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Glacial Chronology in Parts of Southwestern Norway

KARL ANUNDSEN

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Ice-terminal deposits in the area, consisting of prominent morainal ridges which can be correlated, indicate glacial advances both in Younger Dryas and Pre-Boreal, and possibly also in Boreal. The possibility of these moraines all being related to climatic changes are discussed. Norwegian Pre-Boreal glacial events are compiled. A description is given of glacial lakes which formed along the glacial border in Younger Dryas and Pre-Boreal. The trend of the moraines indicates that the recession velocity after the Younger Dryas advance was highly influenced by the fjord topography.

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Introduction

This paper is the result of a systematic mapping of the ice-terminal deposits in the map area (Pl. 1), with an attempt to correlate the various glacial deposits of the region.

The age of the different glacial substages can partly be determined by C–14 datings and pollen-analytical studies. The development of vegetation and climate, however, will be described in a subsequent paper, as will be the glacial striae. Only the main trend in former ice movements is shown in Pl. 1.

Although the limit of the Younger Dryas glacial advance has been frequently indicated in geological literature, no attempt has been made to establish the precise limit until that of Undås (1963). The Younger Dryas limit of Undås does not conform with the present author's results in the district between Vindafjord and Åkrafjord.

The morainic ridges of the three glacial substages described in the present account are very prominent, and indicate actively flowing inland ice. It should be possible, therefore, to find traces of corresponding glacial advances in neighbouring districts, and perhaps even in wider areas.

The description of each of the substages starts with a brief introduction, and the name of the corresponding substage in other parts of Norway, Scandinavia and other parts of the worlds is given, if a viable correlation can be made.

Moraines of the Ra substage

The moraines occurring in the district between Erfjord and Åkrafjord form a direct continuation of those in the Lysefjord–Josenfjord district (Andersen 1954), shown to be correlatable with the Younger Dryas Ra-moraines in southeastern Norway (Andersen 1954, 1960). These correspond with the middle-Swedish end moraines (Lundqvist 1965) and the Salpausselkä in Finland (Donner 1965), again of Younger Dryas age. A correlation of the moraines in the Erfjord–Åkrafjord district with the Younger Dryas moraines mentioned above therefore seems likely.

LOCALITY DESCRIPTIONS

Erfjord–Økstrafjord

Along the southern side of Erfjord a lateral morainic ridge can be traced continuously for 2 km near the mouth of the fjord, where the fjord side is not so steep as further east. From the northern side of Erfjord a corresponding moraine can be traced to Bogsfjord and the mountain Helgafjell.

As the moraine is traced further towards Fuglastein at the mouth of Økstrafjord (Fig. 1), it is observed to descend to the contemporaneous shore-level, now at 62 m a.s.l., where a distinct wave-cut platform is present (long profiles of the glaciers in Figs. 2, 3, and gradients in Table 1, p. 5.)

Fig. 1. The moraine ridge at Fuglastein at the mouth of Økstrafjord. View towards the SSW. The island of Ombo in the background. (Photo: K. A. 25/6–68.)

The district around Hålandsdalen valley

From Erfjord, Hålandsdalen valley stretches approximately 7 km towards the NE to the lake Natlandsvatn. On either side of the valley prominent lateral moraines can be traced. According to their position above the modern shore-line they are most likely to correspond with the morainic ridges in Erfjord (see Table 1, p. 5, Fig. 2). In addition, the morainic ridges along the southeastern side of the valley can be traced directly to the Ra-moraine in Jøsenfjord. The steepest slope occurs at the mouth of the valley (Fig. 2) where the glacier formerly spilled out into Erfjord.

From the northwestern side of Hålandsdalen the ridge can be traced continuously towards the N to Sørhusdalen valley. At the northern side of the Reinsnuten – Skotaskardnuten mountains (NW of Natlandsvatn) a number of nunatak-moraines occur, and are regarded as belonging to the Ra substage.

Økstrafjord – Sandsfjord

A morainic ridge can be traced eastwards across the hill of Barkåsen, between Økstrafjord and Jelsa. From the summit of this hill the ridge swings towards the SE; it can be followed down the hillside to about 100 m a.s.l., and is further found in the present strand-zone.

The pattern of the moraines demonstrates that the tongue of the Økstrafjord glacier was divided by Barkåsen into two segments. One segment moved southwards, and the ice-front was presumably situated somewhere S of the lighthouse on the headland of Barkeneset. The other segment was forced towards the WSW and presumably joined the Sandsfjord glacier near the centre of Jelsa.

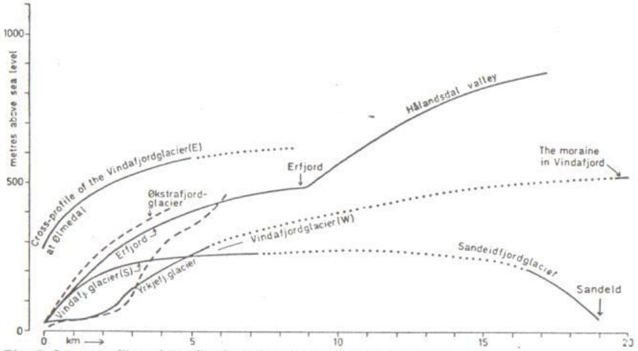


Fig. 2. Long profiles of Ra fjord glaciers in southwestern Norway.

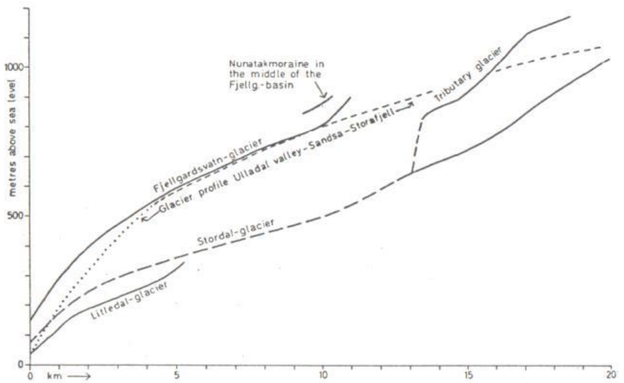


Fig. 3. Long profiles of Ra and Trollgaren valley glaciers in southwestern Norway.

From Asheim the morainic ridge can be traced around the Jelsaheii mountain. At lake Gjerdevatn a small outlet glacier of the Sandsfjord glacier formerly followed the valley as far as Gjerde farm.

A terrace (60 m a.s.l.) occurs in contact with the distal slope of this moraine (see Kaldhol 1941 p. 116 and Undås p. 5 and Pl. 1a); it represents outwash material from this glacier.

Beyond the mouth of Sandsfjord is the island of Foldøy, which consists of two knolls (28 m high to the W and 35 m high to the E) with a broad ridge-like morainic deposit between them. A till fabric analysis at the school-house locality (Pl. 1) clearly shows that the moraine was derived from the NNE, i.e., from Sandsfjord. This morainic deposit has been interpreted as representing an ice-front deposit ('Glacial Map of Norway' in O. Holtedahl 1960), and Undås

Table 1. Surface slope, length, width and thickness of the glaciers

	Gradient in m/km									
	0–2 km from the front	0–4 km from the front	0–6 km from the front	0–11, 12 km from the front	4–9 km from the front	9–15 km from the front	15–→km from the front	Length in km	Max. width in km	Max. thickness in metres
Ulladal glacier		130			50	34	22	ca. 11	3	700
Erfjord – Hålandsdal glacier		90			20	60	25	14	4	600–700
Økstrafjord glacier	137	100						4	3.5	500
Vindafjord glacier (East) (cross-section)	100	70			10					1250
Vindafjord glacier (South)	95	60						9	5–5.5	950
Yrkjefjord – Vindafjord glacier	15	50			30	22	10	27	7–8	1500
Sandeidfjord glacier	70	44						8	4	650
Sandsfjord glacier	15	64	80					6	6	650
Litledal glacier	67	56			70			11	1.5	250
Stordal glacier				40		42	60	22	2–2.5	600–700
Fjellgardsvatn glacier	125	72			46	65		11	2.5–3	350–400
Åkrafjord glacier				50				23	7–8	1500–1600
Suldal glacier									7–8	1100
Sørdal glacier				80				12		
Løyningsdal glacier									3	500
Reinsnos glacier									4.5	450

(1963) is further of the opinion that it was deposited by the Sandsfjord glacier in Ra time. Presumably this is the case, but a definite correlation between the Foldøy moraine and the lateral moraines on either side of Sandsfjord cannot be made without confirmation across the mouth of Sandsfjord.

At the northwestern side of Sandsfjord the moraine can be traced at a few localities along the fjordside from Hebnes to a thick morainic belt 400–450 m a.s.l. NW of lake Grytevatn. Undås (1963) was of the opinion that the ice-front was situated between Indre Rødne and Imsland in Vindafjord, and in contact with a moraine ridge at Imsland. The present author, however, has not found any terminal moraine here.

Vindafjord – Yrkjefjord – Vatsfjord

At Askfjord a short morainic ridge occurs down to a narrow wave-cut platform about 52 m a.s.l. The latter presumably represents the Younger Dryas shoreline.

The moraine ridge is clearly a lateral moraine deposited by a glacier which moved southwards in Vindafjord. On aerial photographs a morainic ridge is observed N of Askvik, which is probably correlatable with that at Askvik.

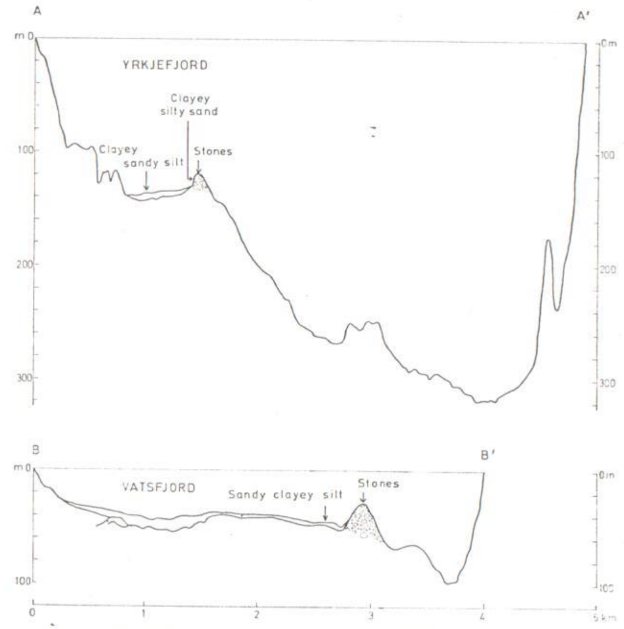


Fig. 4. Long profiles of the bottom topography of Yrkjefjord (A–A') and Vatsfjord (B–B'), drawn on the basis of echo profiles. The bank which appears in each of the fjords is the moraine ridge. A penetration echo also appears beyond the ridge. Arrows show locations of grab-samples. (See Fig. 5 for locations of the profiles.)

The echo profiles available at present, from the fjord bottom at and S of Askvik, show no clear evidence of moraine-like ridges, and as the fjord is 350–400 m deep here the glacier terminus was most likely floating and calving. Along the western side of Vindafjord a morainic ridge can be traced almost continuously from Amdal to Hapnes, and further westward along Yrkefjord to the small bay Toskavik. At the farm Vassendvik a wave-cut platform is present at 44 m a.s.l.

In order to establish the true position of the ice-front in Yrkefjord, 9 echo-sounding profiles of the bottom topography were carried out. Most of these profiles show a max. 25 m high crest-like bank at Toskavik (Fig. 4). Three grab-samples have been obtained: one from the top of this bank, one from its southwestern slope, and one from about 500 m SW of the bank (Fig. 4). The course of the bank has been determined on the basis of the echo profiles. The pattern described makes it clear that the bank is the end-moraine of a former Yrkefjord glacier.

The concave course of the moraine should indicate that the ice-front was calving, as should the profile of the lateral moraine (Fig. 2). This can be shown to have been only partly the case, as a 50 m high rock-threshold (80 m below the modern sea-level) appears in the middle of the fjord.

The lowest passpoint between Yrkefjord and Skjoldafjord is situated at the road-junction at Yrkje, at about 40 m a.s.l. This is at about the Younger Dryas marine limit, according to the wave-cut platform at Vassendvik. This implies that the western part of Yrkjefjord must have been a glacier-dammed lake, 6–7 km long, during (at least) parts of Younger Dryas time, when the rock-threshold was elevated above sea-level. A morainic ridge occurs at Raunes in Vatsfjord; its course clearly shows that the material was derived from the Yrkjefjord glacier. West of Raunes a prominent crest-like bank occurs on the bottom of the fjord. Grab-samples (Fig. 4) show that this bank is an ice-terminal deposit. No morainic ridges apparently are preserved between Vatsfjord and Sandeidfjord, as the fjordside is very steep here.

Sandeidfjord

According to the position of the moraine at Hapnes the Ra glacier in Vindafjord must have also moved northwards into Sandeidfjord.

Between Ilsvåg and Ile a prominent ice-front terrace (51 m a.s.l.) occurs (Fig. 5); it is considered most likely to be of Ra age.

One km south of Sandeid along the western side of the fjord, a lateral moraine descends northwards. At the mouth of Leirdalen valley a prominent ridge occurs, the axis of which is oriented E–W. This ridge has previously been interpreted as having a northerly derivation from a glacier in Leirdalen valley, prior to the Younger Dryas advance (Anundsen 1968). The following lines of evidence, however, show that the moraine was most likely derived from the south during Younger Dryas time:

I) The morainic ridge at the mouth of Leirdalen seems to be a direct continuation of the lateral moraine mentioned above (Fig. 5 and Pl. 1.)

II) A ridge of glaciofluvial material with an E–W orientation occurs just to the east of the church at Sandeid. The top of this ridge is 58 m a.s.l. and it rises approx. 35 m above the surrounding terrain. The morphology and position of the ridge exclude the possibility of it being an erosional remnant, and it is considered most likely to be a continuation of the terminal moraine to the W, and of a lateral moraine which can be traced along the eastern side of the fjord to the village of Vikedal.

III) In Helgelandsdalen valley a series of terraces occur (Fig. 5) at 60 m a.s.l., i.e., 4–9 m higher than the marine terraces in the neighbourhood, but at the same level as the passpoint in Leirdalen (see below).

IV) Between Sandeid and Ølen (i.e., in Leirdalen) the passpoint is situated at about 60 m a.s.l. Between Sandeid and this passpoint a sequence of stratified silts and clays, between 30 and 35 m in thickness, can be traced for a distance of about 4 km (Fig. 5).

Today there is only a minor stream in Leirdalen draining a small fluvial basin. The present author is therefore of the opinion that these great

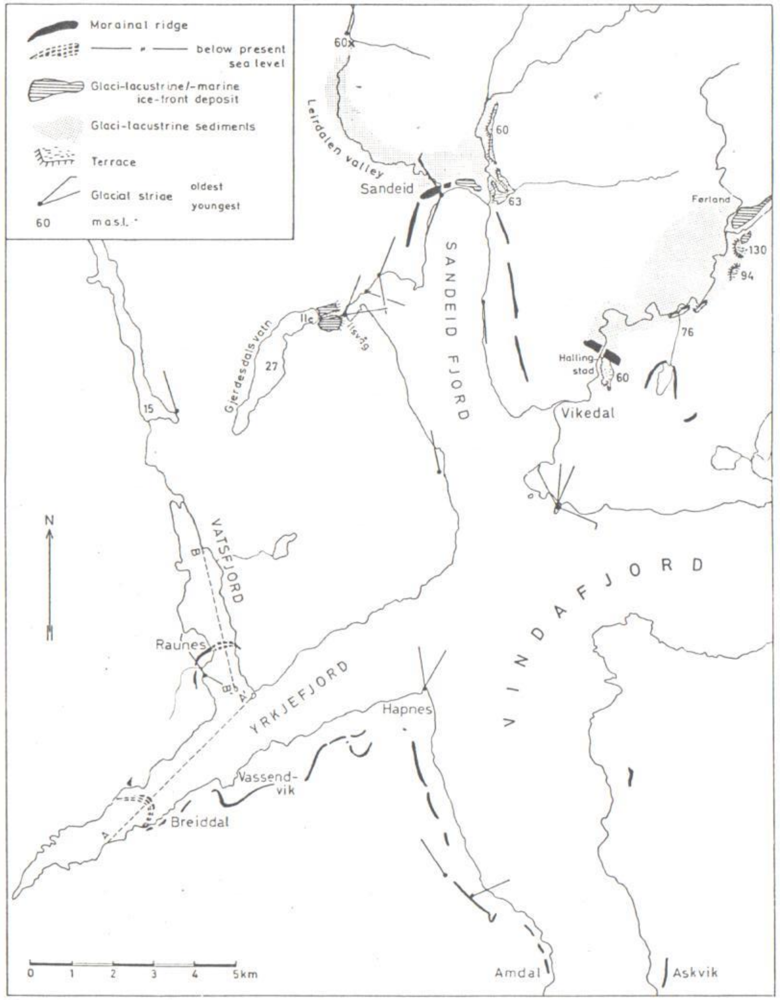
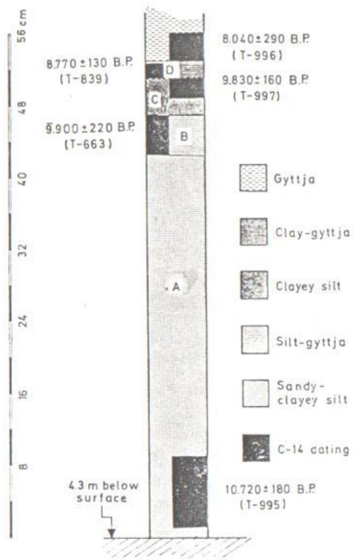


Fig. 5. Detail map of the fjord-cross area (see Fig. 11 for location). A–A' and B–B' are the locations of the profiles in Fig. 4. X: The location of the core shown in Fig. 6.

Fig. 6. The lowest sequence of the sediments at the passpoint in Leirdalen valley. (For location, see Fig. 5.)



volumes of sediments must have been deposited by meltwater streams in an ice-dammed lake, which formed between a glacier tongue in Sandeidfjord and the passpoint in Leirdalen..

V) The orientation of glacial striae, and the large roches moutonnées in Leirdalen, from the valley bottom to the highest mountain top (570 m), indicate a former ice movement towards the south. However, from Sandeid and southwards, glacial striae are found which indicate a subsequent movement of ice in the opposite direction (Fig. 5).

The stratigraphy at the passpoint in Leirdalen

In a 5 m deep rock basin a few metres S of the passpoint in Leirdalen (Fig. 5) a series of ten cores has been taken in an attempt to obtain information about the glacial advance (vegetation, climate, sediments). Only the lowest part of the sequence is shown (Fig. 6), as the results of the pollen analysis will be described in more detail in a future paper.

The fine-grained sediments in Leirdalen decrease in thickness towards the passpoint, and it is considered that the bed A (Fig. 6) at the passpoint most likely corresponds to these sediments. If this is the case, the lake, and thus also the moraine ridge at Sandeid, were formed at about 10,720 ± 180 radiocarbon yrs B. P. (T—995, Fig. 6). This is in agreement with a Younger Dryas age for the moraine, as suggested above.

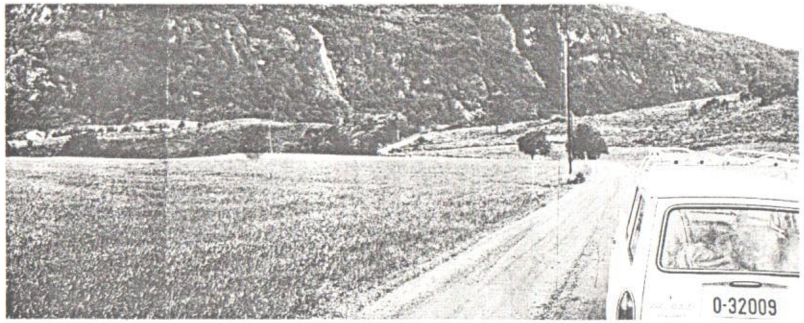


Fig. 7. The moraine ridge at Hallingstad, Vikedal. View up the valley, towards the ice-contact slope. In the foreground the highest marine terrace, 60 m a.s.l. (Photo: K.A. 29/6–67.)

The series of cores shows that the C bed exists all over the basin, which at that time was occupied by a small lake, as shown by the AqP pollen content. The basin does not lie along any river course, and it seems unlikely, therefore, that the C bed is a stream deposit.

The pollen-analytical position of the C bed seems to be Pre-Boreal, which has been confirmed by radiocarbon datings (Fig. 6). The samples T–663 and T–997 give ages 9,900 ± 220 B.P. and 9,380 ± 160 B.P., respectively, for this bed. Both the pollen analysis and the radiocarbon datings T–839 (8,770 ± 130 B.P.) and T–996 (8,040 ± 290 B.P.) further indicate either a hiatus above the C bed, or a very slow deposition of both organic and minerogenic matter. The pollen-analysis and the samples T–663 and T–997 probably suggest the possibility that the C bed is related to the Pre-Boreal climatic deterioration, first pointed out by Zoller (1960), who applied the term 'the Piottino Oscillation' for this stadial. This was dated at 10,050–9,650 B.P. (Zoller 1960). An increase of minerogenic matter during a previous cold spell has also been reported by Mangerud (1970, p. 126 and Pl. 1). Furthermore, a Pre-Boreal glacial advance is shown to have occurred in different parts of Norway (references in Table 2, p. 14).

It seems likely that a climatic deterioration in Pre-Boreal times caused an increasing amount of snow, and hence an increasing importance of nivation, facilitated by the thinning out of the vegetation cover. This process caused a change in sedimentation rate ratio between organic and minerogenic matter in the small lake.

Vikedal

At the farm Hallingstad a prominent morainic ridge crosses the valley (Fig. 7), and has been thought to be derived from the north (Undås 1963, Anundsen 1968). Later investigations by the author have shown the ridge at Hallingstad

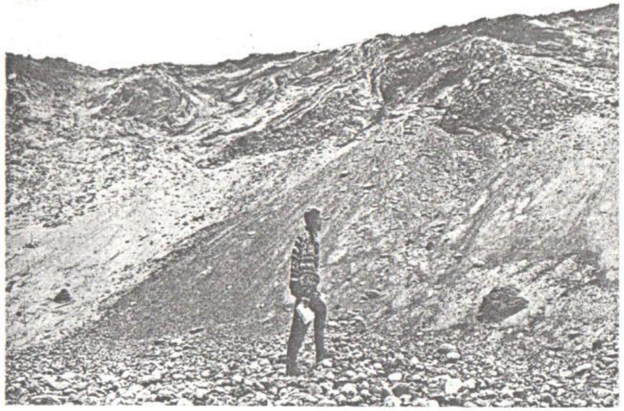


Fig. 8. Folded glaciofluvial sediments in the proximal parts of the ice-front delta at the village Etne. (Photo: K. A. 23/7–66.)

to contain considerable amounts of silt and clay; this is taken to indicate a partially marine origin for the deposit, as is the case with the Foldøy moraine. The author has further observed the occurrence of thick stratified sediments in the valley between the farms Hallingstad and Førland, the latter situated 4.5 km further up the valley (Fig. 5). These sediments are terraced at an altitude of 130 m a.s.l., i.e., 70 m above the highest marine terrace at Hallingstad (Figs. 5, 7). From Hallingstad an increase in average grain size can be traced in these deposits northeastwards beyond Førland, were an 80 m thick accumulation of glaciofluvial sediments occurs. The latter deposit is also terraced at about 130 m a.s.l., whilst the top of the deposit reaches an altitude of 155 m a.s.l. This deposit is 300–350 m broad at Førland, and narrows to a crest-like ridge, 40–50 m broad, towards the NE. The surface of the deposit is uneven, partly due to the presence of a number of kettle-holes. This outwash material is considered to represent an ice-terminal deposit (perhaps a pro-glacially erosional remnant) built up by the same valley glacier which produced the lateral moraines along the valley sides at lake Fjellgardsvatn. These latter moraines can further be traced into Vindafjord and Vikedal (Pls. 1, 2).

The features described above indicate that the sediments between Hallingstad and Førland were deposited in an ice-dammed lake which formed between an ice-lobe at the site of Fjellgardsvatn and a contemporaneous ice-lobe moving from the fjord to Hallingstad.

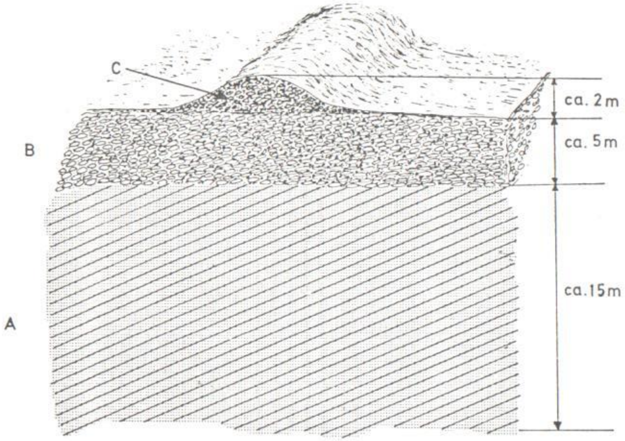


Fig. 9. Layers of sediments at the farm of Austreim, Etne. A — Stratified sand: ice-front delta sediments. B – Stones and gravel, rounded and well rounded. C – The proximal moraine ridge.

Fjellgardsvatn – Etne – Stordalen

From the northern side of Fjellgardsvatn a belt of morainic material can be traced northeastwards to the lake Joravatn, where the morainic belt is divided into two parts of different ages.

The position of the latter moraines indicates that ice did not occupy Litledalen valley at this time. However, the earlier ridge demonstrates that the glacier must have previously extended down this valley. The moraines at the mountain of Borfjell, at lakes Grindheimsvatn and Krokavatn, respectively, and the lateral moraine in Litledalen further show that the glacier must have extended to Etne.

At the southwestern end of lake Stordalsvatn there occurs a prominent glacio-fluvial ice-front terrace with an uneven surface. The highest levels are at about 80 m a.s.l. In the proximal parts folded structures (Fig. 8) can be seen beside the road. On the surface of this deposit there are six closely spaced parallel morainic ridges, deposited by a glacier in Stordalsvatn, which was also responsible for the formation of the terrace. In the gravel-pit at Austreim farm three different beds of loose deposits can be seen (Fig. 9). The stratified beds is considered to have been deposited by meltwater when the ice-front was situated along the proximal slope of the terrace. During a subsequent glacial advance, which presumably produced the folded structures, several small ice-front oscillations occurred upon the terrace, forming the morainic ridges and the ground moraine between them.

Along the valley sides of Stordalen, Hellaugdalen–Nordstøldalen (NE of Stordalsvatn) and their tributaries morainic ridges can be traced, showing that a number of glaciers joined in the basin of Stordalsvatn. If these moraines and the moraines at Etne are of the same age the surface of the glacier sloped at about 40 m/km (Table 1 p. 5), which is a reasonable gradient. The lower bed at Austreim (Fig. 9), however, was most likely deposited during an occasional stop at a rock threshold during the retreat stage of the glacier, and therefore the morainic ridges upon the terrace most likely correspond with the moraines NE of Stordalsvatn.

Lateral moraines can also be traced along the sides of both Stordalen and Åkrafjord (gradients in Table 1 p. 5). At Skånevik, a morainic ridge can be traced almost down to the modern shore level. At 83 m a.s.l. a pronounced wave-cut platform occurs in this ridge representing the contemporaneous shore level. The ice-terminal moraine at Skånevik is the only one in Åkrafjord–Skåneviksfjord. The gradient from Skånevik to lake Vyrdalsvatn (11 km) is 50 m/km, which is again reasonable. The moraine at Skånevik is, therefore, most likely of Ra age. From the northern side of Åkrafjord the corresponding moraine can be traced to the island of Halsenøy (Follestad 1972), and Holtedahl (1967) has shown that the Halsenøy moraine is of Ra age.

Moraines of the Trollgaren substage

In the district between Lysefjord and Jøsenfjord in south-western Norway, Andersen (1954) has described a glacial substage younger than the Ra substage to which he has given the name Trollgaren substage after a prominent boulder moraine on the mountain plateau Jøsenfjordheia. This boulder moraine is called Trollgaren (i.e. a stone wall made by trolls). Accurate age determinations of this substage in this part of the country are not yet available. However, as this substage is apparently to be correlated with the Odda–Eidfjord–Osa glacial substage (Anundsen & Simonsen 1968), according to the following descriptions, the Trollgaren moraines were deposited during the Eidfjord Stadial (Mörner 1969 pp. 423–424). This stadial seems to correspond with the Piottino Oscillation (Zoller 1960, Behre 1966, 1967, Anundsen & Simonsen 1968). Further, the two oldest Stordahl phases in Northern Norway are of Pre-Boreal age (Holmes & Andersen 1964 p. 159, Andersen 1965 p. 53, Nydal 1960 p. 86, Andersen 1968 p. 87, Table 2 p. 14). The Eide substage in Sogn og Fjordane is also of Pre-Boreal age (Fareth 1970, Table 2). In south-eastern Norway the Ås–Ski substage, and perhaps the Aker substage, are of Pre-Boreal age (Holtedahl 1960 pp. 375–377). The juncture of this latter event, however, is still a little uncertain, which is due to the great variations in age determinations of this substage (Table 2).

LOCALITY DESCRIPTIONS

The district between Jøsenfjord and Sandsavatn

A moraine of this substage can be traced at a number of localities from the Segadalsheia mountain plateau N of Jøsenfjord northeastwards to the lake

Table 2. C^{14} datings of Pre-Boreal glacial events in Norway

Events	B.P. (1950)	Laboratory numbers and dating lists	Dated material	Locality	Comments, references
Ås–Ski glacial substage	9,750 ± 250	T–179 Nydal 1962, p: 168	Chlamys septemradiatus	Søreng, Eidsberg SSE of Oslo	From a type locality for the Middle Arca clay (Brøgger 1900–1901).
Aker glacial substage	10,050 ± 350	T–118 Nydal 1960, p. 86 and 1962 p. 161	Mostly Arca glacialis	Øvre Foss Teglverk, Oslo	In Younger Arca clay. deposited in front of the Aker moraine, comment Holtedahl 1960, p. 377: evidently too high.
	9,250 ± 250	T–119 A Nydal 1960 p. 87	Mytilus edulis	Skådalen, Oslo	Comments O. Holtedahl, in Nydal 1960, p. 87: T-119B too young, most likely contaminated.
	7,300 ± 200	T–119 B Nydal 1960	Balanus porcatus	Skådalen, Oslo	
	9,450 ± 250	T–119 C Nydal 1960	Mytilus edulis		
	9,500 ± 200	T–286 Nydal 1962, p. 169	Mytilus edulis	Strømmen Verksted, Akershus	The locality is situated inside (NE of) the Aker moraines, and the molluscs are therefore younger than the moraines.
Eidfjord–Osa glacial substage	9,720 ± 330	T–585	Gyttja	Busnes, Hardanger	Date the glacial advance. Discussed by Anundsen in Anundsen & Simonsen (1968, pp. 35–36).
	9,680 ± 90	T–886	Wood	Eidfjord, Hardanger	A piece of a juniper branch, found in the ice-terminal deposit, is dated. Discussed by Rye (1969, pp. 33–36).
	9,300 ± 300	T–412 Nydal 1970, p. 215	Gyttja	Flåm, Sogn	Described by Hafsten & Klovning (1965, pp. 337–338). Discussed by Anundsen (in Anundsen & Simonsen 1968, p. 36) The gyttja is younger than the moraine.
Eide glacial substage	9,420 ± 200	T–616 Nydal 1970, p. 212	Marine molluscs, various species	Håheim, Olden, Nordfjord. Sogn og Fjordane	The molluscs are younger than the Eide moraine (Kaldhol 1912, pp. 32, 54, Fareth 1970)
Stordal old glacial phase	9,880 ± 240	T–125 Nydal 1960, p. 86	Mya truncata	Birtavarre, Lyngen, Troms.	Discussed by Andersen 1965, p. 53 and 1968, p. 87.
Stordal middle glacial phase	9,560 ± 120 9,470 ± 160 9,520 ± 190	T–512 A Nydal 1970 pp. 208–209 T–512 B Nydal 1970 T–630 Nydal 1970	Marine molluscs. various species	Gratangen, Troms	Discussed by Andersen 1968, p. 87
Deposition of a clay horizon, caused by a climatic deterioration, Sandeid, SW Norway.	9,900 ± 220	T–663	Clayey gyttja	Sandeid, Rogaland	Give the age of a clay horizon in a bog. Discussed on p. 10 in this paper.
	9,830 ± 160	T–997	Clayey gyttja	Sandeid Rogaland	

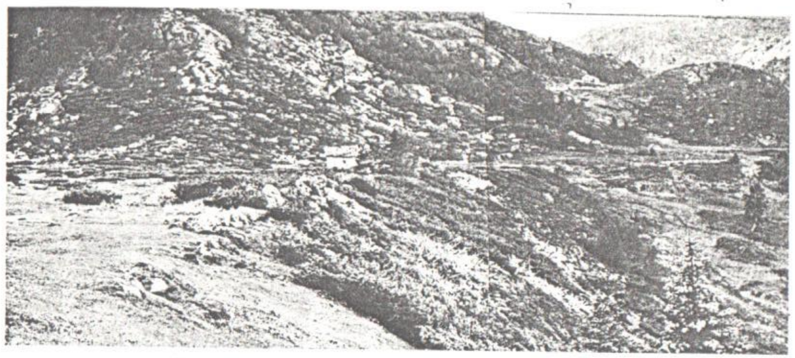


Fig. 10. Part of the glaciolacustrine terrace 606–607 m a.s.l. at lake Mosvatn, between the valleys of Ulladal and Suldal. View towards Stavastøldal (the E). (Photo. K. A. 8/9–70.)

Tverrheivatn, where it swings towards the southwest around the mountain of Øyrafjell. A (lateral) moraine corresponding to an Ulladal valley glacier can also be traced at a few localities along the northern valley-side of Ulladal. In the valley extension between Ulladal and lake Mosvatn, 3–4 parallel moraine ridges occur at 610–620 m a.s.l., rising 2–3 m above the surrounding boggy land, and damming a number of small lakes. These ridges are most likely to be correlated with those at the mountain Longelihei further to the S. From this mountain the morainic ridges can be traced northwards to Ås and Vindvodl. About 1 km further north a 15–20 m thick morainic ridge occurs in contact with a large terrace of glaciofluvial sediments (Fig. 10), the surface of which is at 606–607 m a.s.l., i.e., 90 m higher than the passpoint to the N (to Suldal valley), and 10 m higher than the passpoint to the S (to Ulladal). A lower-lying, narrow platform occurs at 595–596 m, i.e., at the same level as the passpoint to the S. The material in the terrace was derived from a glacier tongue occupying the pass between Suldal and Stavastøldalen.

When the terrace was formed, the passpoint to the N was closed by ice up to 650 m a.s.l. (see below), and the morainic ridges to the S show that the surface of the Ulladal glacier was situated somewhere between 600 and 610 m a.s.l. during the Trollgaren substage. A lake was thus formed in the basin of Mosvatn between two ice-lobes (Pl. 2), the lake surface being controlled by the glacial surface to the S. As this latter ice surface was lowered, the outlet of the lake was shifted eastwards to the passpoint now at 595 m a.s.l., and a narrow platform was cut into the slope of the terrace at this level. The glacial lake drained towards the S until the ice surface to the N was lowered below the passpoint level to the S.

From Ås and Vindvodl the moraine can be traced towards the E to the mountain Reinsnut (Fig. 11) and further east to the mountain Storafjell, where

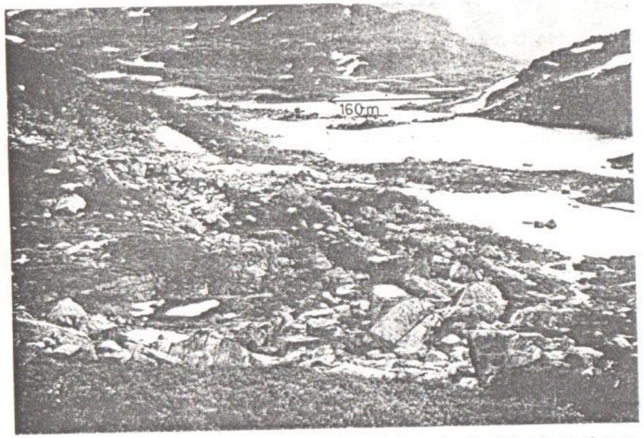


Fig. 11. Moraine ridges (850–970 m a.s.l.) at Reinsnut Mountain, N of the lake Sandsavatn. View towards the E. (Photo: K. A. 20/6–66.)

it makes a sharp bend towards the W. It can be traced along the valley-side of Suldal to the small lake Vassbottevatn.

As a preliminary attempt to locate the position of the ice front in Suldal in Trollgaren times, some possible lines of evidence can be discussed: From the mountain Kotleskårnut (4 km NW of Sandsa) to the plateau NW of Mosvatn the ice surface apparently had a slope of approx. 30 m/km, according to the lateral moraine. If a model with the ice front at Sand is considered, the ice surface would slope about 55 m/km between Sand and Mosvatn, and correspondingly more if the glacier front has been situated further up the valley. However, along the same distance the valley bottom falls only 50 m, and no pronounced thresholds occur. The present author is therefore of the opinion that the Suldal glacier spilled out into Sandsfjord.

A few hundred metres N of the isthmus Lovraeid, S of Sand, an islet consisting of morainic material occurs. This moraine continues as a bank across the fjord. The isthmus, which consists only of large boulders, is considered to have been derived from a series of rock avalanches from the eastern fjordside. The material of the islet and the bank is thought to be an ice-terminal deposit, because it cannot have originated in the above-mentioned manner since the fjordside is too steep for any material to have been deposited there. At the farm Lovra a prominent glaciofluvial ice-front deposit occurs, the stratification of which dips towards the S. Just to the north of this deposit, short morainic ridges on either side of the valley are observed.

If the ice-terminal deposit at Lovraeid and Lovra can be correlated with the Trollgaren moraines in Suldal, the average gradient along the 17 km and 21 km

from the ice front would have been 38–40 m/km and 30 m/km respectively. The latter figure seems too small, but the ridge at Lovraeid possibly represents the limit of the Suldal glacier.

No field work has yet been carried out in the district N of Suldal, though a number of morainic ridges which have been observed on aerial photographs in the district of Hylsfjord may well belong to the Trollgaren substage.

The district west of Bratlandsdal valley, Suldal

Along the eastern side of the lake Slettedalsvatn a number of morainic ridges occur, the northern slopes of which represent the ice-contact slopes. In this district no other morainic ridges have been discovered between these moraines and the Ra moraines, and it would seem most likely that they are correlated with the Trollgaren substage.

Northeast of the tourist shelter at Breiborg a number of morainic ridges occur, the southern slopes of which are ice-contact slopes. These ridges are therefore regarded as corresponding with the ridges at Slettedalsvatn.

The Seljestad–Odda district

From the lake Flådalsvatn distinct morainic ridges can be traced continuously towards the E to the gorge of Seljestadgjuvet, where they swing towards the SE. Along the opposite side of the gorge a corresponding lateral moraine to the glacier, which formerly moved from the district of Røldal towards the Seljestad district, can also be traced. The moraine is shown to continue to Løyningsdalen, Reinsnos and Hildalsdalen further to the N.

The moraines indicate actively flowing ice. No morainic ridges can be seen between this substage and the Ra moraines, although evidence of a younger, less pronounced substage is also found here, as is the case in the district between Jøsenfjord and Suldal (p. 18). Although no direct connection can yet be established between the Trollgaren moraines in the Suldal district and the Seljestad moraines, such a correlation seems likely for the reasons stated above.

From Hildalsdalen the morainic ridges can be further traced to the lakes Ringedalsvatn and Bersåvatn (Anundsen, in Anundsen & Simonsen 1968).

The morainic ridges in the Seljestad–Odda district show that glacial tongues derived from Røldal, Løyningsdal, Reinsnosvatn and Hildalsdalen passed into the confluence basin of Seljestad–Skarsmo–Sandvenvatn. Both the course of the morainic ridges and the glacial striae at Seljestad demonstrate that a mighty glacier moved westwards from Seljestad to Åkrafjord. The only glacial deposit which can be seen W of Seljestad is a glaciofluvial terrace 80 m a.s.l. (Kaldhol 1941) at Fjæra, just beyond the basin of Rullestadvatn. It is therefore considered that this deposit is outwash material from the Sørdal glacier, in Trollgaren times. Southeast of the lake Rullestadvatn, a small morainic ridge is observed on aerial photographs, and this may possibly be correlated with the terrace. This gives a reasonable surface gradient for the Sørdal glacier, i.e., 80 m/km, particularly as the valley bottom falls as much as 400 m between Flådalsvatn and Fjæra. From Seljestad a second mighty valley glacier moved northwards to Odda, where a pronounced end-moraine is located (Kaldhol 1941, Undås 1944, 1964, Kvistad 1965, Anundsen & Simonsen 1968, Anundsen 1968). This end-moraine apparently represents the northern limit of the glacier. It is therefore considered that the Odda–Eidfjord–Osa substage (Anundsen & Simonsen 1968, Anundsen 1968) can be correlated with the Trollgaren substage, which is thus further considered to be of Pre-Boreal age.

Moraines of the Blåfjell substage

East of the Trollgaren moraines are found morainic ridges belonging to a glacial substage younger than the Trollgaren substage, to which the author gives the name 'Blåfjell substage', after the mountain Blåfjell E of the head of Josenfjord, where the ridges are most prominent. Although the moraines are poorly preserved in some districts, it seems possible to establish a viable ice-border from lake Nilsebuvatn in the S to Suldal in the N. To date it has not been possible to establish the exact age of this substage, though in relation to its vertical and geographical distribution it is not considered to be much younger than the Trollgaren substage. It is therefore possible that this substage is also Pre-Boreal, or possibly can be correlated with the Cochrane readvance in Canada (Karlstrom 1956, Zoltai 1967, Hughes 1967), with the 'Daun' in the Alps (Heuberger 1967), and in Norway with the Young Stordal glacial phase (Andersen 1968 p. 87) and the glacial readvance described by Vorren (1970).

LOCALITY DESCRIPTIONS

From Nilsebuvatn a belt of boulders and, in part, morainic ridges can be traced northwards, across the mountain plateau of Sandkleivhei to Blåfjell. From this mountain a Blåfjell glacier moved westwards into the gorge of Førregjuvet. This is shown by a lateral moraine which can be traced at some localities from the northern side of the gorge northwards to Sandsavatn. From here the ridge can further be traced at some localities towards Åsen farm in Suldal, where it is found approx. 400 m below the Trollgaren moraine. At the same time a glacier tongue filled the basin of Suldalsvatn and joined the glacier tongue from the S. This is shown by 2–3 parallel lateral moraines that can be traced across the mountain Midtheio towards the hill-farm Møklaberg. In addition, a number of morainic ridges that are possibly correlated with the Blåfjell substage have been discovered. These include:

I) Pronounced morainic ridges on the mountains at the northern side of the main road of Austmannalia (Røldal). These are situated too low to be correlated with the Seljestad moraines further to the W.

II) To the N of the small village of Roaldkvam (at the northeastern end of Suldalsvatn) a number of morainic ridges can be traced on the mountain of Kårafjello.

III) East of Røldalsvatn a group of morainic ridges are similarly considered to be of probable Blåfjell age, on account of their position.

The firn limit

RA SUBSTAGE

In the district of Stordalen valley the morainic ridges are found at a maximum altitude of 1050–1100 m a.s.l. Taking into account the post-glacial isostatic adjustments the Younger Dryas firn limit in this district is thus found at a minimum between 950–1000 m a.s.l. The present firn limit in this district is at 1350 m a.s.l. (Østrem & Liestøl 1962, p. 326). This implies that in Younger Dryas time the firn limit was at a maximum some 350–400 m lower than the firn limit found today in this district.

TROLLGAREN SUBSTAGE

The firn limit during this substage can be calculated from the Seljestad–Reinsnos district, where the morainic ridges at a number of localities can be traced to a maximum height of 1250–1300 m a.s.l., implying a firn limit at a minimum height between 1150–1200 m a.s.l. The present firn limit in this district is at 1550 m a.s.l. (Østrem & Liestøl 1962, p. 326). Thus it can be stated that the firn limit during the Trollgaren substage occurred at a maximum of 350–400 m below the present-day firn limit. This confirms the results from the Eidfjord–Osa district in Hardanger (Anundsen, in Anundsen & Simonsen 1968).

BLÅFJELL SUBSTAGE

The district where moraines of the Blåfjell substage have been established unfortunately occurs to the S of the area in which the Norwegian Polar Institute has carried out the investigations concerning the present firn limit (Østrem & Liestøl 1962). It is also difficult to establish the exact firn limit during the Blåfjell substage in the area S of Suldal. However, in the district of Kårafjello (Suldal) and Høljanosi (Røldal) morainic ridges of probable Blåfjell age can be traced to a maximum height of 1350 m a.s.l.

The moraines E of Røldalsvatn can similarly be traced to a maximum height of 1320 m a.s.l. In these districts the present day firn limit occurs between 1550–1600 m a.s.l. This may similarly indicate that the firn limit during the Blåfjell substage was also at a maximum of 350 m lower than that of the present.

Discussion and conclusions

If inland ice is in a steady state and the base of the ice is horizontal, the glacier front will remain at a fixed position. The ice itself moves because of pressure differences in the ice. Moraines may therefore be formed, their shape and size depending on the glacier regimen and the material transport. If then a positive net balance (of the ice sheet) occurs, the ice front will advance, forming sharper and more convex moraines, and the glacier surface will be more arched. However, in nature the base of the ice is never horizontal. Therefore the glacier flow is also highly influenced by topography, and a strongly arched terminal moraine in a valley does not necessarily suggest an increased (positive) net balance for the ice (or change from negative to positive). However, a regional geographical distribution of such moraines, not only in valleys, but also across plateaux, presumably shows such a change in the net balance for the ice.

The pattern of the moraines described (sharp ridges, convex ice fronts, arched ice surfaces) no doubt shows that both the valley glaciers and the inland ice were actively flowing both in Ra, Trollgaren and Blåfjell times. No stratification in the deposits, however, tells what the ice-front oscillations amounted to.

In general, glaciers are sensitive indicators of climatic changes (Paterson 1969, p. 161), but it is still difficult to interpret the indications in detail. For instance, what do the advances in the Ra, Trollgaren and Blåfjell stadials tell about the amount of net balance in these periods compared with that of the interstadial periods?

In Younger Dryas a great change in the net balance obviously occurred. A cold spell is also shown to have occurred during the middle phase of Pre-Boreal (Behre 1966, 1967, Beug 1964, Mörner 1969, Simmons 1964, Zoller 1960), causing a glacier advance (Andersen 1965, 1968, Anundsen & Simonsen 1968, Goldthwait 1966, Holmes & Andersen 1964, Table 2, p. 14). Was the Blåfjell advance a result of a similar climatic deterioration? Although glacier advances are reported to have occurred in Boreal (p. 18), no climatic deterioration has yet been detected from botanical evidence in this period (or later), nor in Pre-Boreal in Norway. This may indicate that the Blåfjell advance was caused by a slight and short change (from a negative to a positive) in the net balance. Since a glacier is a sensitive indicator of climatic changes, this change might be too small and too short to influence the vegetation to such a degree that it can be detected in pollen analysis. Another possibility is that a slight climatic deterioration requires a dense pollen analysis (short vertical intervals) for its detection, as demonstrated by Behre (1966, 1967). The study of the moraines might indicate that the firn limit was situated more or less at the same level in Ra, Trollgaren and Blåfjell times. This might further indicate that the climatic conditions were much alike during these three periods in this part of Norway. This, however, seems unlikely as it does not seem to have been the case in other parts of Norway and Europe (e.g., Andersen 1968, pp. 126–130, with further references; Heuberger 1967, p. 271 with further references). In this case the moraines apparently do not provide a basis for climatic conclusions. It seems most likely that the Blåfjell advance was caused by a slight, regional, and short-lived change in the net balance of the inland ice sheet in Pre-Boreal or Boreal.

The location of the ice margins of the various substages is shown in Pl. 2, and is based on the trace of the morainic ridges (Pl. 1). Reconstruction of Late glacial and Holocene ice-front positions in Southern Norway are shown in Fig. 12, which has been compiled on the following basis: 'Glacial Map of

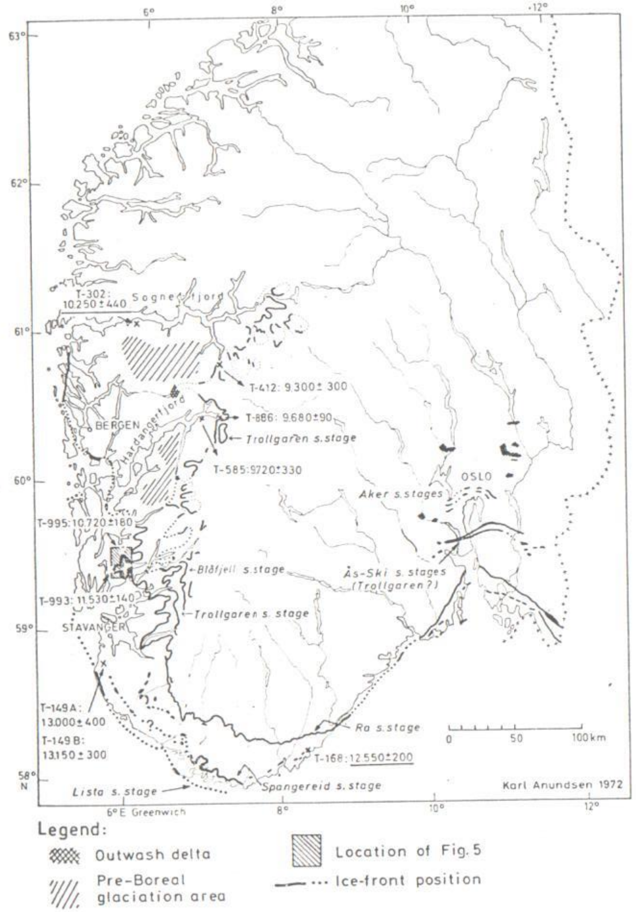


Fig. 12. Reconstruction of Late glacial and Holocene ice-front positions in Southern Norway. Some C^{14}-datings which are assumed to provide a minimum age for the last time the locality was covered by ice, are also shown. An exception is T-886 (at the head of Hardangerfjord) which gives the maximum age of the ice-front delta (Rye 1969). Dating which are underlined refer to marine shells, the rest to gyttja or wood. (For further C^{14}-datings, see Mangerud 1970, Fig. 9, p. 135). Lista and Spangereid substages are of Oldest Dryas age, Ra substage is of Younger Dryas age (Andersen 1960), Trollgaren substage is Pre-Boreal and Blåfjell substage is Pre-Boreal or Boreal.

Norway' (O. Holtedahl 1969; southeastern, and southern parts of Norway to Jøsenfjord), Klemsdal (1969; the coastal area between Lista and the island of Karmøy), H. Holtedahl (1967; Hardangerfjord), Mangerud (1970; the coastal area between Hardangerfjord and Sognefjord) and the author's investigations (Anundsen, in Anundsen & Simonsen 1968, Anundsen 1968, and the present work).

A striking feature is the increasing distance between the Ra border and the Trollgaren border from the S towards the N. (What happens to the Ra border in the Sognefjord district is still unknown.) Presumably the diverging ice borders are to be explained by means of topographical differences. Towards the N there is an increasing density of fjords (and valleys, whose bottoms are below the marine limit) and also an increasing depth of the fjords (Lysefjord 460 m, Jøsenfjord 670 m, Vindafjord–Hylsfjord 710 m, Hardangerfjord ca. 900 m, Sognefjord ca. 1300 m). This must have caused an increasing amount of ablation in the fjord districts towards the N. In the areas between the fjords this increasing ablation has again led to a more rapid retreat and shrinkage of the ice from different directions.

However, on high mountains in the latter areas, isolated bodies of ice may have represented local centres of outflow, at least during Pre-Boreal, but according to the firn limit perhaps also during Blåfjell times. This may have occurred, e.g., at the Folgefonn glacier plateau (15–1700 m a.s.l.), and in the mountainous area between Voss–Evanger and Sognefjord (Fig. 12). In the first area Follestad (1972) has found moraines younger than Younger Dryas, deposited by glaciers coming from the plateau. In the latter area Klovning (1963) and Mæland (1963) have found traces of a former ice culmination.

From the present investigations it is clear that a continuous ice sheet existed in southwestern Norway at least until Blåfjell times. The Blåfjell substage is the final trace of an ice-sheet advance, though a few sandurs occur, and also a number of small moraines across the bottom of some small mountain valleys inside this substage. The latter moraines only show that the small valley glaciers that formed along the rim of the shrinking inland ice were still dynamically alive. Thus, the isolated glacial deposits younger than Blåfjell times cannot be used to establish any ice-recession lines.

At present no geological, botanical or archaeological data available from the mountain area can tell anything about the ice-recession velocity after Blåfjell times.

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