Large-scale patterns of glacial streaming flow deduced from satellite imagery over Sør-Trøndelag, Norway

Bjørn A. Follestad

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Streamlining features such as drumlinoid forms and glacial striations, deduced from satellite imagery and maps over the Oppdal area, show distinct streamlining patterns that indicate the passage of a marked northeasterly-directed ice-stream across the area. This ice- flow had its origin in an ice-dome/ice-shed in the high plateaus of west central Norway. In the southern parts of the Oppdal area cold-bridges formed in the mountains of Skrymtheimen during an early phase of this glaciation/deglaciation and here the inland ice froze to the ground surface. Wet-bedded conduction appears to have existed in the lower plateau areas. The ice-flow divided into a western and an eastern branch, moving on both sides of the Skrymtheimen mountains. The westerly branch of this flow moved in a northeasterly direction traversing the deep valleys of Sunndalen and Gjevilvatnet. The relief amplitudes are here 800-1000 meters, and the ice flow must have been more than 1600 meters thick to overcome the prevailing relief. Throughout the phase of deglaciation in Scandinavia the thickness of the inland ice decreased and the influence of the topography (terrain amplitude) increased towards the end of glaciation, first in the western parts of the Oppdal area where deep valleys dominate and later in plateau areas in its eastern parts. Lateral moraines formed in some of the valleys, and were used to reconstruct a glacial surface extending in a westward direction. Tentatively this surface is correlated with an earlier described glacier surface in the Oppdal area formed during the YD (Younger Dryas) Chronozone. In the eastern parts of the Oppdal area this northeasterly ice-flow seems to have continued in the YD Chronozone. Deviations in the marked northeasterly directed streamlining features towards Drivdalen valley occur. This is to be expected as the remaining inland ice in the eastern parts of the Oppdal area served as source areas for ice-flows emanating from this plateau area into the valleys where valley glaciers formed and flowed in a westward direction. Streamlining features with a westerly trend were later developed in the most easterly parts of the Oppdal area and together with lateral moraines belong to a late phase of the YD Chronozone.

Bjørn A. Follestad, Geological Survey of Norway, NO-7491 Trondheim, Norway.

Introduction

Reusch (1905) pointed out that in the Oppdal area major landforms are preglacial in age but have a glacial imprint in the western areas. Tills are the dominant superficial deposits, and show an increase in thickness to the east, southeast and south. In the geomorphological and geological record elements aligned parallel to the ice-flow form potentially the most powerful tools for reconstructing paleo ice-flow patterns as indicated by Kleman (1990), Kleman & Borgstrøm (1996) and Sollid & Sørbel (1994).

The purpose of this paper is to use a large-scale pattern analysis of glacial streamlining features deduced from a SPOT 5 satellite image (with a pixel resolution of 5m x 5m) together with observations of striations, lateral moraines (Sollid 1964) and lateral melt-water formations (Follestad 2003a) to:

(1) describe the deglaciation of the southern parts of Sør-Trøndelag County and
(2) establish a base for understanding the deglaciation dynamics of the area and thereby updating the existing model.

In this paper, SPOT 5 satellite image (reference no. 038221_020823) data, and map data recorded during revisions of existing Quaternary maps at scales of 1:250,000 (Reite 1990), 1:100,000 (Sollid et al. 1980), 1: 75,000 (Follestad 2005) and 1:50,000 (Sollid & Sørbel 1979; Follestad 1994a, 1994b, 2003b), are used.

Data for reconstruction of ice-flow extent and sub-glacial conditions

Striations on exposed bedrock, or below till surfaces, are important features for reconstructing former distributions of ice-sheets and ice-flow patterns in Scandinavia, (e.g., Hørbye 1857; Holtedahl & Andersen 1960; Kleman 1990). Most of these studies are based on the observation of striations on exposed bedrock. Striations situated on rock surfaces in sheltered positions and may be left untouched when the ice-flow changes direction, and can thus frequently be used to give information about successive ice flows.

Till lineations are elongated flow-aligned ridges, wholly or partly composed of till. These have also been used for deductions about former ice-sheets and ice-flow patterns, e.g., Punkari (1980, 1995), Sollid & Sørbel

(1994) and Kleman & Borgstrøm (1996). This term will, in most papers, include drumlins, crag-and-tail ridges and flutes in different stages of maturity. Kleman & Borgstrøm (1996) emphasized that these forms for lineation (streamlining) can only be formed subglacially under wet-based glacial conditions and were continuously created and reshaped as new, flow-aligned lineaments were produced and destroyed. In this manner, a pattern of flow-aligned lineaments indicating the same flow-direction does not have to be synchronously developed, but more likely was formed over a period of time. Streamlining on rock surfaces can, in some cases, be difficult to separate from tectonically derived features such as rock lineations, foliation and fractures. However, the scale-enlarged satellite image used in this study has made the analysis of the different forms rather straightforward and allowed separation to be made in most cases. If there have been doubts about the genesis of any features observed on the satellite image, they have been omitted from the compilation.

Ice-marginal forms and patterns of marginal systems of meltwater channels have been important sources of information for studies of deglaciation models in the Scandinavian mountains, e.g. Hansen (1886), Mannerfelt (1940), Gjessing (1960) and Andersen (1954, 1960, 1968), Sollid (1964), and more recently Reite (1990, 1994), Kleman & Borgstrøm (1996) and Follestad (2003a).

Block fields are well developed above 1400 m a.s.l. in this area (Follestad 2005). The limit between the till and block fields is often very distinct and is used in this paper as an indicator of areas where the glacier was wet-based (lower-lying areas) or dry-based (cold, and at a higher elevation). The lack of fluting in the block fields, represented as blue/white coloured areas on the Spot 5 scene, strongly supports this view regarding cold-based glacial conditions, as is the case over extensive areas of the Snøhetta mountains (Figs. 1 & 8). Further description of the study area follows the subdivision (framed areas) shown in Fig. 2.

Fig. 1. Location map of the described areas in the surroundings of Oppdal Municipality (gray box) and the areas covered in the SPOT 5 scene (boron box), which has been used in this study.

Regional description

The regional description of the area follows a sequence of images (Fig. 2) based on the SPOT 5 satellite image (reference no. 038221_020823).

The Jærhøa - Storhornet area

The Jærhøa-Storhornet research area (Fig.3) is situated in the northwestern part of the studied area and is characterized by high mountains such as Storhornet (1589

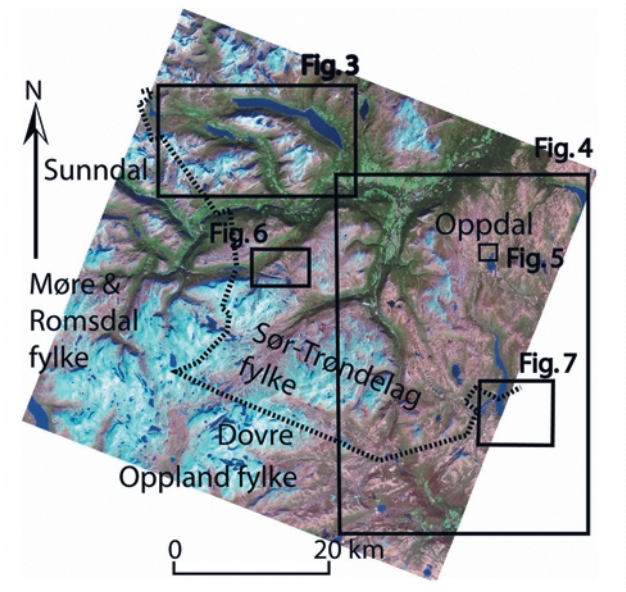

Fig. 2. A colour-coded SPOT 5 scene (resolution 5m x 5m) provided by Statens Kartverk over the Oppdal area. The different test areas are outlined and numbered using caption numbering (Figs 3 to 7). Their relation to county boundaries is also evident.

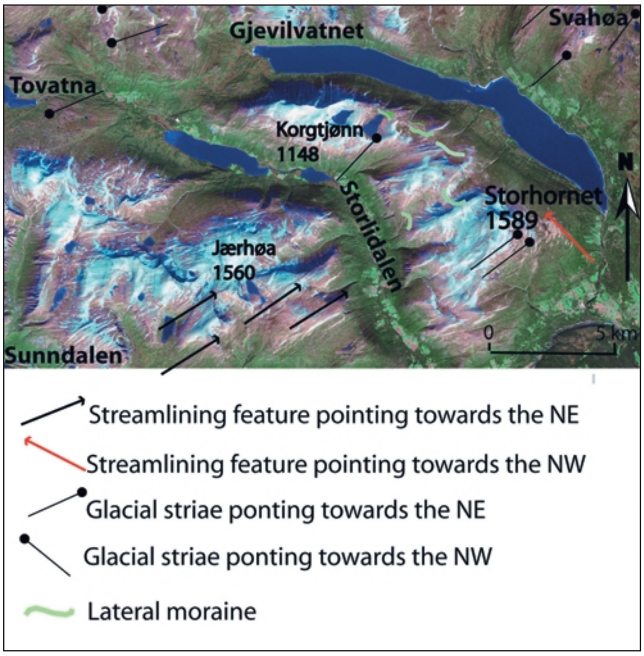

Fig. 3. Colour-coded SPOT 5 image covering the lake Gjevilvatnet area. Streamlining features such as flutes and glacial striae are shown together with lateral moraines in the area.

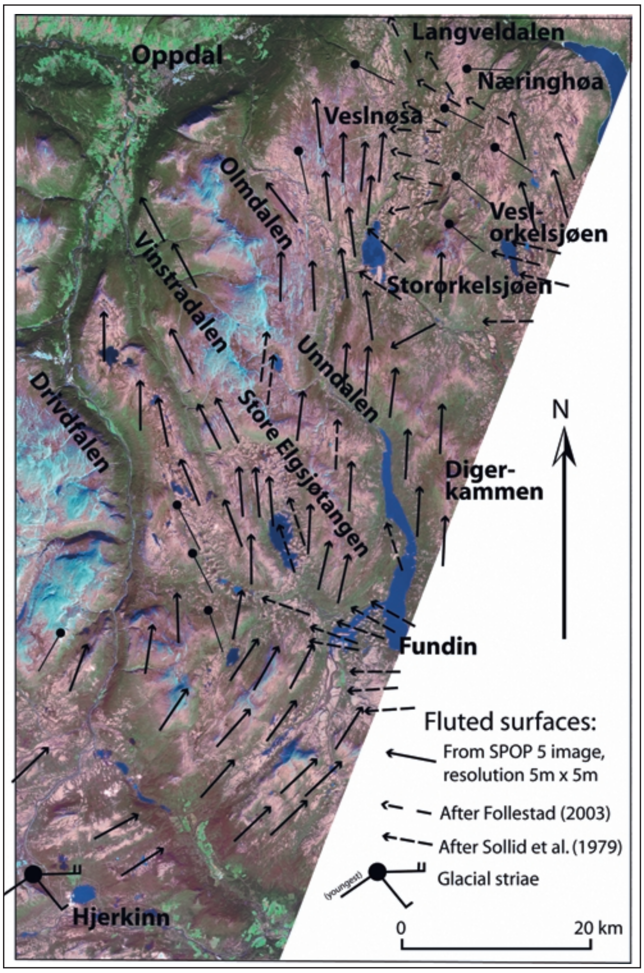

Fig. 4. Colour-coded SPOT 5 scene covering the Hjerkinn – Langveldalen area. Streamlining features such as flutes and glacial striae are shown. Observations of flutes and drumlinoid forms in earlier studies are shown together with observations based on the SPOT 5 scene.

m a.s.l.) and Jærhøa (1560 m a.s.l.) which lie between the valley of Sunndalen to the southwest and the valley occupied by the lake Gjevilvatnet to the north.

Ice-streamlining on rock surfaces and a thin cover of till, are seen on the ridges and plateaus in the mountains between the valleys of Sunndalen and that occupied by Gjevilvatnet i.e. south of the mountain Jærhøa (1560 m a.s.l). Here, at an altitude of 1200-1300 m a.s.l. streamlining features are observed pointing towards the northeast. These northeasterly directed features can further be seen on the southern side of the mountain Storhornet at an altitude of 1200 - 1300 m a.s.l. On the southern side of Gjevilvatnet (at Korgtjønn (1148 m a.s.l.), and in the mountainous areas northeast of this lake, glacial striations point in a northeasterly direction. These streamlining features formed outside the areas occupied by a former glacier in the Gjevilvatnet area, marked by lateral moraines north and east of the lake Korgtjønn. In the mountains of the Svahøa area northeast of Gjevilvatnet and further northward, streamlining features such as glacial striae point in a northeastly direction (Follestad 2004).

Lower-lying flutes and glacial striations along the eastern side of the Storhornet mountain and south of the Svahøa mountain on the eastern side of Gjevilvatnet, point towards northwest. These streamlining features turn more westerly as we follow the valley occupied by Gjevilvatnet towards the valley in which lake Tovatna lies, and are considered to have been formed by a topographically dependent ice-flow.

The Hjerkinn – Veslnøsa area

The Hjerkinn – Veslnøsa area (Fig. 4) is situated in the eastern parts of the Oppdal Municipality. This area is characterized by high mountains, for example, the mountains of Snøhetta (2286 m a.s.l.) in the western parts, and the plateau area of Store Elgsjøtangen and the Stororkelsjøen lake district in the eastern part. The central part of the Drivdalen valley area is eroded and follows a north-south direction from Hjerkinn in the south to Oppdal in the north. Tributary valleys, such as Vinstradalen and Olmdalen-Unndalen, join Drivdalen from the east.

Streamlining features on rocks and in thin covers of till are frequently seen on the plateaus of Store Elgsjøtangen and in the basins of lake Fundin and Stororkelsjøen. These features consist of flutes and drumlinoid forms of different sizes and shapes (Fig. 5). In the Hjerkinn area these forms are orientated towards the northeast. Further to the east and north these features are more orientated to the north-northeast, and later on, to the north. In the area of Veslnøsa mountain northerly streamlining features dominate (Follestad 2003a).

On the valley slopes (shoulders) along the eastern side of Drivdalen we see marked streamlining features tangential to the valley direction. However, it is obvious that from a certain point in time the relief amplitude influenced more and more the ice-flow causing it to take a northwesterly direction, as seen, for example, in the valleys and on the valley shoulders of Olmdalen and Vinstradalen (Fig. 4).

In the areas west of Drivdalen, streamlining features are not observed in the boulder- rich areas characterized by the blue colours in Fig 4. On the western valley shoulder of Drivdalen, streamlining features are orientated to the north following the direction of the main Drivdalen valley.

In the areas of the Oppdal municipality bordering Hedmark county (Fig.1), marked westerly orientated streamlining features occur in the Stororkelsjøen lake area (Follestad 2003b) and in the basin of lake Fundin (Sollid & Sørbel 1979). In the areas north of Stororkelsjøen Follestad (2003b) showed that the corresponding ice-flow forming these streamlining features did not cross the mountain Veslnøsa (see Fig 4 and 5), as these features are absent here. In the areas southward to the basin of lake Fundin these westerly orientated streamlining features are frequently seen, as shown by Sollid & Sørbel (1979). (See the Fundin lake area, Fig. 7). In the areas north of Stororkelsjøen these streamlining features diverge fan-like. Such forms are usually observed in marginal tongue positions of an ice- flow and are thus considered to be formed in close connection with the marginal deposits shown on the maps of Sollid & Sørbel (1979) south of Stororkelsjøen.

The Dindalen area.

The Dindalen area is situated west of the valley of Drivdalen on the border between the counties of Sør-Trøndelag and Møre & Romsdal (Figs. 2 and 6). On the uplifted plateau south of the Dindalen valley marked drumlins are seen. These are up to 2 km long and have a relief of a few meters. They point in a northwesterly direction. On both sides of the Dindalen valley, marked flutes and smaller streamlining features occur, all pointing to the northwest.

A conspicuous set of marginal moraines has been deposited along the southern side of the Dindalen valley. This moraine belt can be followed from an altitude of 830 m a.s.l. on the valley floor of Dindalen up to c. 1300 m a.s.l. As the horizontal distance is about 15 km, this gives a vertical gradient of c. 33 m/km. It seems

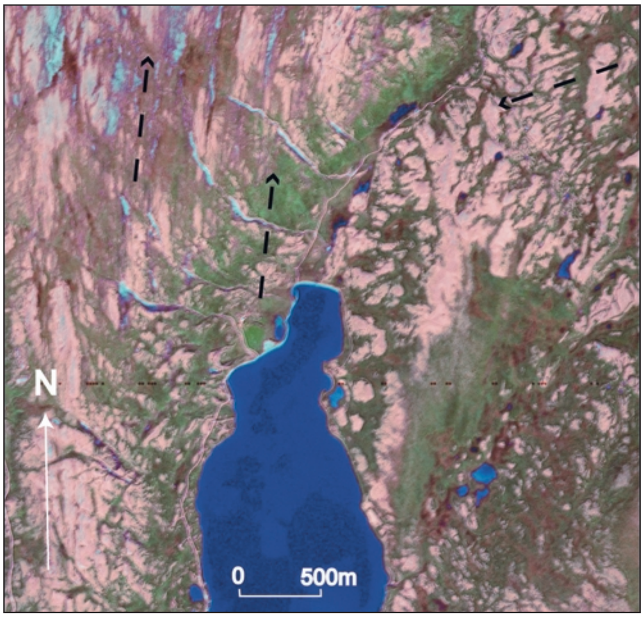

Fig. 5. Colour-coded SPOT 5 scene from the areas north of Stororkelsjøen. To the left streamlining features (mostly flutes) can be seen on bare rock surfaces shown by the blue colour on the image, and on the thin cover of till shown with reddish colors. Small drumlins up to 100 meters are seen in the upper left part of the image. It should be noticed that these features do not continue across the northerly orientated streamlining features to the left.

reasonable to argue that the lateral moraine belt was formed during a standstill period or re-advance of the Dindalen valley glacier. Sollid et al. (1980) describe lateral moraines in the Sunndalen valley which might represent a possible continuation of the lateral moraines in Dindalen to the west. These formations in Sunndalen are believed to have been formed during the Younger Dryas (YD) Chronozone (Sollid et al. 1980).

The Fundin lake area.

The Fundin lake area (Fig. 7) represents the western parts of Einunndalen and has played an important role in the deglaciation history of central Norway where the highest run-off passes to the Sør-Trøndelag areas occurred (Holmsen 1915). The map of Sollid & Sørbel (1979) shows distinct areas of fluted surfaces pointing to the northeast in the area of Kvittjørnin, north-northwest in the areas of Elgsjøen and west of the lake Fundin. These directions are also seen on the Spot 5 imagery which covers the western parts of the area (see Fig 4).

In the areas south and east of lake Fundin fluted surfaces and drumlins show a westerly trend according to Sollid & Sørbel (1979) and this can also be seen further east in the Einunndalen valley. It should however, be noted that northeastward orientated streamlining features are seen on the elevated plateau area

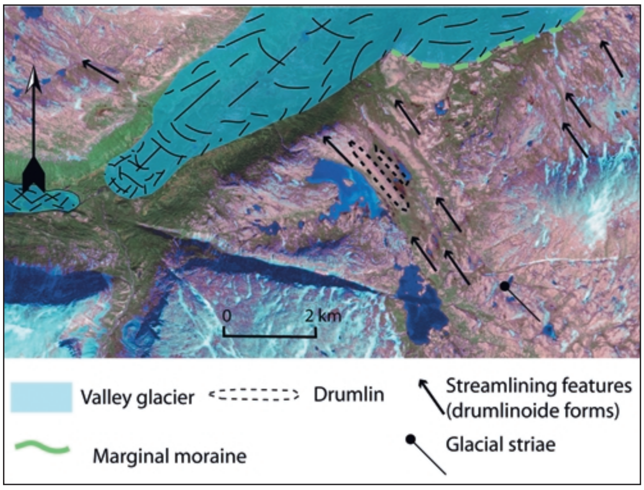

Fig. 6. Colour-coded SPOT 5 scene from the Dindalen area. The extension of the supposed Younger Dryas (YD) glacier is superimposed on the image together with lateral moraines. Two conspicuous drumlins are seen in the central parts of the image. Streamlining features occur on both sides of the valley of Dindalen and are indicated on the image by arrows.

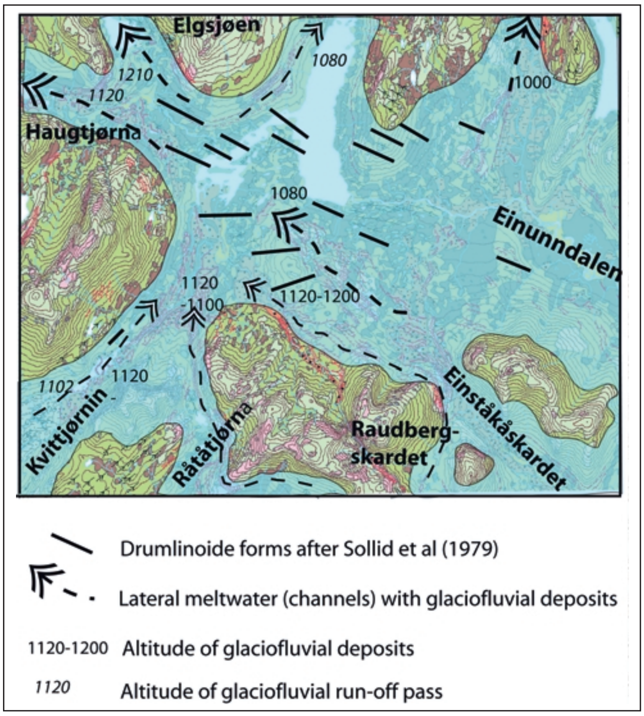

Fig. 7. Two ice-flows merged in the upper parts of Einunndalen. The numbers shown at the ends of the mapped lateral/subsurface meltwater channels indicate the top levels of the glaciofluvial formations. The latter can be related to these meltwater channels and formed when the meltwater reached the saturated zone in the subglacial meltwater table in the ice body. This was determined by the melt-water passes shown in the valleys occupied by Elgsjøen and Haugtjørna (lakes), situated at 1120 m a.s.l. and 1210 m a.s.l. respectively. This meltwater drainage was subglacial and thus indicates the existence of a glacier in the Einunndalen area when an ice-flow entered the area through the valleys of Kvittjørnin, Råtåtjørna and Einståkåskardet from the Hjerkinn-Folldal area. Later, the lower-lying run-off pass at an altitude of 1080 m a.s.l. at the northern end of the Fundin lake took over the melt-water drainage of the upper parts of Einunndalen .

of Digerkammen (Fig. 4) and on high plateaus further to the east. As the northeasterly directed streamlining features and the westerly orientated streamlining features cannot have formed simultaneously, they are considered to have formed during different stages of the deglaciation.

Sollid (1964, 1968) found that the Knutshø lateral moraine system in the Hjerkinn area points northwards through Drivdalen and south-eastwards into the valleys of Kvittjørnin (1104 m a.s.l.) and Råtåtjørna (1169 m a.s.l), from a glacier that occupied parts of the upper Folldal valley (Fig. 7). Due to the altitude of the lateral moraines and meltwater formation in the valleys of Kvittjornin and Råtåtjørna respectively, the thickness of the ice in these passes is estimated to have been about 100 metres.

The marked lateral meltwater channels along the southern side of Einunndalen as well as the sub-glacially formed melt-water deposits further north through the area of Haugtjørna demonstrate that a lateral glaciofluvial drainage took place in this direction when the ice surface in Einunndalen was c. 1150-1200 m a.s.l. Evidence for a south-westerly drainage from Einunndalen to the Hjerkinn area has been observed in the passpoint area. Thus it is suggested that the glacier in Einunndalen made a small re-advance, as is illustrated by the streamlining features (in the Fundin lake area), when the formation of the Knutshø moraine system took place in the Hjerkinn area. Hence it is proposed that the Knutshø event in the Hjerkinn area took place when the glacier in Einunndalen existed. The ice-marginal deposits northeast of Fundin lake (Sollid & Sørbel 1997) and the streamlining features south and north of Stororkelsjøen (Follestad 2003a) indicate a reasonable continuation for this stage to the north.

Discussion

Hørbye (1857) documented the northeasterly directed ice movement in the Hjerkinn area as well as a westerly directed ice-flow in the eastern parts of the Oppdal municipality. Sollid & Sørbel (1979) and Follestad (2003a, 2004) have later confirmed these ice-flow directions. In this paper a marked northeasterly directed ice-flow is shown by streamlining features in the north-westerly parts of the Oppdal Municipality. Follestad (2004) has shown that these features can also be traced and followed into the areas north of the Oppdal Municipality where Reite (1990) suggested a northerly ice-flow model. In the Oppdal area this ice-flow moves independently of the terrain even though the terrain relief can be as much as 800-1000 meters in the western, valley-dominated landscape. In the southern parts of the Oppdal Municipality and in areas adjacent to Hedmark county, a marked pattern to the streamlining features is seen. These features become gradually more northerly giving the streamlining pattern a clear northward trend. In the mountain area of Skrymtheimen (Snøhetta) streamlining features have not been observed.

Boulton et al. (2003) and Kleman & Borgstrøm (1996) have shown that cold-bridges will form in high topographic positions underneath an inland ice and thereby create cold-based conditions. In the lower ground, outside the cold-based areas, a wet-based glacier may exist according to their model. Applied to the study area this model explains the formation of the north-easterly directed streamlining features on both sides of the mountains of Skrymtheimen, as well as the lack of streamlining features on Skrymtheimen itself. Erratic boulders have, however, been found in some of the high-lying block fields. This indicates that a glacial transport occurred through Skrymtheimen at some time, but gives no evidence as to when it took place. From the patterns of the streamlining features it can further be concluded that the northeasterly patterns were formed by ice-flows emanating from an ice-dome or an ice-shed southwest of the Oppdal municipality, i.e. in the adjacent counties of Møre & Romsdal and Oppland (Fig. 1).

Reite (1990) suggested a northerly ice-flow model for the central parts of Sør-Trøndelag County. As we have

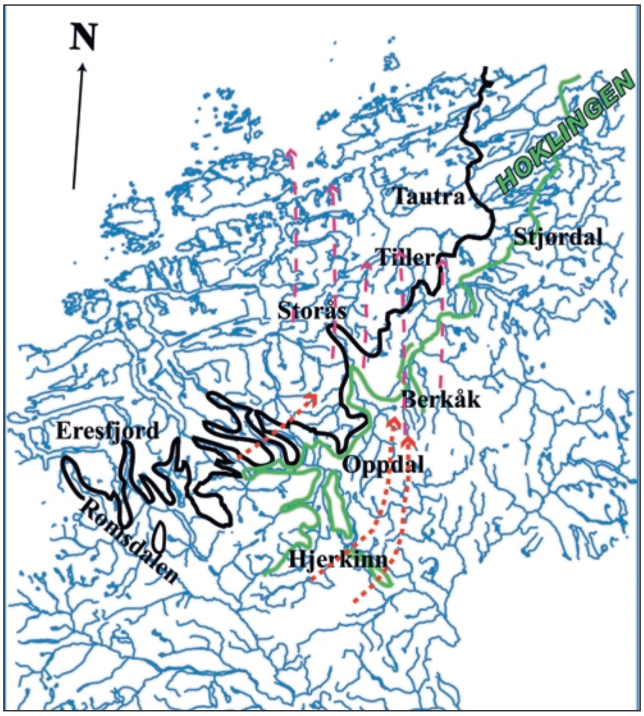

Fig 8. Sketch showing ice-marginal zones in Sør-Trøndelag and Oppland counties after Reite (1994), Follestad (1994a, 2003b) and Sollid (1964). The YD Tautra-Tiller-Storås Substage is shown by a black line, while the late YD Hoklingen Substage is shown by a green line. The suggested northerly ice-flow model for the central parts of Sør-Trøndelag County (Reite1990) is shown by pink dotted arrows. The continuation of the YD Tautra-Tiller-Storås Substage from Storås to Oppdal and further on to Romsdalen is drawn on the basis of observations carried out by Follestad (1994a, 2003b).

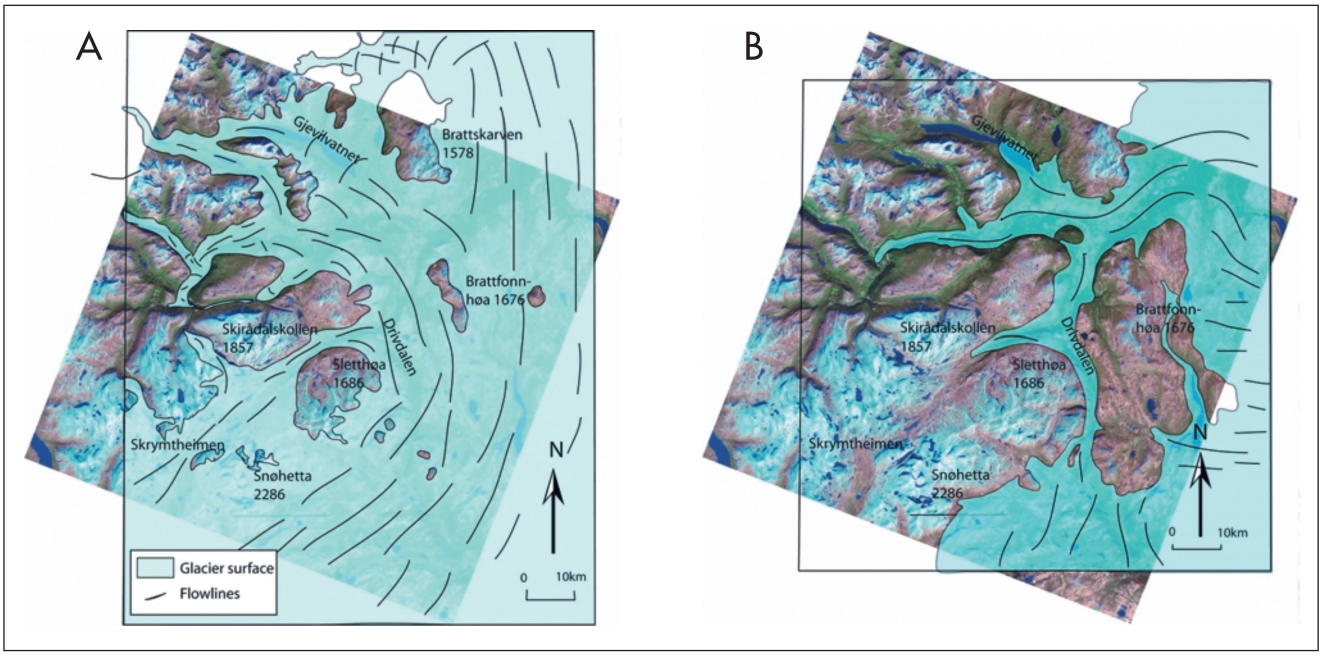

Fig. 9. Southerly and westerly tentative reconstructions of the two main ice-stream phases during deglaciation of the Oppdal area, according to Follestad (2003b). A: The early/middle YD ice-surface which reached the Storås marginal deposits in the northern parts of the Meldalen valley and the central parts of the Sunndalen valley in Møre & Romsdal. B: The late YD ice surface dominated by a westerly moving ice-stream from an easterly situated ice- dome or ice-shed. This ice-stream in the main Oppdal-Berkåk valley was divided into two major ice-flows, which can be demonstrated in the Oppdal and Meldal areas, respectively.

seen, the patterns of streamlining turn northward when approaching the northern parts of the eastern Oppdal area and thus support the ice-flow model of Reite (1990) and cf. Fig. 7 (this article). It should also be noticed that my observation does not support the traditional northwesterly flow lines model used for Sør-Trøndelag(Sollid et al. 1980) as the northwesterly and westerly streamlining features seen in the Oppdal area are clearly terrain-guided forms found in the valleys and on the valley walls.

Follestad (2003b) argued that the high-lying moraine ridges in the Oppdal area represent a glacier surface during the YD chronozone. This can be followed from the Storås area to Oppdal (Fig. 7). The high-lying lateral moraines in the valleys of Gjevilvatnet (Fig. 3), Dindalen (Fig. 6) and in Drivdalen and Åmotsdalen (Follestad 2004) are situated at altitudes which can, with some reason, be correlated with the suggested YD glacier surface of 1300 m a.s.l. in the area of Oppdal (Follestad 2003a). The lateral moraines are thought to represent the approximate extension of the YD glacier surface in south- and westward directions and are correlated with the YD Tautra-Tiller-Storås Substage in Sør-Trøndelag.

On the basis of ice-marginal deposits a late YD glacier surface at c.1000 m a.s.l. is indicated in the surroundings of Oppdal (Follestad 2003b) and is correlated with the late YD Hoklingen Substage dated to c. 10,300-10,400 ^{14}C years BP (Sollid & Reite 1983), cf. Fig. 7. The marked westerly orientated streamlining features found in the areas north of Stororkelsjøen are, in this paper, correlated with the westerly orientated streamlining features and ice-marginal deposits (Sollid 1964; Sollid & Sørbel 1997) in the south-eastern areas of Oppdal and in the northwesterly areas of Hedmark County. Although it should be kept in mind that streamlining features were continuously being created and reshaped (Kleman & Borgstrøm 1996), a tentative glacier surface, represented by the westward orientated streamlining features and the ice-marginal deposits during the Knutshø Substage (Sollid 1964), is indicated (Fig. 9B). It should be noticed that the northeast (northerly directions in the northern parts of eastern parts of the Oppdal area) and westward oriented streamlining features will be effected by terrain relief as the ice became thinner and thinner approaching the YD Substage and late YD Substage. However, as seen (Fig. 9A) the inland ice flowing in a northeasterly direction and further north in a northerly direction seems to have been the main source for the westerly oriented valley glacier during the YD Substage in this part of Norway.

Conclusion

Thus it can be concluded that a combined use of streamlining features and ice-marginal deposits make it possible to differentiate between:

(1) An early stage dominated by a northeasterly orientated ice-flow west and east of Skrymtheimen when cold-based inland ice most probably existed at this high altitude mountain area. In the northern parts of the Oppdal area these two ice-flows turn northwards and are presumed to be compatible with the northerly ice flow model in the central part of Sør-Trøndelag County.

(2) The northeasterly ice-flow, which was more northerly orientated in the northern areas of Oppdal municipality, continued in the eastern parts of the Municipality into YD Chronozone time and became the main source for the westerly orientated valley glaciers during the YD Substage.

(3) The westerly orientated streamlining features seen in the eastern parts of the Oppdal Municipality can have coincided with the Knutshø event in the Hjerkinn area and can be correlated with the late YD Hoklingen Substage in central Sør-Trøndelag.

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