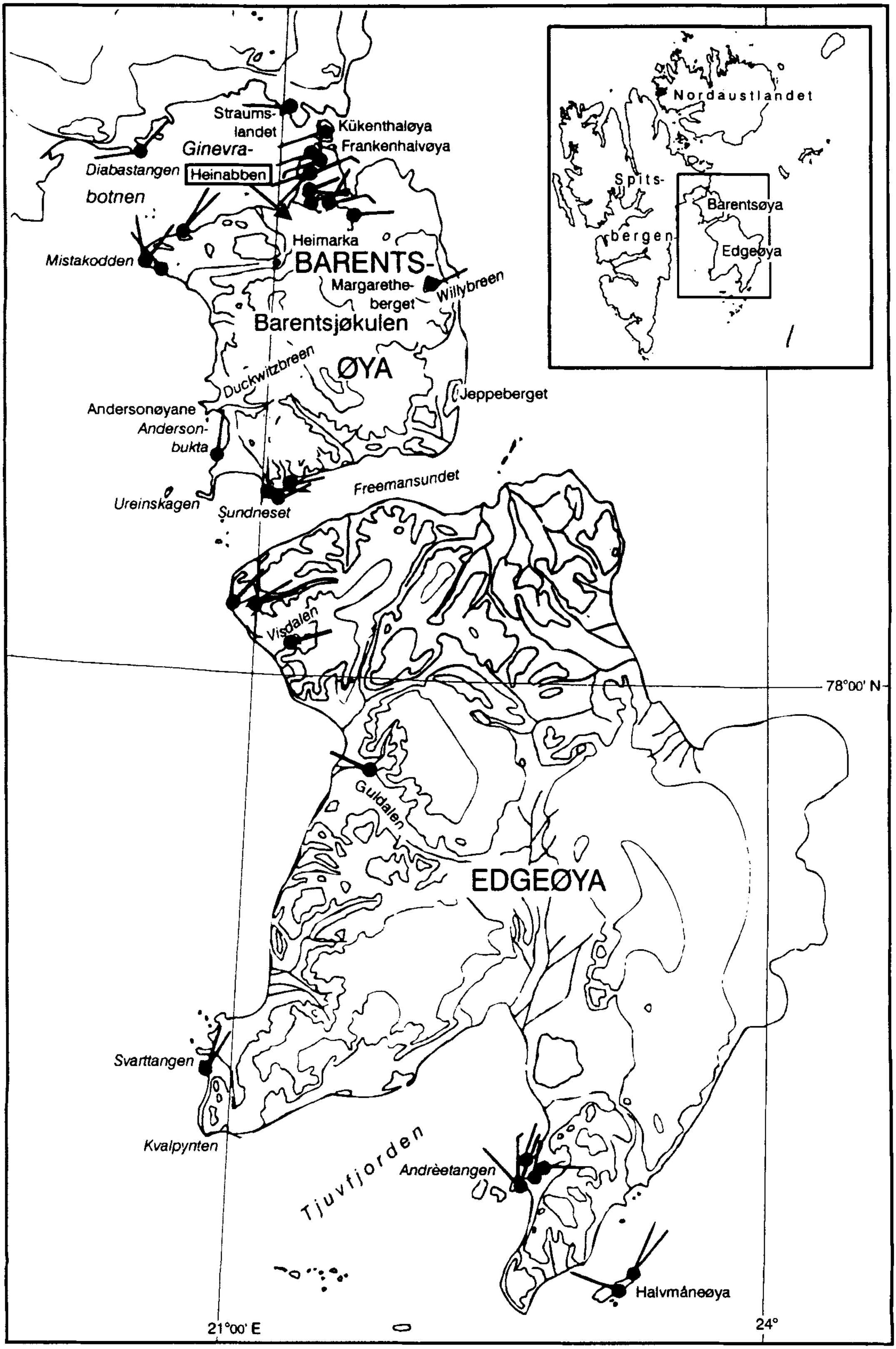
Introduction

The glaciation of Svalbard and the adjacent western Barents Sea has been discussed and disputed for more than 100 years. The presence of a former ice sheet in this area was originally suggested by De Geer (1900). His hypothesis was mainly based on the direction of glacial striae on roche moutonnées and on observations of glacial erratics. Schytt et al. (1968) showed a centre of isostatic uplift in the Barents Sea and interpreted this to be the result of the unloading of a large ice sheet. Later, ice marginal features and glacial flutes on the floor of the Barents Sea also proved the existence of a Late Weichselian Barents Sea ice sheet (e.g. Elverhøi & Solheim 1983; Elverhøi et al. 1993).

The present paper summarises the available evidence of ice movement furnished by indicators such as glacial striae, roche moutonnées, and erratic stones and boulders in eastern Svalbard. The possibilities for the regional use of such ice movement indicators are limited in Svalbard and highly dependent on local bedrock lithology. Weathering has in most places almost completely erased glacial striae, sculpturing and polishing. Only on rocks highly resistant to weathering, for example dolerites, quartzites, granites and gneisses, are the traces of former glaciers well preserved. Thus, owing to the distribution of such bedrocks, glacial striae have been most thoroughly studied in northern Svalbard (Salvigsen 1977; Salvigsen & Österholm 1982; Österholm 1978, 1988). Some directions of glacial striae are also shown on the geological maps in scale 1:100,000 (Winsnes et al. 1993).

Barentsøya, Edgeøya and western Kongsøya (Figs. 1 and 2) were thoroughly searched for ice movement indicators during the 1991 PONAM (Polar North Atlantic Margins, Late Cenozoic Evolution) expedition. The bedrock of these islands consists mainly of poorly consolidated Triassic shales, siltstones and sandstones (Winsnes & Worsley 1981). However, glacial sculpture often occurs on widespread doleritic sills and dykes. Due to varying weathering conditions, the preservation of glacial striae is favoured on outcrops close to sea level, whereas


Nordaustlandet
Spits-
bergen
Barentsøya
Edgeøya
Straums-
landet
Kükenthaløya
Frankenhalvøya
Ginevra-
botnen
Diabastangen
Heinabben
Heimarka
Mistakodden
BARENTS-
ØYA
Margarethe-
berget
Willybreen
Barentsjøkulen
Duckwitzbreen
Jeppeberget
Andersonøyane
Anderson-
bukta
Ureinskagen
Sundneset
Freemansundet
Visdalen
78°00' N
Guldalen
EDGEØYA
Svarttangen
Kvalpynten
Tjuvfjorden
Andrèetangen
Halvmåneøya
21°00' E
24°

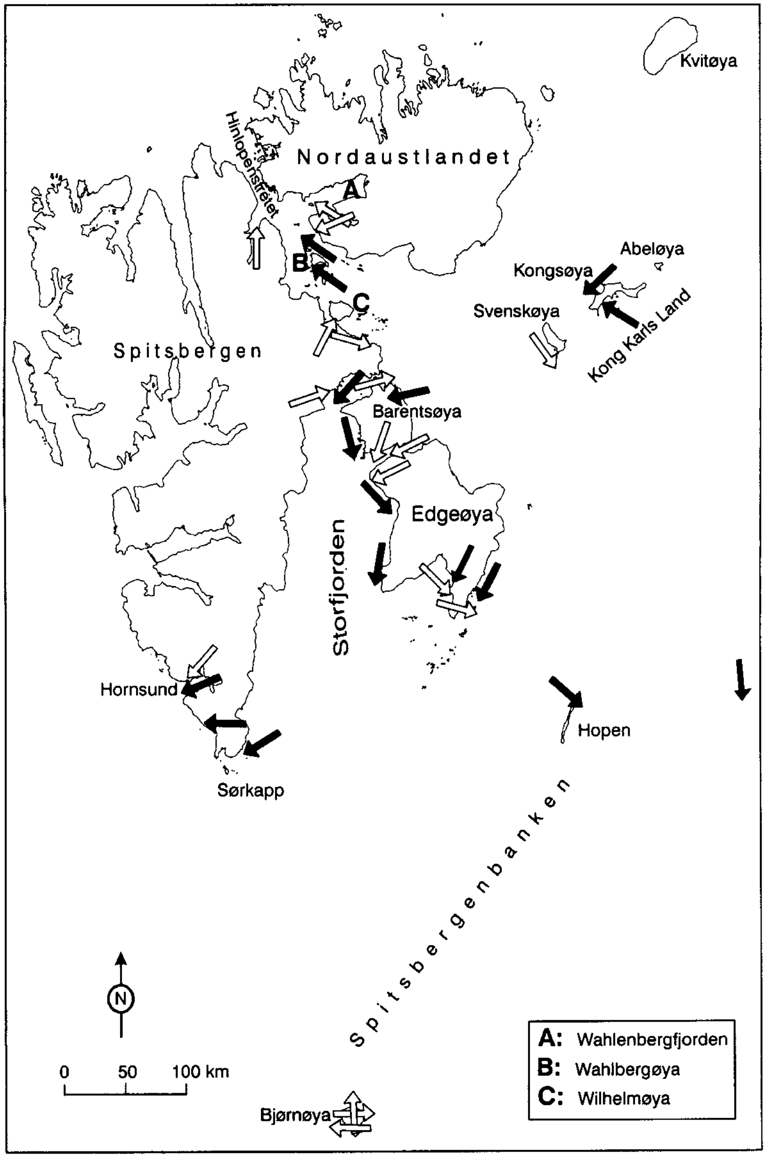


Fig. 2. The map shows a synthesis of the inferred older (solid arrows) and younger (open arrows) phases of ice movement in eastern and southern Svalbard. The reconstruction is based on PONAM observations shown in Fig. 1 and observations from De Geer (1900, 1923), Strømberg (1972), Salvigsen (1981), Solheim et al. (1990) and Salvigsen & Slettemark (1995).

glacial striae are usually lacking at higher altitudes.

The study of ice movement over eastern Svalbard has a long history, and many observations made by Swedish expeditions in the second half of the 19th century are reviewed by Liljequist (1993). Strømberg (1972) reviewed previously published observations and reported new observations of ice movement indicators from southern Hinlopenstretet, Barentsøya and Kong Karls Land (Fig. 2). Some of his accounts are discussed in this paper.

Fig. 1. Location map for the authors' observed glacial striae in the Barentsøya and Edgeøya areas. Ice movement directions are shown as movements towards the observation point (solid black circle). Directions in Visdalen and Guldalen are based on till fabric studies.

Tills and glacial erratics on Barentsøya and Edgeøya

The general till cover on the two islands is very thin and in most places difficult to distinguish from the weathering residues of the Mesozoic sedimentary rocks. In dolerite areas there is often no till cover, and only scattered erratic blocks are found. The sedimentary rocks of the sea floor east of Barentsøya and Edgeøya are difficult to distinguish from those of the islands (Elverhøi et al. 1988). Thus the only source area for characteristic erratics is the crystalline complexes on Nordaustlandet and northeastern Spitsbergen (Lauritzen & Ohta 1984). Some crystalline blocks are found below the marine limit, where their presence can be explained by ice rafting; only blocks of local affinity were found above the marine limit. Even if several plateaux are covered by diamictones of probable glacial origin, it is remarkable that no erratics occur in the highest dolerite areas; an example is the up to 459 m high plateau Jeppeberget on southwestern Barentsøya (Fig. 1).

On southeastern Edgeøya, crystalline erratics, probably from Nordaustlandet (Lauritzen & Ohta 1984), are present at two levels. The uppermost level is a 10 m high zone immediately below the marine limit at 75–80 m a.s.l. (Bondevik et al. 1995). Here, large (up to 1 m in diameter) boulders of black and white, and reddish granites, yellowish-brown weathered augengneiss, migmatites and diorites are found. Their position relative to the marine limit suggests that they were transported by icebergs from the north during the Late Weichselian deglaciation. The second level of crystalline erratics is the present shore zone, where erratic stones, usually <20 cm in diameter, are found. These are clearly ice rafted and indicate renewed calving activity in their source area, most probably during the Little Ice Age (Lefauconnier & Hagen 1991).

In some areas, thicker successions of tills and overlying glacimarine sediments have been preserved and exposed in river and gully sections. In Visdalen on NW Edgeøya (Fig. 1), till fabric in a subglacial till underlying a thick succession of marine sediments shows movement of ice towards the sector W to WSW, that is, down the valley (Möller et al. 1995). In Guldalen on western Edgeøya (Fig. 1), however, till fabric indicates that glacier ice flowed from Storfjorden onto land during a late phase of the last glaciation (Landvik et al. 1992).

Glacial sculpture and striae

Surveys for traces of past glacial activity were particularly made in areas with doleritic bedrock, both during helicopter groundstops and during fieldwork on foot. These ice movement indicators

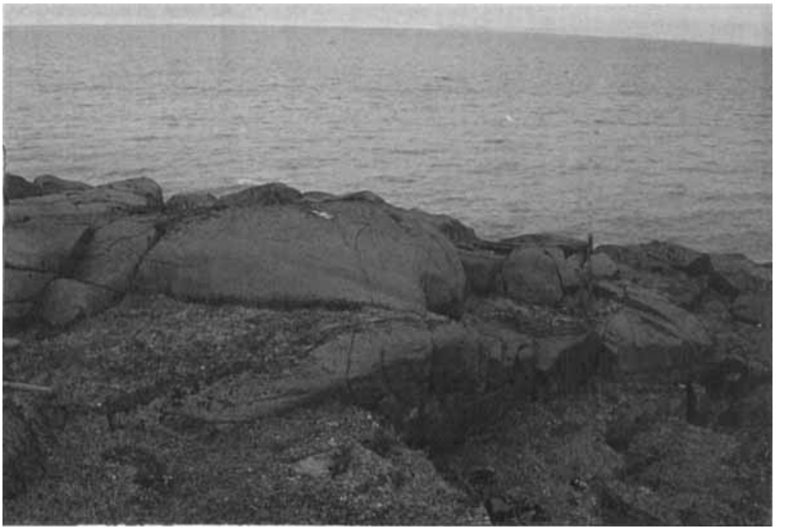


Fig. 3. Mistakodden, Barentsøya. Rock surface near to sea level sculptured by a glacier flow from the north.

are described below according to subarea and discussed in relation to earlier observations from the region. Figs. 1 and 2 show the observations and the inferred ice movement pattern.

Southern Hinlopenstretet

Mesozoic dolerite rocks occur on many islands and along parts of the coasts of southern Hinlopenstretet (Fig. 2). De Geer (1900) observed glacial striae on Wahlbergøya with directions either from the NW or SE. Glacial erratics were also found on high levels on Wilhelmøya. De Geer concluded that a more than 600 m thick glacier had once covered Hinlopenstretet. Later, De Geer (1923) also reported striae directions from the SE at the mouth of Wahlenbergfjorden on Nordaustlandet (Gyldénøyane) (Fig. 2). Striae and glacial sculpturing observed on islands in southern Hinlopenstretet as far south as Wilhelmøya indicate glacier movements from S to SE. However, on some small islands further south (Bastianøyane), well-developed roche moutonnées with striae indicate an ice movement from the W (Strömberg 1972).

From striae on doleritic outcrops along the southern coast of Wahlbergfjorden, Strømberg (1972) concluded two main ice movement directions: (1) from the sector NE to E and (2) from the SE. The former was most probably formed by glaciers only slightly larger than the present ones, whereas the latter was interpreted as formed by an ice-flow from the Barents Sea during the waning stages of the Late Weichselian glaciation (Strømberg 1972).

Northern Barentsøya and adjacent Spitsbergen

Glacial features are well preserved on northern and northwestern Barentsøya. On the summit of Mistakodden (235 m a.s.l.) on western Barentsøya (Fig. 1), De Geer (1900) found striated roche moutonnées with stoss sides facing the NE. He also noted an older set of striae from ENE cut by a younger set from NNE. We also found striae on lower levels which were formed by ice movements both from the NE and from N to NW (Fig. 3). The latter shows the youngest movement.

On both the northern and southern coasts of Ginevrabotten (Fig. 1), Salvigsen et al. (1992) reported several ice movement directions which indicate a complicated system of ice drainage during the final stages of the deglaciation.

On the Spitsbergen side (Diabastangen), roche moutonnées with glacial striae from NE are found together with some vague striae from W. The latter direction is also found further east on Straumslandet.

The dolerite surfaces in the Frankenhalvøya area are rich in ice movement indicators (Fig. 4). Many surfaces on Kükenthaløya and northern Frankenhalvøya are characterised by features

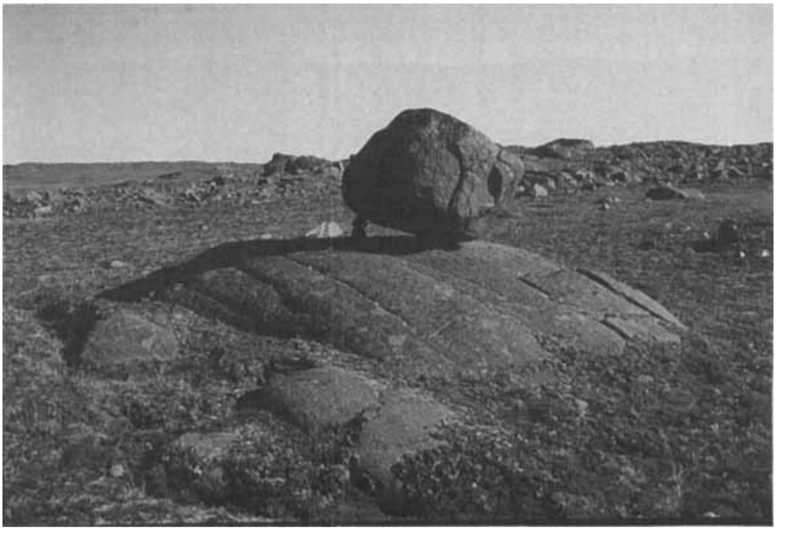


Fig. 4. Plastically sculptured dolerite surface with perched boulder (diameter 1 m) on Frankenhalvøya, Barentsøya. The last glacier movement was from the SW, i.e. from the lower right of the photo.

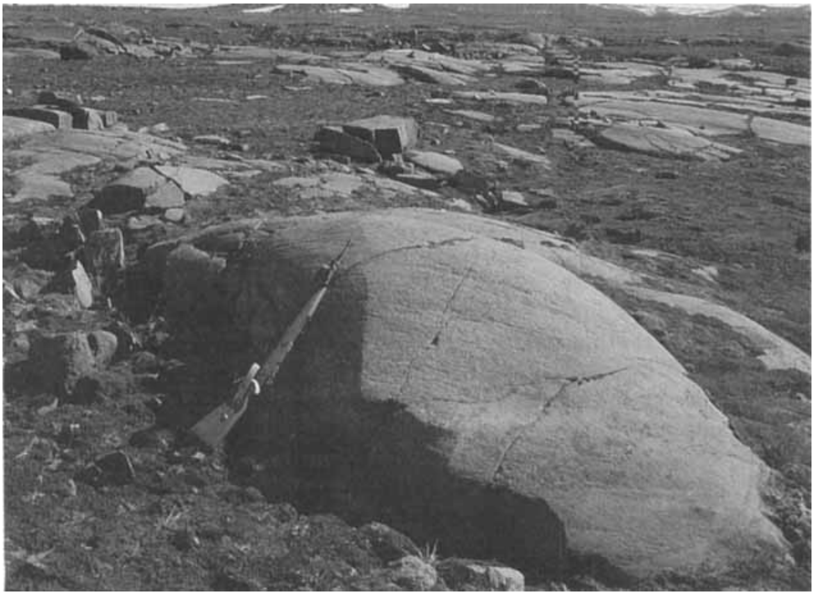


Fig. 5. Frankenhalvøya. Roche moutonnée with two stoss sides demonstrating ice movements from two almost opposite directions. The gun leans toward the oldest surface which is separated from the younger to the right by a distinct edge.

formed by ice flowing from WSW. In addition, vague striae from ice flowing from N and W were seen in a few places.

On the southern part of Frankenhalvøya (Fig. 1) there is an area where roche moutonnées with striated stoss sides facing opposite directions occur (Figs. 5 and 6). The ENE facing stoss sides are usually steeper than those facing WSW, and the two surfaces often meet in a distinct edge. Crescentic gouges and the microrelief on the two surfaces confirm the existence of two almost opposite ice movement directions. The striae on the WSW facing surfaces are usually coarser than those from the ENE. The ice moving from ENE

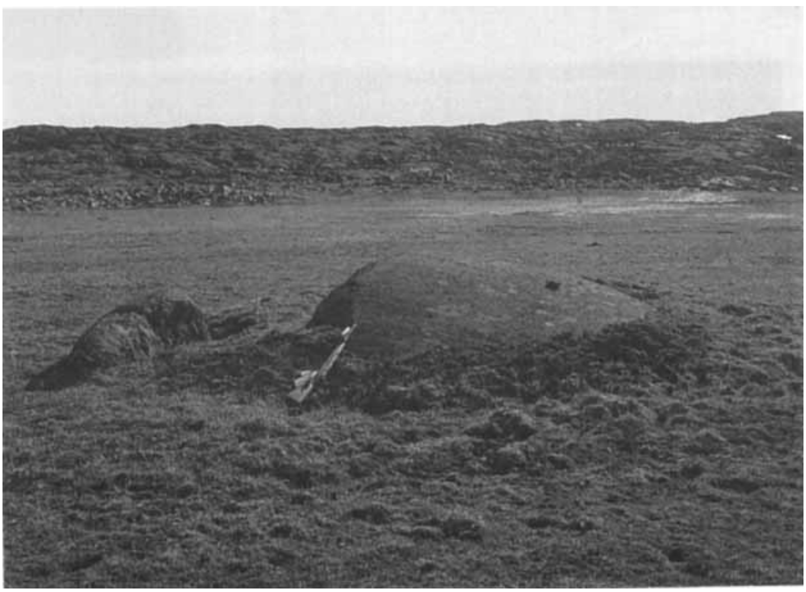


Fig. 6. Frankenhalvøya. Roche moutonnée with a well-developed stoss side formed by ice from WSW. Older glacial sculpturing of ice from the opposite direction is preserved on the lee side. Gun for scale.

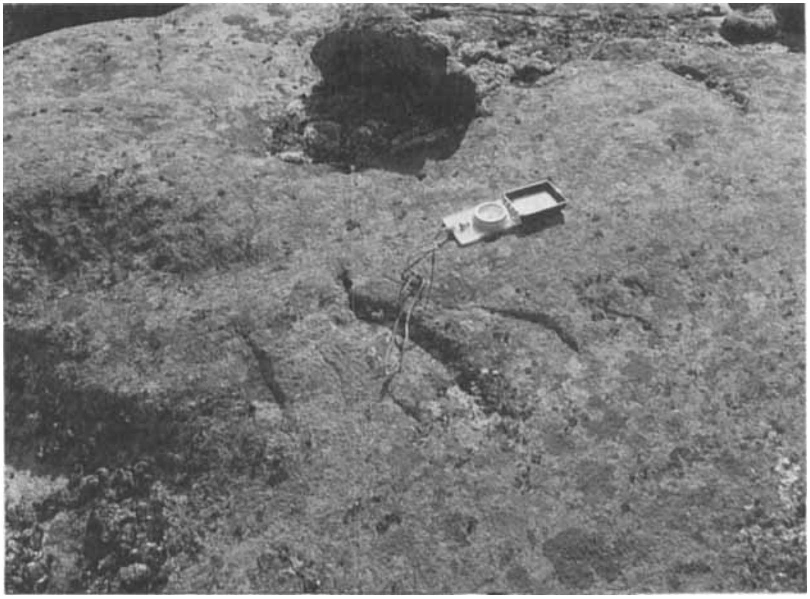


Fig. 7. Heimarka, south of Frankenhalvøya. Crescentic gouges on moderately weathered surface, showing ice movement from the left. Compass for scale.

was able to erode and form striae in small depressions, behind obstacles and on vertical surfaces. This movement probably produced a plastically sculptured landscape with the roches moutonnées. The lee sides of these were subsequently transformed to stoss sides by the ice flowing from WSW. The original stoss sides have in most cases been preserved, probably because plucking was not efficient in the homogeneous dolerite (Figs. 5 and 6). The final result is a landscape sculptured by ice from two opposite directions where roche moutonnées with two stoss sides occur. This type of landscape gradually disappears southwards and northwards, where more regular shapedroches moutonnées with stoss sides facing either WSW or ENE are found.

In Heimarka, south of Frankenhalvvøya (Fig. 1), an area about 200 m a.s.l. was studied. The rocks are more weathered, and only traces of striae from ENE were observed (Fig. 7) (Salvigsen et al. 1992).

Further south, on the highest and most weathered mountain plateaux of the peninsula, small roches moutonnées with striae were observed. Directions from NE to E dominate, but in some places striae from a younger ice flow from the N also occur. On Heinabben (375 m a.s.l.) (Fig. 1), for example, glacial striae show an ice movement from 60°. They are located in a topographical open position which indicates unobstructed ice movement from a centre north of Svenskøya (Fig. 2).

The dolerite nunataks around Barentsjøkulen are heavily weathered and block fields occur in most places. However, a few glacially sculptured surfaces were still preserved on the 503 m high mountain Margaretheberget north of Willybreen, on the east coast of Barentsøya (Fig. 1). Also here, sculpture and striae show a flow direction from the ENE.

Western Freemansundet

On Andersonøyane near Duckwizbreen (Fig. 1), De Geer (1900) found evidence for an ice movement from the NE. On Sundneset (Fig. 1), Büdel (1960) found a main set of striae directed from ENE and another set from the west. Based on these observations, he made models for different stages of the Late Weichselian glaciation in eastern Svalbard (Büdel 1960).

The dolerite intrusions on Sundneset and on the north–south trending ridge from the Ureinskagen peninsula to Andersonbukta were studied in detail by Salvigsen et al. (1992). Roches moutonnées and glacial striae formed by a southward moving glacier in Storfjorden occur, but striae on the eastern part of Sundneset show a younger ice flow direction from the ENE (Salvigsen et al. 1992).

An analysis of all observations indicate at least two separate systems of ice flow. The older striae system shows a gradual change in ice flow directions from about N to NE (5° to 30°). A reconstruction of flow-lines (Fig. 1) gives a converging pattern showing confluent ice streams in Storfjorden and over Edgeøya. The youngest striae in the area east of Sundneset are probably from a glacier in Freemansundet, fed from glaciers on the plateaux of southern Barentsøya and northern Edgeøya.

Southern Edgeøya and Halvmåneøya

In the area north of Kvalpynten on southwest Edgeøya (Fig. 1), De Geer (1900) found glacial striae. He concluded that the striae could not be from a local glacier but must have been formed during a total glaciation of Storfjorden. We searched for striae in all areas with outcrops of dolerites; a more detailed documentation is found in Salvigsen et al. (1992). Close to sea level at Svarttangen (Fig. 8), north of Kvalpynten (Fig. 1), striae from the NNE are found on plastically sculptured dolerite.

On the Andréetangen peninsula in eastern Tjuvfjorden (Fig. 1), most striae run from N–NE, parallel to the fjord. Locally, these are cut by younger striae from the E, probably formed by local glaciers in the mountains during the last deglaciation.

The small island Halvmåneøya (Fig. 1) consists entirely of dolerite. The whole island is below the marine limit, and the rocks have experienced both marine abrasion and weathering subsequent to the glacioisostatic uplift. However, several smaller areas with glacial sculpturing and some surfaces with glacial striae have been preserved. On the northernmost part of the island, well-developed roches moutonnées show an ice movement from the NE (Fig. 9). This general ice flow direction is supported by glacial striae at several other sites. At some places, the striae cut remnants of deep weathering pits on the sculptured surfaces.

These features indicate that the island at least once was overrun by an extensive glacier which moved out of the northern Barents Sea and sculptured the rocks. This phase was succeeded by a period of subaerial weathering, whereafter a second less erosive ice-flow from the NE followed. A distinct set of striae from the WNW is found at one site. This ice movement from Edgeøya was probably the youngest one, and steered by calving of the Barents Sea Ice Sheet southeast of the island.

Southern Spitsbergen

On southernmost Spitsbergen, east of Sørkapp (Kikutodden and Tresteinane) (Fig. 2), De Geer (1900) observed that the stoss sides of roche mou-

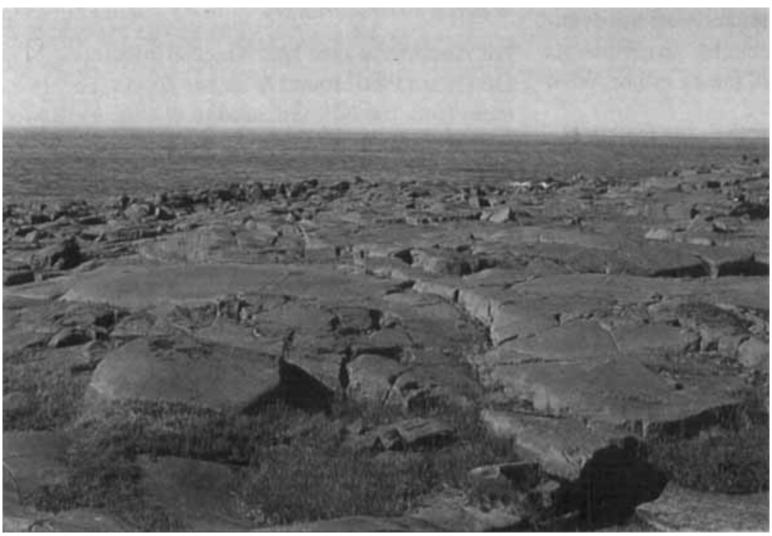


Fig. 8. Svarttangen, Edgeøya. Rock surface with ice movement indicators from a glacier moving southwards in Storfjorden.

Fig. 9. Halvmåneøya. "Old" sculptured surface formed by ice from the NE, from the lower to the upper part of the photo. Compass for scale.

tonnées were dipping towards the NE. He found glacial erratics in the mountains of southern Sørkapp Land and concluded that the ice in Storfjorden had been at least 700 m thick. He also suggested that glacier ice from Storfjorden reached the western coast of Spitsbergen through the low passes (250 m a.s.l.) east of Hornsund. This model was recently confirmed by Salvigsen & Elgersma (1993). The pattern of glacial striae south of the Hornsund fjord (see also Winsnes et al. 1993) indicates that Hornsund was filled with a very active glacier, probably fed by a massive overflow from Storfjorden. Such a topographically independent ice movement from the east is also supported by glacial striae with a roughly E–W direction on the coast about 20 km south of Hornsund (Salvigsen & Elgersma 1993).

The ice movement indicators in Sørkapp Land show that the southern part of Spitsbergen was overrun by glacial ice from the Barents Sea.

Kong Karls Land

Kong Karls Land (Fig. 2) has always had a key position in the discussion of the glacial history of the northwestern Barents Sea. The islands of Kong Karls Land consist of sedimentary rocks from the late Triassic to early Cretaceous, protected by caps of basalt of early Cretaceous age (Lauritzen & Ohta 1984).

Nathorst (1901) was the first to study its geology, and found erratics of granite, gneiss and quartzite up to 273 m a.s.l. Büdel (1968) reported granite boulders at 170 m a.s.l. on Svenskøya. Also, Salvigsen (1981) observed such erratics above the Holocene marine limit (ca 100 m a.s.l.) and concluded that they were indisputable traces of a former extensive glaciation. The source areas of these erratics is most likely Nordaustlandet or Kvitøya (Fig. 2) (Lauritzen & Ohta 1984). Numerous erratics are also found below the marine limit where most of them have been transported by ice rafting.

Nathorst (1901) observed some striated boulders on Svenskøya and Kongsøya, but no in situ striated rock surfaces. However, Büdel (1968) reported glacial striae with many different directions from Abeløya east of Kongsøya (Fig. 2). Based on his experiences from other weathered doleritic areas in Svalbard, Strömberg (1972) questioned the glacial striae on Abeløya. From Kongsøya, he described an apparent stoss and lee topography and even fine-striated surfaces, which he concluded to be the result of weathering and exfoliation (Strömberg 1972). But Strömberg (1972) also found distinct glacial striae at two sites on Kongsøya and considered them to have been formed by local glaciers of modest extent. Ingólfsson et al. (1992) revisited the sites but were unable to find any traces of glacial sculpturing. They concluded that Strömberg's sites no longer existed due to rock fall and weathering (Ingólfsson et al. 1992).

Salvigsen (1981) searched Svenskøya and eastern Kongsøya thoroughly for traces of former glaciation and found only one very small basalt surface near the southern tip of Svenskøya where glacial sculpturing was preserved. Crossing glacial striae and crescentic gouges show glacier movement from NNW and the N.

From stratigraphic studies of glaciotectonised marine and glacial sediments, Ingólfsson et al. (1995) found that the deforming glacier had moved across Kongsøya from an ice divide east of Kong Karls Land, some time during the Weichselian.

The ages of the striae etc. on Kong Karls Land are not known, but the different directions probably mainly reflect different stages of the Late Weichselian glaciation. The glaciotectonic deformation of the older sediments on Kongsøya (Ingólfsson et al. 1995) probably belong to a maximum stage when the ice was centred east of Kong Karls Land (Elverhøi et al. 1993; Lambeck 1995). The striae on Svenskøya may be younger, perhaps formed during ice recession when deglaciation of the Barents Sea had started and ice remains covered Nordaustlandet and Hinlopenstretet.

The Barents Sea, Bjørnøya and Hopen

Both sedimentological and morphological evidence for a Late Weichselian glaciation of the Barents Sea have been presented by Elverhøi & Solheim (1983), Solheim et al. (1990) and by Elverhøi et al. (1993). Glacial flutes and transverse ridges on the sea floor have been identified as far south as 74°55′N, proving the former existence of grounded glacier ice in the northern Barents Sea. The reconstructed ice had predominantly a southerly flow direction before the final retreat.

Roche moutonnées and glacial striae on the shores of Hopen (Fig. 2) were reported by Hoppe et al. (1969), but later rejected after reinvestigation (Hoppe 1981). Large glacial flutes oriented roughly NNW–SSE on the mountain plateau (200–280 m a.s.l.) on northern Hopen were suggested by Kristiansen & Sollid (1986). However, this interpretation was made from air photos and the genesis of the structures has not yet been confirmed by ground observations. On Bjørnøya (Fig. 2) only striae from glaciers centred on the island itself have been observed, and there is no evidence for any regional ice movement from the Barents Sea (Salvigsen & Slettemark 1995).

Pattern of Holocene emergence

The hypothesis of an ice sheet centred in the Kong Karls Land area is strongly supported by the Holocene emergence pattern of Svalbard. This was first shown by Schytt et al. (1968), who presented the isobases for the 6500-year-old shore line on Svalbard and Franz Josef Land, in many places identified by the occurrence of pumice at this particular raised beach. This pattern of emergence indicated that the last ice sheet was centred east of Kong Karls Land. Boulton (1979), however, suggested pre-Late Weichselian ages for the highest beaches on Kong Karls Land and believed that these islands had not been glaciated during the Late Weichselian, except for small local glaciers. However, Salvigsen (1981) showed that beaches up to 100 m a.s.l. were of Holocene age, an elevation that only can be explained by rebound from a major late Weichselian ice sheet.

Forman (1990) reviewed many emergence curves from Svalbard and concluded that Nordaustlandet, the islands of eastern Svalbard, and central Spitsbergen had sustained the greatest glacier loads during the Late Weichselian. Later reconstructions of the 10,000 BP isobase (Bondevik et al. 1995) and the 5000 BP isobase (Forman et al. 1995) close in upon a centre of uplift in the northern Barents Sea, southeast of Kong Karls Land. An ice sheet with its maximum thickness in this area is also compatible with the results obtained from glacial rebound modelling based on the mapped uplift (Lambeck 1995, 1996), whereas glaciological ice-sheet models so far have failed to reproduce such an extensive ice sheet (e.g. Siegert & Dowdeswell 1995).

Our reconstruction of the oldest ice movements (Fig. 2) is compatible with ice flow from a centre over the northern Barents Sea. This suggests that the Barents Sea Ice Sheet at this time had its maximum surface elevation to the southeast of Kong Karls Land. Such a configuration corresponds with the location of the largest ice thickness as indicated by both the Holocene uplift pattern (Bondevik et al. 1995; Forman et al. 1995) and the isostatic models (Lambeck 1995, 1996).

Summary and conclusion

Observed glacial striae and other ice movement indicators provide information about the glacial history of southeastern Svalbard and the adjacent

Barents Sea. The absolute ages of the reconstructed ice movements are more speculative. However, stratigraphic studies in the region have shown that eastern Svalbard experienced extensive glacial erosion during the last glaciation (Landvik et al. 1995), suggesting that most of the glacial striae and related features are of a Late Weichselian age. Using the relative ages between different ice flow directions at the individual localities, the ice movements may be grouped into three main stages of glacial flow:

1. The most extensive stage of the Late Weichselian glaciation in the Barents Sea is shown by the deformed sediments on western Kongsøya (Ingólfsson et al. 1995) and the mapped subglacial flutes and sediment accumulations on the sea floor east of Hopen (Solheim et al. 1990; Elverhøi et al. 1993). On land, the oldest glacially sculptured bedrock with striae shows ice movements from a Barents Sea ice sheet centred in the area of Kong Karls Land or north of it. Observations, especially from high-lying positions on northern Barentsøya, indicate that ice flowed from a centre between Kong Karls Land and Nordaustlandet for a long enough period to establish a consistent pattern of glacial sculpturing with striae over a wide area. Also, our southernmost observations from Halvmåneøya demonstrate an ice movement from a northern Barents Sea ice sheet.

2. After the disintegration of the Barents Sea ice sheet, there are indications of ice flow from glaciers centred on eastern Spitsbergen and in northern Storfjorden. A local ice stream crossed northernmost Barentsøya, flowing from about WSW to ENE. Along western Barentsøya the glacier flow was southwards along Storfjorden. Features resulting from this southward flow can be seen on dolerite outcrops on southwestern Barentsøya as well as on southwestern Edgeøya.

3. The youngest striae in the area were probably formed by local glaciers on Barentsøya and Edgeøya during a late phase of the last deglaciation. Most of the glacial sculpturing and striae at Sundneset may be from a glacier in Freemansundet fed from high-lying areas on southern Barentsøya and northern Edgeøya, but an earlier age can not be excluded.

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