Stratigraphy of the Fonndalsbre Neoglacial maximum, Svartisen, Arctic Norway

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Abstract: The stratigraphy of the two outmost Engabre end moraines demonstrated that they were formed prior to the classical 'Little Ice Age' (LIA). In contrast, the evidence from the comparable Fonndalsbre end moraine in the adjacent valley of Fonndalen suggests conformity with the 'LIA' norm for the region. Preservation of a biogenic rich stratigraphic record supporting this assertion is due to the nature of the fluvial geomorphological network during and after the ice advance maximum, whereby the main outwash river fortuitously both bifurcated and incised, forming an 'island' within the main valley bottom sandur. This 'island' preserves a fragment of the pre-existing valley floor which lies immediately distal to the outermost Neoglacial end moraine and is capped by an ombrogenous mire. A succession spanning a significant part of the Holocene is investigated. The probable age of the end moraine is established by (a) comparative soil profiles, (b) lithostratigraphy with an ice-marginal clastic fan sandwiched within a peat sequence and (c) a well-constrained stratigraphic signal suitable for radiocarbon dating. The data support a classical 'LIA' age for the Fonndalsbre maximum.

Holandsfjorden is a classic Norwegian glaciated valley occupied by an arm of the sea (Fig. 1). Despite its remoteness, it is one of the most viewed glacial environments in Norway as it is a popular point of call for cruise liners which follow the west coast en route to the North Cape. The fjord extends over 20 km eastwards from the main coastline and ends spectacularly where the outlet glacier Engabre descends through *c*. 1000 m from Vestisen, the western plateau ice cap of Svartisen. This glacier has on at least two occasions, including the 'Little Ice Age' (LIA), been extensive enough to have been washed by the sea during major storm events. Due to glacial recession, the terminus of Engabre is currently located on a bedrock surface over 15 m above sea level and some 3 km inland, being isolated from the sea by Engavatn, a deep freshwater lake and a belt of end moraine ridges (Alexander and Worsley 1973; Worsley and Alexander 1976; Worsley 2020).

On the southside of the main fjord, immediately adjacent to the mouth of the Enga valley, is a U-shaped valley known as Fonndalen (also spelt Fondalen).

***Figure 1**. Holandsfjorden and its subsidiary branch Nordfjorden. Part of the western ice cap of Svartisen occupies the bottom right with its outlet glaciers Engabre (right) and Fonndalsbre (left). Ice margins correspond to c. 1960. Grid squares of 10 km.*

Unlike the Enga valley, the main bedrock floor of lower Fonndalen lies over 100 m above sea level, in part explaining why during the Neoglacial, Fonndalsbre failed to reach the sea. However, this was not the case during the Younger Dryas between 12,900 and 11,500 years BP (Glomfjord event of Rasmussen 1981), when a huge marine delta moraine was constructed by outwash from a glacier occupying Fonndalen. Sub-fossil marine shell material from within the delta have yielded a marine calibrated age of 13,400 ± 70 years BP - UtC 5465 (Olson 2002). This landform was controlled by a Main Shoreline relative sea level of *c*. 100 m above present, and blocked-off the valley mouth. Sadly, extensive quarrying of the sands and gravels of the end moraine on the eastern valley side has disfigured the landscape. The historic Fonndal farm is situated on the crest of this moraine. Like the Enga valley, Fonndalen is only accessible by boat from the northern side of Holandsfjord (Fig. 2).

Following the recognition that the stratigraphy of the two outermost end moraines indicated an anomalous pre-classical 'Little Ice Age' Neoglacial maximum for Engabre, it was logical to investigate the situation in Fonndalen, which is only *c*. 2.5 km distant. The stratigraphy there proved to be of a quite different character and proved to be consistent with the 'LIA' date norm for the area. The objective of this contribution is to present the evidence supporting this conclusion.

Fonndalsbre and its valley

According to the 'Inventory of Norwegian Glaciers', in 1999, Fonndalsbre (Glacier ID 1097) had an area of 13.87 km² and a height range of 302–1421 m above sea level (Andreassen *et al* 2012). Both the Enga and Fonndal glaciers are sourced by the same Vestisen accumulation area, with their domains being defined by their hydrological basins. On this criterion, Fonndalsbre is just over a third of the size of Engabre. Although in the past both glaciers could be classified

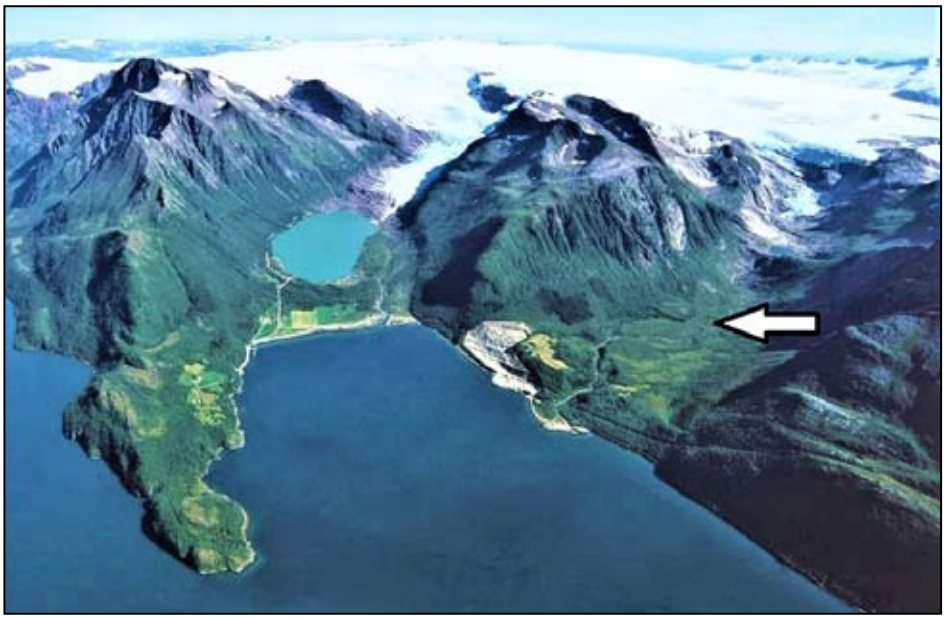


***Figure 2**. Oblique air photograph looking ESE towards the eastern end of Holandsfjorden. On the left is part of Nordfjord, a branch of the main fjord; Engabre descends from the Vestre Svartisen plateau ice cap in the centre and on the right is Fonndalen. The pale area is the aggregate quarry. The study site is arrowed. Helgalandsbukken, 1454 m above sea level, is between Nordfjord and the Enga valley.*

morphologically as outlets, because of recent glacial recession, Fonndalsbre is no longer a true 'outlet' glacier since its lowest margin is now defined by the plateau ice cap edge which currently lies above a precipitous bedrock wall. Periodically blocks of ice are discharged over this to nourish a regenerated glacier below. In the late 1970s, an ice advance caused the glacier to revert to being an outlet type when for several years there was physical continuity between the ice cap and the regenerated ice mass (Fig. 3).

Geomorphologically, Fonndal is a U-shaped valley some 4 km long and divisible into upper and lower basins separated by a transverse bedrock bar. The upper basin is mainly bedrock and likely a palaeocirque, whereas the floor of the lower basin has a cover of glacially derived sediments. The main drainage system is the northward flowing Fonndalselva, sourced by the ice cap, and this crosses the bedrock bar via an incised gorge, which at least in part is a former sub-glacial meltwater channel. In the latter part of the nineteenth century the glacier was large enough to submerge the bar and the early observers encountered the glacier terminus ending at the lower bedrock-proximal sandur boundary, and down valley, glacial and post glacial sediments form the valley floor (Fig. 4). Northwards, about 1 km beyond the bedrock bar, lies the Neoglacial limit which is marked by a clear end moraine. Beyond this limit, some small glacigenic ridges are present before the river enters a gorge through the major Younger Dryas delta end moraine just before the coastline. The small-scale ridge features are assigned to the main deglacial phase in the earliest Holocene (see later).

Previous investigators

The first published glacial geological observations of Fonndalsbre and its surroundings were made in 1865 by a three-man expedition consisting of Archibald Geikie (1835–1924), his younger brother James (1839–1915), and William Whitaker (1836–1925), all of whom were serving employees of the embryonic British Geological

***Figure 3**. Uppermost Fonndalsbre in 1980. The ice cliff capping the bedrock is the marginal of the Vestisen plateau ice cap. Below is the cone shaped regenerated glacier. Over several years a tongue of ice flowed from the ice cap down to the regenerated glacier due to a minor glacial advance. Note the stratification in the glacier ice beneath a cover of old snow and ice debris created by ice blocks avalanching down the cliff. A subglacial meltwater river can be seen to emerge from the base of the ice cap (top right) and disappears beneath the regenerated glacier.*

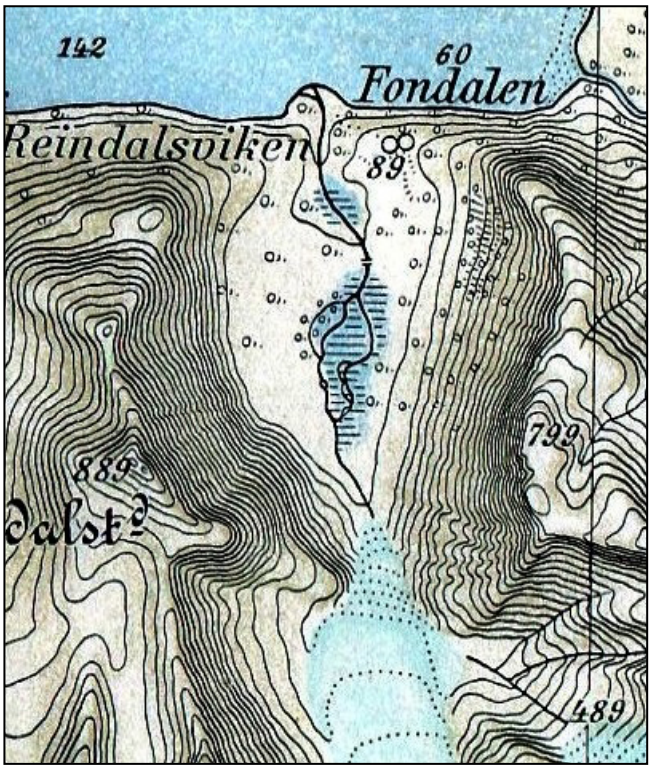


Figure 4. *Extract from the J. Melöy's 1:100,000 scale sheet J 14 published by the Norges geografiske oppmåling in 1900. This superb example of pre-computer cartography shows the ice extent in that year (blue) and the drainage net around the study site. Note how the eastern branch of the Fonndalselva meltwater river was still functioning in the late 1890s. The Fonndal farm site is designated by the two circles just below the name Fondalen.*

Survey. They were based at the old farm house in lower Fonndalen (Geikie 1866; Worsley 2019; Fig. 5). They were followed by the distinguished French geographer Charles Rabot (1856–1944) who used his own idiosyncratic spelling – Fonddal – for the locality. He travelled extensively in the Svartisen area in 1883 and 1885 and stayed in the same Fonndal farmhouse as

Figure 5. *The historic Fonndal Gård in 1973. The Geikie party stayed in the righthand building, which is the original farm building dating from c. 1670. To the left is the Hovedbygning built in c. 1873 and after 1900 used primarily as tourist accommodation.*

Geikie's party, with Johan Peter Ölson again being the host. He was the first to identify the presence of the end moraine which is the focus of this paper — he wrote 'a un kilométre de som extrémite inférieure, ou recontre une moraine important envahie par une végetation arborescente' (Rabot 1899, p 333). Over 130 years later little appears to have changed as the end moraine remains masked by trees! He also photographed the glacier snout (Fig. 6), these images being some of the first to be taken in Norway. For comparison, the contemporary situation is shown in Fig. 7. A Norwegian geologist, John Bernhard Rekstad (1852–1934), whilst working as a schoolteacher, first visited Fonndalen in 1890 and returned in the following year. He later established an annual programme of recording frontal variations of both Fonndalsbre and Engabre in 1909. From 1900 he became an employee of the Norwegian Geological Survey specialising in glacial geology (Rekstad 1912). Like Rabot, he had an interest in photography, with glaciers featuring prominently in his work. In particular,

Figure 6. *Charles Rabot's historic photographs of the Fonndalsbre snout resting on bedrock with the main meltwater stream emerging from a subglacial tunnel. The upper photograph dates from Rabot's first visit in 1883 and the lower from 1885 (22 July) when the glacier had retreated about 10 m. The glacier ended at the same spot when described and sketched by Archibald Geikie in 1865 suggesting little variation in the ice marginal position over the intervening 18 years. Courtesy of the late Professor Fridtjov Isachsen, University of Oslo.*

***Figure 7**. The same location as seen in Figure 6. The key identifier is the bed rock controlled right-angle bend in the meltwater stream in the foreground. On the skyline is the vertical edge of the Vestisen ice cap immediately above a steep bedrock wall and a subglacial meltwater river (the source of the Fonndalselva) emerges from the glacier bed and cascades down the wall. In the middle distance is the bedrock bar which separates the lower valley from the upper basin. Twentieth century glacier retreat is about 2 km.*

he photographed Fonndalsbre in 1911 when the glacier was almost at its twentieth century maximum (1913; Fig. 8). In 1932, Konrad Richter (1903–1979), a German geologist, visited Holandsfjord whilst seeking contemporary glacigenic sedimentary fabric data to compare with similar materials associated with the Weichselian glaciation of the North German Plain. His observations were the basis of a seminal paper on modern till and outwash fabrics (Richter 1936). Apart from two unpublished scholastic reports by Bergerson (1953) and Bang and Fitzsimmons (1968), no further published field investigations are known to us.

The end moraine study site

Spatial aspects of the Neoglacial history of Fonndal are shown in Fig. 9. At the Neoglacial maximum the glacier extended a third of the way down the lower basin and fed a sandur *c*. 1 km long (Fig. 10). The latter was pinched out where the outwash river entered the gorge through the delta moraine. A glacial geological map of the study site (Fig. 11) shows the main end moraine some 60 m long and 8 m high, terminating at a mire, with outwash sediments on either side. The 'island' feature extends 62.5 m northwards and ends at a break of slope related to a minor channel cutting across it. Beyond this is a small moraine ridge only 2 m high but which is of importance for this study. In Fig. 12 the upper longitudinal profile shows the morphological relationship between the Neoglacial end moraine and the minor ridge. Fig. 13 shows the section exposed at column 'A' in Fig. 12.

The initial field examination focused on the riverbank section associated with the western end of the moraine ridge. Unusually, this revealed an exposure of a glacio-tectonically disturbed mass of sphagnum peat containing broken birch tree branches, dispersed rock clasts, sand stringers and fragments of a podzol soil profile. The horizontal base of this complex unconformably overlay a boulder-rich diamict which extended below the river level. Apart from obvious slumping, evidence of active riverbank erosion was a block of segregation ice within the peat surviving in July (Fig. 14).

Some 50 m downstream, a bluff was separated from the river by a low terrace. A section was excavated into the bluff which revealed almost a metre of *in situ* peat overlying diamict with an abrupt contact (Fig.13).

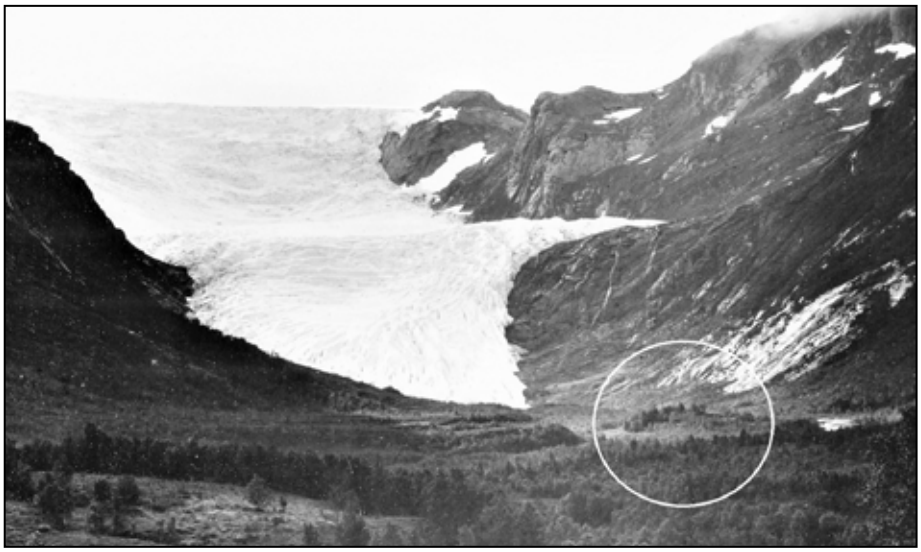


***Figure 8**. John B. Rekstad's photograph of Fonndalsbre in 1909 when it was advancing to its twentieth-century maximum achieved in 1913. Compared to the 1882 position, by 1909 the ice had advanced approximately 80 m. The study site is circled, with a line of trees on the outer moraine ridge like today. The Fonndalselva outwash stream is just visible to the right. University of Bergen geological archive.*

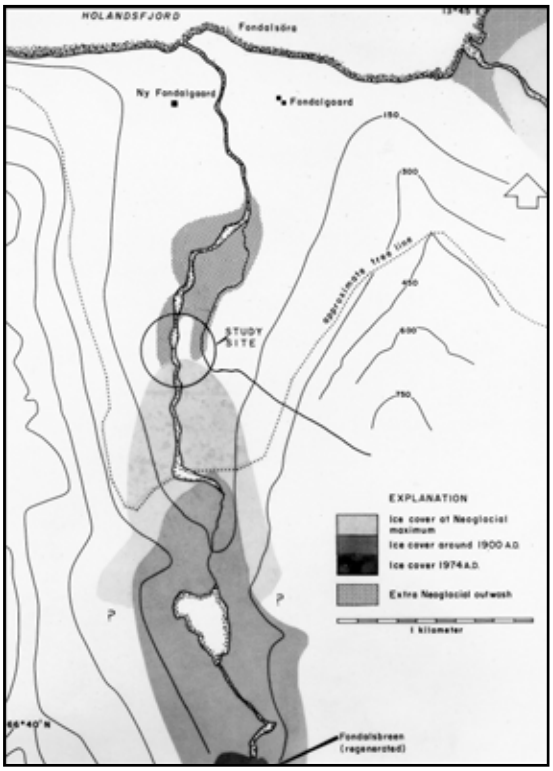
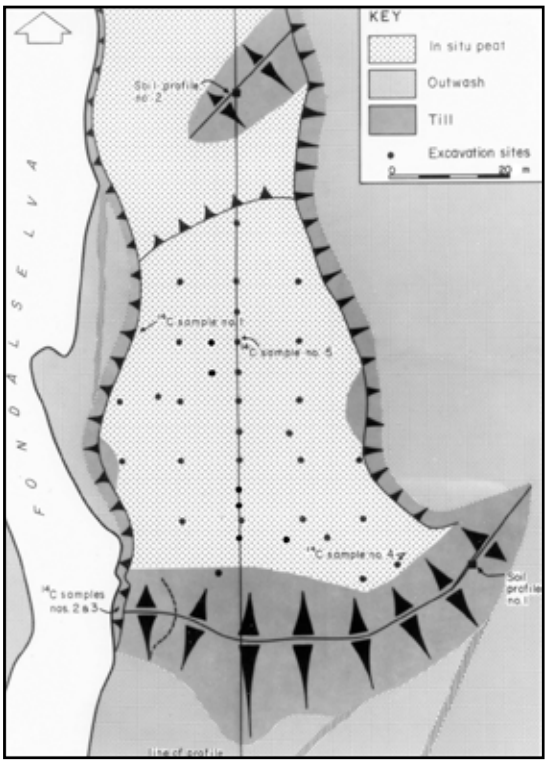


Figure 9 *(left). Map of Fonndalen showing the areas of Neoglaciation, ice extent in c. AD 1900 and 1974, extent of the valley sandur and location of the study site. The regenerated glacier margin is just evident at the bottom margin. Base map revised from the 1950 Durham University Exploration Society 1:10,000 scale map of 'Engen and Fondal'.*

Figure 10 *(above). The main lower valley viewed from the eastern slope, with the Fonndalselva flowing from left to right. The study site is highlighted.*

Towards the top of the peat sequence a seemingly anomalous thin clastic bed was evident. This prompted an examination of the sequence below the peat surface which extended away from the river. This involved digging 35 pits into an ombrogenous mire, 23 of which established the total peat thickness when the diamict substrate was encountered. All the excavation sites are plotted in Fig. 11. The data obtained showed that the thin clastic bed seen in the river bluff could be traced in the sub-surface, across most of the peat-covered 'island' with the exception of the northern tip and that it both thickened and coarsened towards the end moraine and vice versa. The pattern of thickness variation suggested that originally the clastic horizon formed a fan sourced by a glacier margin coinciding with the end moraine and that this both thinned and fined away from it northwards — see the lower section in Fig. 12. The north-south longitudinal section corresponds to the levelled transect through the middle of the 'island'. Away from this profile the two logs A and B relate to sections 10 m apart in the river bluff and are plotted using the same reference datum.



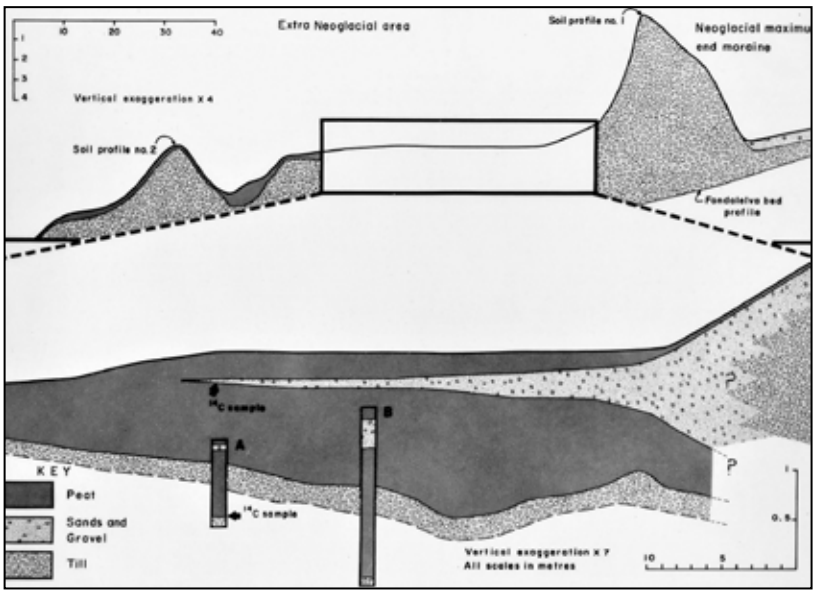


Figure 11 *(left). Glacial geological map of the study site with locations of (a) the pits excavated into the peat, (b) the soil profile pits, (c) the radiocarbon sample locations and (d) the line of the surveyed profile (Fig. 12).*

Figure 12 *(above). Levelled longitudinal profile (north-south) through the study site with the underlying stratigraphy.*

Pedological data

Following our study of the soils on the two outermost moraines of the adjacent Enga valley (Worsley and Alexander 1976), the soil development that has taken place on the outermost two moraine ridges recorded in Fonndal (Fig. 11) was investigated. A series of soil pits were excavated along the crest of each ridge; sites were restricted to the crest of the moraine ridges to ensure as far as possible that the environmental variables influencing soil development were standardized between the sites, thus allowing the time element of formation to be investigated. In the case of the assumed Neoglacial (LIA) end moraine, the fact that a considerable part of it was comprised of peat limited where the mineral soils could be examined.

Two sites, one from each moraine, were selected for detailed soil description (following procedures recommended by Hodgson 1974) and bulk samples were collected from each horizon for laboratory analysis. In the laboratory all samples were air dried, ground to pass a 2 mm mesh sieve and analysed for the following: pH, total organic carbon, total cation exchange capacity, pyrophosphate and dithionite extractable iron and aluminium. The descriptions are given below, and analytical data are given in Table 1 (p 98).

Site One

Morphologically this soil profile shows very limited development (see description, Table 1 and Fig. 15). A thin litter layer overlies a very thin F layer of partially decomposed organic material, this in turn overlies a weakly developed mineral Ah horizon containing some organic matter, which accounts for the brown colouration of the soil. Beneath the Ah horizon the Bw horizon is paler in colour as a consequence of its reduced organic matter content and fewer roots. This horizon gradually pales further with depth, merging at around 270 mm with the underlying C horizon, which is paler still in colour and lacking organic matter and also roots.

The analytical data reinforces the interpretation of the profile morphology. The Ah horizon has significantly higher organic carbon (3.2%) than either of the underlying horizons at 0.4 and 0.2% respectively. The soil acidity (pH) gradually increases with depth (5.2–5.9) suggesting that some leaching of bases is occurring. Given the sandy texture throughout the profile, total cation exchange capacity (CEC) is very reliant on organic matter content, this can be seen to mirror the decrease in organic matter with depth. The pattern of extractable iron and aluminium and associated ratios are fairly constant throughout the profile, indicating that little if any sesquioxides are being leached.

The soil can be classified as an Arctic Brown soil; alternatively, a Humic Dystrochrept (Soil Survey Staff 1999) or Dystric Arenosol (FAO & IUSS 2015); and is the same as the soils found in the adjacent Enga valley that have developed on the MR3 end moraine. Similar soils have also been identified on post 'LIA' moraines associated with the outlet glaciers of Okstindan Ice cap, some 80 km to the south east (Ellis 1979).

Figure 13*. Section excavated into the bank of the Fonndalselva showing clastic materials overlain by peat. Sample 1 which yielded an age estimate of 5181–4832 cal B.P. (HAR-1932) came from the base of the peat.*

Site Two

In contrast to the soils developed on the Neoglacial end moraine, the soils on this ridge show very marked profile development (see description and Fig. 17 and Table 1). A well-developed 200 mm thick organic horizon comprising L, F and H layers, overlies a pinkish grey, 'bleached' sandy E horizon. This in turn overlies a sandy, black, very compact and partially cemented Bhs horizon; beneath this horizon is a redder Bs horizon, having a coarser texture but similarly cemented. Below 900 mm the C horizon colour pales and the texture becomes gravelly and there is no longer any cementation.

The horizon differentiation is strongly reflected by the analytical data (Table 1). The pale grey colour of the E horizon with its bleached sand grains is almost totally devoid of organic carbon (0.1%). This has been leached out to accumulate in the black Bhs horizon (5.6%) and to a lesser extent in the Bs horizon (1.7% C), which explains the redder colour. The C horizon, as is to be expected, contains little organic carbon (0.4%). Given the sandy-gravelly texture of the whole profile,

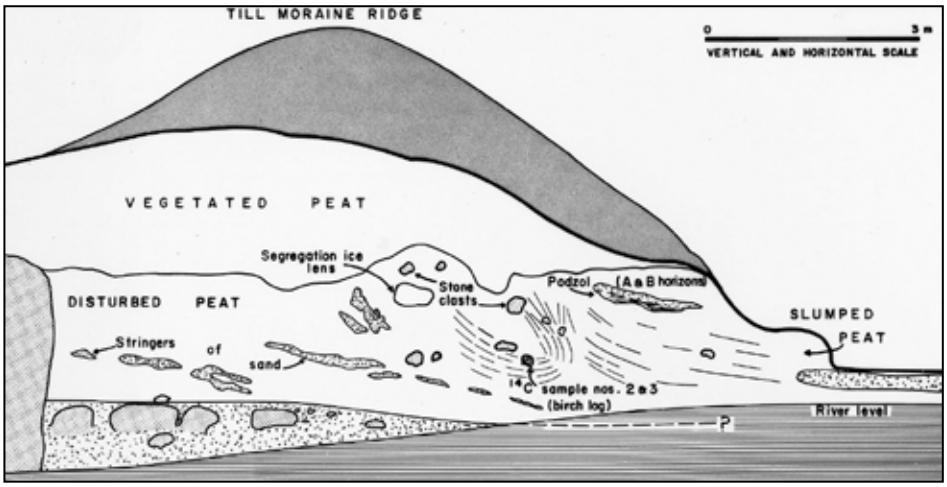


***Figure 14**. Sketch of the east bank of the Fonndalselva where it dissects the outer Neoglacial end moraine ridge. At this site, the ridge consisted of glacio-tectonically deformed sphagnum moss peat containing dispersed rock clasts, thin sand lenses and fragments of podzolic soil profiles. This complex overlay a diamict within which was a large boulder. This also was partially buried by the peat (extreme left in diagram).*

total cation exchange capacity of all the horizons is extremely low; the slight variation between horizons tends to parallel the organic content. The distribution of extractable iron and aluminium down the profile varies dramatically, reflecting the processes that are occurring with depth in the profile. Of crucial importance here are the two ratios – Fep+Alp/ Fed+Ald and Fep:Fed, as these are recognised as indicators of the loss and accumulation of sesquioxides in soil horizons (FAO 2015; Rennart, 2018; Soil Survey Staff 1999). The E horizon ratios are extremely low, which, coupled with the pale colour due to the presence of bleached sand grains, indicates the loss of sesquioxides by leaching and accumulation in the underlying Bhs and Bs horizons, which have significantly higher levels of both ratios. These high ratios coupled with the dark colours and organic carbon content indicate that the accumulation of both organic carbon and/or sesquioxides has, and is taking place, in both horizons; this also explains their cemented nature. The C horizon shows much lower ratios that suggest little if any accumulation is occurring here. These soils can be classified as Humic Podzols (alternatively Typic Fragiorthod (Soil Survey Staff 1999), or Orsteinic Albic Podzol (FAO & IUSS 2015).

Thus, the soils which have formed on two moraine ridges some 90 m apart show significantly different degrees of development in overall morphology. Given that the soils are currently subjected to the same environmental inputs, vis-à-vis the climate, topographic position, parent material and similar vegetation cover (though site 2 has a greater variety of ground flora than site 1), the only plausible explanation for the marked difference in degree of development is the time factor. Site 1 (Fig. 15) with the Arctic Brown soil with limited profile differentiation, is very similar to the soil developed on the outer Engabre 'LIA' end moraines, i.e. it represents some 200–300 years of pedogenesis. It also has a similar profile to the *buried* soil on the two outermost Enga moraine ridges M.R.1 and 2, tentatively dated to *c*. AD 1200 (Worsley 2020). Similar soils showing the same degree of development have been found on moraines attributed to 'Little Ice Age' related to the outlet glaciers of the Okstindan ice cap some 80 km to the south-east (Griffey and Worsley 1978). In contrast, Site 2, with the well differentiated Humic Podzol indicates a soil of considerable age, as the process of sesquioxide and organic matter mobilisation (cheluviation) transfer and redeposition forming Bhs and Bs horizons takes considerable time. This is supported by the degree of weathering shown by the decomposing mica schists in the B horizon. Accordingly, this moraine ridge would appear to be significantly older than the LIA and interestingly much older (in terms of profile development) than the buried soil from the Enga outermost moraine ridges.

Investigations of podzol development distal to assumed 'LIA' end moraines and from palaeo-podzolic soils around the ice cap of Okstindan (Alexander and Worsley 1973; Griffey & Ellis 1979, Ellis 1980) suggest that podzol development has taken at least 2000–3000 years, possibly associated with the onset of climatic deterioration at the Sub-Boreal/Sub-Atlantic transition. Following a study of a Neoglacial end moraine at Haugabreen, an outlet glacier from the Myklebustbre plateau ice cap in southern Norway, Ellis and Matthews (1984) argued that humic podzol formation commenced around 3000–4000 years BP. Thus, the pedological evidence indicates that the Site Two end moraine is significantly older than that at Site One.

***Figure 15**. Arctic Brown Soil: Profile no.1 on the crest of the end moraine. Scale – lens cap diameter 60 mm.*

Soil profile descriptions (Munsell colour notation)

Soil Profile No. 1 – Fig. 15

Location: On the crest of the LIA end moraine, *c*.40 m east of the longitudinal profile (Fig. 12).

Surface features: Shedding site; abundant angular and sub-angular boulders on surface up to 1 m diameter, most devoid of lichen and moss.

Vegetation: *Betula odorata; Sorbus aucuparia; Vaccinium myrtillus; Cornus suecica; Trientalis europaea; Poa spp.; Deschampsia spp.; Festucca spp.; Equisetum spp.;* moss and lichen.

Description:

Depth (mm)	Horizon	
0–30	L	Dry, mainly moss with leaves of above vegetation. Sharp smooth boundary.
30–50	F	Dark brown (7.5YR3/2); moist partially decomposed organic matter; abundant fibrous roots and small woody roots. Abrupt smooth boundary.
50–100	Ah	Brown-dark brown (7.5RY4/2); Humose, loamy medium sand; many medium stones, few boulders; single grain. Many Fine fibrous roots; common medium woody roots. Clear wavy boundary.
100–270	Bw	Olive brown (2.5Y4/4), paling with depth. Loamy medium sand; many medium stones, few boulders; single grain. Many fine fibrous, decreasing with depth, few medium roots. Diffuse boundary.
270+	C	Olive (5Y4/3). Clean washed loamy medium sand to fine gravel; abundant medium stones, few boulders; single grain.

Classification – Arctic Brown Soil (Humic Dystrochrept (Soil Survey Staff 1999); Dystric Arenosol (FAO)

Soil Profile No. 2 − Fig. 17

Location: On the crest of the first moraine 90 m distal to LIA maximum moraine (Fig. 12).

Surface features: Shedding site; Few sub-angular boulders on surface up to 1m diameter, all covered in lichen and moss.

Vegetation: *Betula odorata; Calluna vulgaris; Empetrum hermaphroditum; Vaccinium myrtillus; V. uliginossum; Melampyrum pratense; Rubus chamaemorus;* moss.

Description:

Depth (mm)	Horizon	
0–50	L	Moist litter of above vegetation, principally composed of moss and *Vaccinium spp*., mainly moss with leaves of above vegetation. Abrupt smooth boundary.
50–140	F	Dark Brown (7.5YR3/2). Very moist, partially decomposed remains of above vegetation. Abundant very fine fibrous roots; common fine woody roots. Abrupt smooth boundary.
140–200	H	Black (5YR5/1). Amorphous organic matter; many very fine fibrous roots; common fine woody roots; few medium woody roots. Common bleached sand grains towards base of horizon. Sharp wavy boundary.
200–280	E	Pinkish grey (7.5YR6/2). Variable thickness (70-160 mm). {Sporadic, discontinuous patches of thin (<50 mm) brown-dark brown (7.5RY4/2) A1 horizon between H and E horizon}. Medium sand; weak sub-angular blocky. Common very fine fibrous roots; few medium-coarse woody roots. Abrupt irregular boundary.
280–370	Bhs	Black (7.5YR5/1). Variable thickness (70-160 mm). Loamy medium sand, common small-medium rounded stones; few large-very large sub-angular stones, mainly gneiss, several decomposing *in situ*; all heavily stained; granular; very compacted, partially cemented. Abrupt-clear boundary.
370–900	Bs	Very dark reddish brown (7.5YR3/2 & 3/3). (7.5YR3/3 colour at boundary with Bhs1 darkening to 7.5YR3/2 within 50). Coarse sandy gravel; abundant small rounded stones; few large sub-angular stones; all heavily stained; mainly gneiss, some decomposing *in situ*. Clear wavy boundary.
900+	C	Brown-dark brown (7.5YR4/4), (being unstained coarse sandy gravel (no proper Munsell colour equivalent). Coarse sandy gravel; abundant small rounded stones; occasional clast of greyish brown (2.5Y5/2) loamy fine sand; single grain.

Classification – Humic Podzol (Typic Fragiorthod (Soil Survey Staff 1999); Orsteinic Albic Podzol (FAO)

	Horizon	Sample depth mm	pH	% Organic Carbon	Total CEC	%Base Saturation	Iron %		Aluminium %		Fep+Alp / Fed+Ald	Fep:Fed
							Pyr*	Dith**	Pyr*	Dith**		
Pit 1	Ah	60-90	5.2	3.20	11.25	12.9	6.50	23.00	5.20	7.10	0.39	0.28
	Bw	120-125	5.5	0.40	6.25	7.0	3.89	23.00	7.30	10.20	0.34	0.17
	C	300-350	5.9	0.40	5.00	12.4	2.00	23.00	4.50	4.90	0.23	0.09
Pit 2	E	210-270	5.3	0.10	2.50	23.6	1.30	2.30	2.22	5.10	0.34	0.57
	Bhs	290-350	5.0	5.60	5.00	14.8	61.00	28.00	61.50	5.00	3.71	2.18
	Bs	400-800	5.5	1.70	6.25	9.9	23.50	24.20	71.50	13.50	2.52	0.97
	C	910-1110	5.8	0.40	5.00	11.2	4.80	18.00	22.50	8.40	1.03	0.27

***Table 1**. Soil analytical data* *Pyr = sodium pyrophosphate extractable ** Dith = Dithionite extractable

Radiocarbon Dating

Atypically, in a Neoglacial context, the study site was characterised by an abundance of materials appropriate for radiocarbon assay and five samples were selected. The results are listed in Table 2 along with their calibrated ages using the Ox Cal 4.4 version. To facilitate discussion, the mean age after calibration will be cited in the text although it has to be remembered that this ignores the standard deviation factor, and all are age estimates. All dates relate to years before the present (BP), where 'present' is AD 1950.

Sample 1

This was collected from the base of the river bluff profile (Figs. 11-13) with the objective of dating the commencement of peat accumulation. The date of 5006 years BP is clearly mid Holocene and indicates likely ice-free conditions at the site since then. Using Occam's razor, the underlying diamict relates to the deglaciation at the Weichselian/Holocene transition. It also confirms that the minor moraine ridge into which Soil Pit 2 was dug probably originated from *c*. 10 ka during the main deglaciation event. A pollen count of the basal peat showed 67.9% arboreal pollen, dominated by *Betula* with minor *Alnus* and *Pinus*. The bleaching of the sediment immediately below the peat hints that a gley soil had developed as a consequence of water logging prior to the commencement of peat accumulation.

Samples 2 and 3

These came from the river-cut section through the end moraine where it is dominated by biogenic sediment (Fig. 14) which is not in situ. The Sample 2 wood branch was highly likely to have been initially pushed over by the advancing glacier in the same manner as happened at the neighbouring Engabre site (Worsley 2000). Unfortunately, the assay only produced a provisional result of 869 years BP. However, the assay for the associated *Betula* bark yielded an age of 765 years BP which is only slightly younger than the tree branch result, thereby supporting the interpretation of Sample 2. Remarkably this age (765 years BP) is virtually coincident with the 790 years BP mean from 12 different trees over-ridden by Engabre although the significance of this should not be over-emphasised. If the degree of present-day woodland cover in Fonndal is a guide to conditions around 800 years BP, then the *maximum* amount of potential glacial transport would be 550 m, the distance from the outer Neoglacial end moraine to the base of the bedrock bar. Unlike the situation in Engadal, where the former woodland grew on glacigenic sediments, the association of wood and peat in the exposure suggests that in this part of Fonndal the woodland was probably growing on a peat cover.

Samples 4 and 5

Inspection of the longitudinal section in Fig. 12 shows that the height of the base of the clastic bed within the peat succession falls as the end moraine is approached. This suggests an erosional interface which is likely to be diachronous. Sample 4, a peat from the base of the sand bed close to the foot of the distal end moraine slope, yielded an age of 590 years BP. In contrast, Sample 5 came from the same lithological interface but was 45 m more distal. At this locality the sequence was: upper peat 0.3 m; sand 20 mm; lower peat 0.82 m (Fig.16). Just 20 m more distal the sand layer thickness

***Figure 16**. Section in the peat bog with the distal sand layer. Sample 5, a thin slice of peat, was taken from immediately below the sand bed.*

had reduced to a trace. It is assumed that the deposition of the sand was a lower energy event at this sample location and the top of the lower peat was not eroded. Sample 5 was a thin slice taken from the top of the lower peat. The age 354 years BP (AD 1696), or more precisely AD 1560–1696, must be very close to the time of fan sedimentation and hence when the end moraine was constructed by Fonndalsbre.

Sample 6

Unlike the previous samples, Sample 6 was from the surface Humic Podzol soil developed along the crest of the small moraine ridge beyond the ombrogenous mire covering the 'island'. Modern soil dating by radiocarbon is a literal 'can of worms'. In the laboratory the humic content from a sample taken from the Bh horizon was separated and the contained residual radiocarbon measured. However, such material is not part of a closed system, rather it is part of a dynamic open system with continual infiltration of modern carbon down profile. Hence, the conventional 'date' of 880 ± 45 years BP has no precision (calibration is inappropriate) and is indicative only. It does, however, fully support the notion that the moraine ridge is much older than the one marking the Neoglacial maximum advance.

Buried soils are different in that potentially they are isolated from the surface environment. In interpreting radiocarbon assays from such contexts, the concept of 'mean residence time' is important, since this value has to be deducted from a buried soil age. Specifically, the question is: 'what is the age of a surface soil prior to burial?' In the Okstindan mountains, three samples of surface mineral-organic humus on solifluction lobes yielded ages of 50 ± 100 years BP (Birm-824), 1005 ± 90 years BP (SRR-5289) and 1345 ± 90 years BP (SRR-5290) (Elliott and Worsley 2012). A sample of amorphous humus from the buried podzol 0.3 m depth overlying Engabre end moraines M.R.1 and 2, was submitted for radiocarbon assay. The result was 'Modern' (Birm-612). The count statistics actually indicated 'newer than new' (pers comm Fred Shotton), and highlighted the problem of modern root penetration. In the light of this data, the Fonndal Bh result is unremarkable.

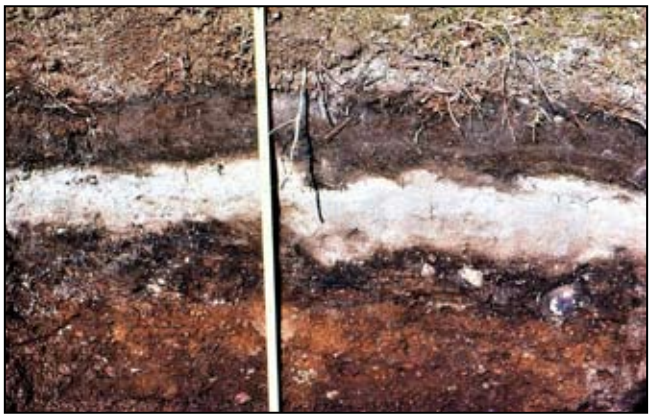


Figure 17*. Humic Podzol Soil: Profile no.2 on crest of minor moraine ridge beyond the raised peat bog. Scale 0.5 m.*

Discussion

It is perplexing that the conclusions of our study of the Engabreen end moraines, published almost 40 years ago, have been either ignored or misrepresented, and it is frequently asserted that the Engabre glacial maximum is *c*. AD 1750. Both editions of the influential book 'The Little Ice Age' (Grove 1988; 2004) make the latter error. One recent example is the publication by Jansen *et al* (2018, p 1) who state 'Except for the two moraines overridden by the LIA glacier maximum at Engabreen…', yet this is **not** the case, but they nevertheless cite Worsley and Alexander (1976) as their source. They also add that 'little is known about pre-LIA glacier maximum fluctuations at Austre- and Vestre Svartisen'!

We can only speculate why this is the case. One factor may be that the use of detailed pedological evidence is uncommon in Scandinavian Holocene glacial geological contexts despite the fact that its value was shown by us at Engabre and Austre Okstindbre (Alexander and Worsley 1973). Indeed, a number of papers/theses by Mike Alexander, David Bertie, Charlie Harris, Nigel Griffey, Steve Ellis and Graham Elliott, each a member of the University of Reading 'Okstindan Research Project' during the period 1969–*c*. 2000, have demonstrated the value of pedological/palaeosol techniques in glacier variation and solifluction studies. Generally, lichenometry and radiocarbon dating are the dominant techniques used in

Table 2*. Fonndal C14 conventional dates (1σ) and OxCal 4.4 calibration.*

Sample 1	*In-situ* peat, base of peat bog: 5180±70, 5181–4832 cal BP (HAR-1932)
Sample 2	Wood, outermost rings of glacio-tectonically moved *Betula* branch: 910, 869–780 cal BP preliminary result, (HAR-1935)
Sample 3	*Betula* bark, glacio-tectonically transposed: 720±80, 785–545 cal BP (HAR-1936)
Sample 4	*In-situ* peat, at base of sand bed at moraine ridge foot: 590±70, 667–514 cal BP (HAR-1934)
Sample 5	*In-situ* peat, base of sand bed within peat: 190±70, 390–319 cal BP (HAR-1933)
Sample 6	Bh horizon, modern humic-ferro podzol soil on crest of pre-LIA ridge: 880±45, 720–693 cal BP (SRR-1341)

HAR = Harwell; SRR = Scottish Universities Research and Reactor Centre.

glacier reconstruction outside the period of historical observations, due apparently to the lack of stratigraphic evidence, although it is recognised that limnological approaches have proved instructive of late. But the wise old adage 'the eye sees what the mind looks for' could be one reason why pedological evidence is often overlooked.

Conclusions

The sequence of landscape changes at the study site can be summarised by four hypothetical longitudinal sections A–D (Fig. 18).

A. Early Holocene land surface after the Younger Dryas deglacierization. A relict from this latter event is a small moraine ridge (on left).

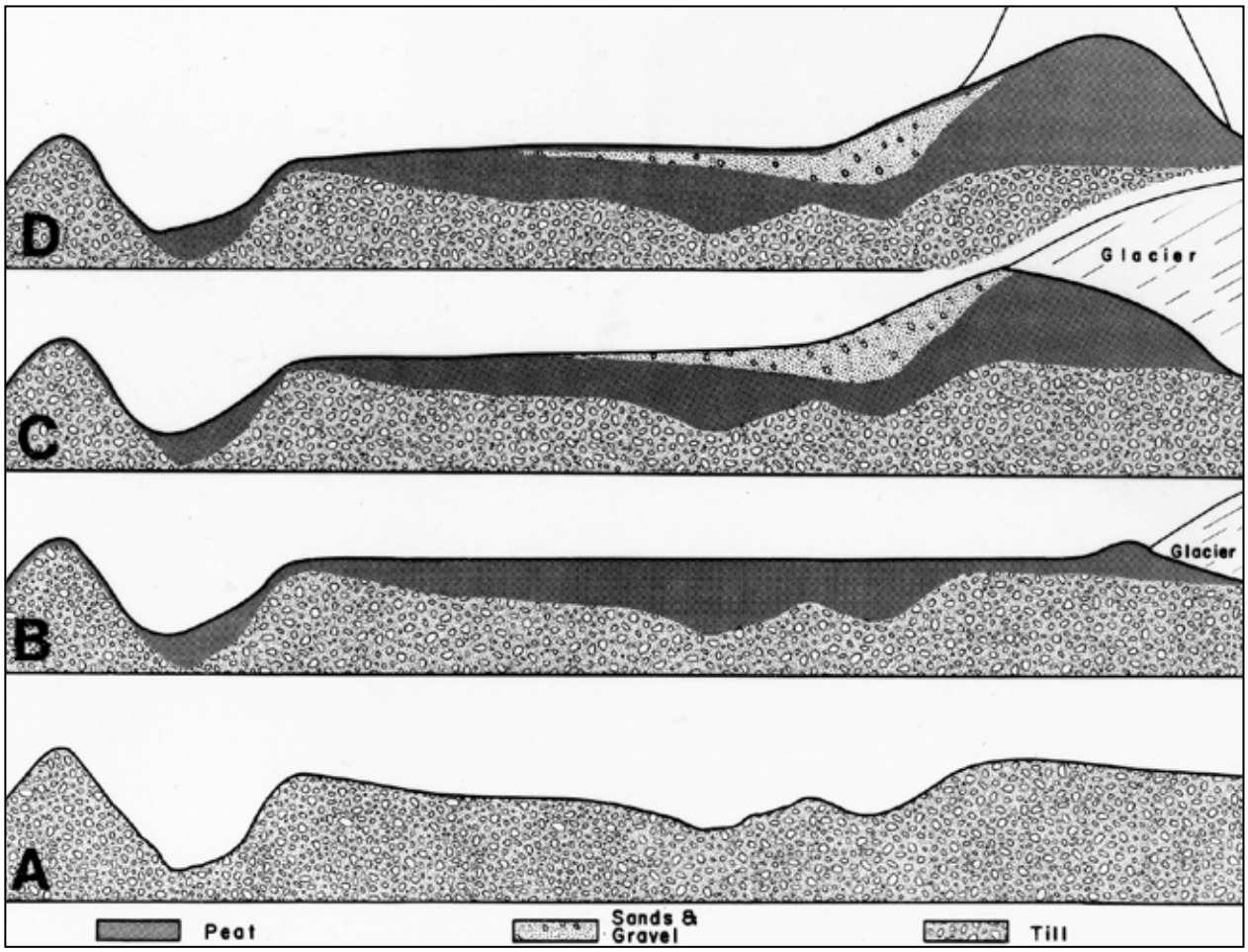
B. Podzolic soil development starts on the well-drained small moraine ridge and from the mid Holocene, growth of a blanket peat bog commences, a process which has persisted to the present day. An advance of Fonndalsbre c. AD 1500 in part crosses a blanket peat bog covered by birch trees (*Betula*).

C. Fonndalsbre reaches its maximum extent and close to the outwash stream builds an end moraine largely formed of peat; eastwards the ridge is formed of diamict. A minor glacier meltwater stream emerges at the ice margin and proximately deposits a small fan of cobbles and gravel, more distally sand spreads over the peat bog surface.

D. Following glacier retreat, the end moraine is fully exposed, and the meltwater stream no longer functions. Further away (eastwards) the peat moraine passes laterally onto a diamict (till), which has a steeper profile and greater height. Peat growth recommences and buries the clastic materials which formed the fan. Pedological processes on the diamict ridge crest produce an Arctic Brown soil.

Stratigraphically, the Fonndalsbre Neoglacial advance maximum is captured by the small outwash fan spreading into the pre-existing mire and later being buried by further peat growth. The radiocarbon age estimate from the distal part of the fan, suggests deposition of the fan just after AD 1560–1631. On face value this is close to a century earlier than the equivalent end moraine M.R.3 in the adjacent Engadal where the historic records support an advance culmination *c*. AD 1723. This age difference may be real and the two adjacent glaciers have diachronous LIA limits but the alternative interpretation is that at both sites the evidence is insufficiently precise to sustain such a conclusion. What is more certain is that the two limits concerned are both LIA landforms. In Fonndalen there is no evidence of end moraines equivalent to the M.R.1 and 2 of Engabre.

***Figure 18**. Four cartoons, along a north-south profile, to show the sequential landscape changes during the Holocene at the study site.*



Acknowledgments

John Dalrymple and Ian Fenwick stimulated our use of pedological techniques in geomorphological contexts. The Universities of Durham, Ottawa and Reading supported the investigation. Bob Otlet (Carbon-14/Tritium Measurements Laboratory, Harwell) and Doug Harkness (NERC Radiocarbon Laboratory, East Kilbride) managed the age determinations. Both Fonndal farmers, the late Knut Dahl and Konrad Kilvik, gave every encouragement to our investigation on their land. Hilary Worsley kindly assisted with the figures.

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