

Weichselian interstadial sediments on Jæren (SW Norway) – paleoenvironments and implications for ice sheet configuration

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Interstadial glaciomarine sediments at Jæren in south-western Norway have been investigated for their composition, distribution and age, and a model for the depositional environment is proposed. In the northern and central parts of Jæren, the interstadial sediments consist of laminated and homogenous silty clays overlain by homogenous glaciomarine diamictos. In the southernmost part, homogenous silt and stratified glaciomarine diamictos prevail. The sediments are found below the uppermost till, and radiocarbon dating of marine fossils suggests an age of c. 35–30 ¹⁴C ka BP. The sediments were probably deposited during a relatively short period during the deglaciation into the Middle Weichselian Sandnes interstadial. The glaciomarine sediments are commonly found well above the postglacial marine limit, and their upper limit rises from c. 30 m in the northern part of Jæren to c. 200 m in the southern region. The high elevation of the glaciomarine sediments suggests a significant glacioisostatic depression, which may be explained by combined loading from both the inland ice and an ice stream in the Norwegian Channel.

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Introduction

During the last decades, our understanding of the Weichselian glaciation history of southern Fennoscandia has become progressively more complex as new data have become available, i.e. Larsen & Sejrup (1990), Houmark-Nielsen (1999), Sejrup et al. (2000), Olsen et al. (2001) and Mangerud (In press). Long and continuous records from the deep sea and from the Greenland Ice Sheet have been especially important in understanding the Weichselian climate changes in the North Atlantic region. Oxygen-isotope records from Greenland ice-cores indicate several rapid climate shifts during the Weichselian (Dansgaard et al. 1993). These oscillations have been correlated to changes recorded in North Atlantic marine sediments (Bond et al. 1993; Fronval et al. 1995; Hafliðason et al. 1995; Elliot et al. 2001) and terrestrial sediments from western Norway (Olsen et al. 2001; Mangerud et al. 2003), suggesting a closely coupled ocean-atmosphere system in the Northern Atlantic region during the Weichselian.

In western Norway, several sites with interstadial sediments have been reported (Figs. 1A & C), e.g. Sunnmøre (Mangerud et al. 1981a; Landvik & Mangerud 1985; Landvik & Hamborg 1987; Larsen et al. 1987; Larsen & Sejrup 1990; Larsen & Ward 1992; Valen et al. 1995; Valen et al. 1996; Mangerud et al. 2003), Karmøy

(Andersen et al. 1983; Sejrup 1987), Fjøsanger (Mangerud et al. 1981b) and Jæren (Feyling-Hanssen et al. 1971; Feyling-Hanssen 1974; Andersen et al. 1981; Andersen et al. 1987; Fugelli 1987; Andersen et al. 1991; Janocko et al. 1998; Sejrup et al. 1998; Stalsberg et al. 1999; Larsen et al. 2000; Stalsberg 2000; Raunholm et al. 2002; Stalsberg et al. 2003). Based on these observations and other available data, a number of glaciation curves have been constructed, e.g. Larsen & Sejrup (1990), Mangerud (1991), Valen et al. (1995), Sejrup et al. (2000), Olsen et al. (2001) and Mangerud et al. (2003). However, the duration and timing of ice-free periods is still not well known, mainly due to lack of precise dating methods beyond the range of the radiocarbon method. The extent of the glacial fluctuations is also uncertain. At Jæren (Fig. 1C), subglacial sediments containing marine fossils and far-travelled erratics have been known since the end of the 19th century (Helland 1885). These sediments are found over large parts of Jæren (Østmo & Olsen 1986; Wangen et al. 1987; Wangen & Lien 1990; Jónsdóttir 1998; Sejrup et al. 1998; Sejrup et al. 1999; Larsen et al. 2000; Raunholm et al. 2002), and they have been suggested to span from 300 to 30 ka BP (Larsen et al. 2000; Sejrup et al. 2000). Such sediments have been found up to c. 190 m above the postglacial marine limit, which rises from 6–8 m in the southern part of Jæren to 22–26 m in the northern part (Andersen et al. 1987). Five alternative depositio-

nal scenarios have been suggested to explain the high-lying position of the marine sediments:

- 1) The sediments are *tills* pushed up by a glacier in the Norwegian Channel. This was first suggested by Heland (1885), and later supported by Reusch (1895), Bjørlykke (1908), Hansen (1913) and Isachsen (1943). This theory was questioned when some of the sediments were interpreted as *in situ* glaciomarine sediments (Andersen 1964).
- 2) The eastern part of Jæren has been *tectonically uplifted*. Feyling-Hanssen (1964) was the first to suggest this possibility, and was later supported by Fugelli & Riis (1992) and partly by Andersen et al. (1987) and Andersen et al. (1991). Based on the young age (Late Weichselian) of some of the units, Sejrup et al. (1998) and Larsen et al. (2000) argued that the present elevation of the glaciomarine sediments could not be explained by regional tectonic movements alone.
- 3) *Glacioisostatic depression by an ice sheet centred over central Norway combined with tectonic uplift* was suggested by Andersen et al. (1987) and Andersen et al. (1991).
- 4) On the basis of glacial striae, Anundsen (1990) postulated an ice sheet over the coastal district of western Norway and parts of the North Sea. *Glacioisostatic loading* from such an ice sheet would cause subsidence of the Jæren area of 350–400 m, enough to explain the high lying marine sediments (Anundsen 1990).
- 5) Based on morphological features, provenance studies and lithological, biostratigraphical and geochronological investigations of a series of sediment cores across Jæren, Sejrup et al. (1998) suggested that *glacioisostatic loading by an ice stream in the Norwegian Channel* could explain the high relative sea levels during deposition of marine sediments. This interpretation was later supported by Jónsdóttir et al. (1999), Stalsberg et al. (1999) and Larsen et al. (2000).

The youngest known ice-free period at Jæren prior to the Last Glacial Maximum is the Sandnes interstadial (Feyling-Hanssen 1974). It has been confined by radiocarbon dating to c. 32 ka BP (Sejrup et al. 1998), 30–39 ka BP (Stalsberg et al. 1999), 30–34 ka BP (Larsen et al. 2000) and 32–34 ka BP (Sejrup et al. 2000). Glaciomarine sediments correlated with the Sandnes interstadial have been reported from many sites at Jæren rising from the present sea level in the Sandnes area and up to 204 m a.s.l. at Høgemork, e.g. Andersen et al. (1981) and Larsen et al. (2000).

In this investigation, sites along two transects across Jæren with sediments of a possible Sandnes interstadial age below an upper till have been investigated (Figs. 1–4). Profile A is oriented N–S in the eastern part of Jæren and runs from Sandnes in the north (at sea level) to

Høgemork and Elgane in the south (c. 200 m a.s.l.). Transect B is oriented NW–SE in the northern part of Jæren. Sedimentological information from interstadial sediments and variations between different sections can provide information on source area, paleo-environment and depositional processes. Previously published data are combined with new in an attempt to develop a depositional model for the interstadial glaciomarine sediments on Jæren.

Methods

The investigated sections are found between 50 and 140 m a.s.l. (Figs. 1–4). They have been excavated during construction work in the area and exposures are between 3 and 18 m high. The sedimentary units are given informal names with the first letter(s) of the sections succeeded by a number, counting from the bottom. For previously published sites, the original labelling is used. Each section was described and subsequently sampled for sedimentological, micro-paleontological and dating purposes.

Samples for grain size analysis were wet sieved and the <63 µm fractions analysed by Micromeritics® Sedi-Graph 5100. Roundness values of clasts were determined using the division of Olsen (1983). The eigenvalue method (Mark 1973) was used to evaluate fabric analysis from clay-rich diamictites. The principal eigenvector V_1 indicates the direction of maximum clustering and represents the orientation of the mean axis. The calculated value S_1 measures the strength of clustering about the mean axis. Calcium carbonate was measured on a CE EA 1108 Elemental Analyzer. Foraminiferal samples were prepared following the method described by Knudsen (1998). Sediment samples were disaggregated in water and wet sieved. Foraminifera used for radiocarbon dating and fauna analysis were separated from the fraction >125 µm by using tetrachloroethylene (C_2Cl_4).

In the present paper we use the term interstadial for a period within a glacial phase when the investigated area was deglaciated, even if glaciomarine sediments indicate proximity to glaciers.

Sediments and depositional environments

A brief description of the investigated sites is given in Table 1, starting in the northern part of profile A (Figs. 1–4). Sections investigated in this paper are presented with logs, while only the sediment interpretation is presented for other published sections (Figs. 2 & 3). Some

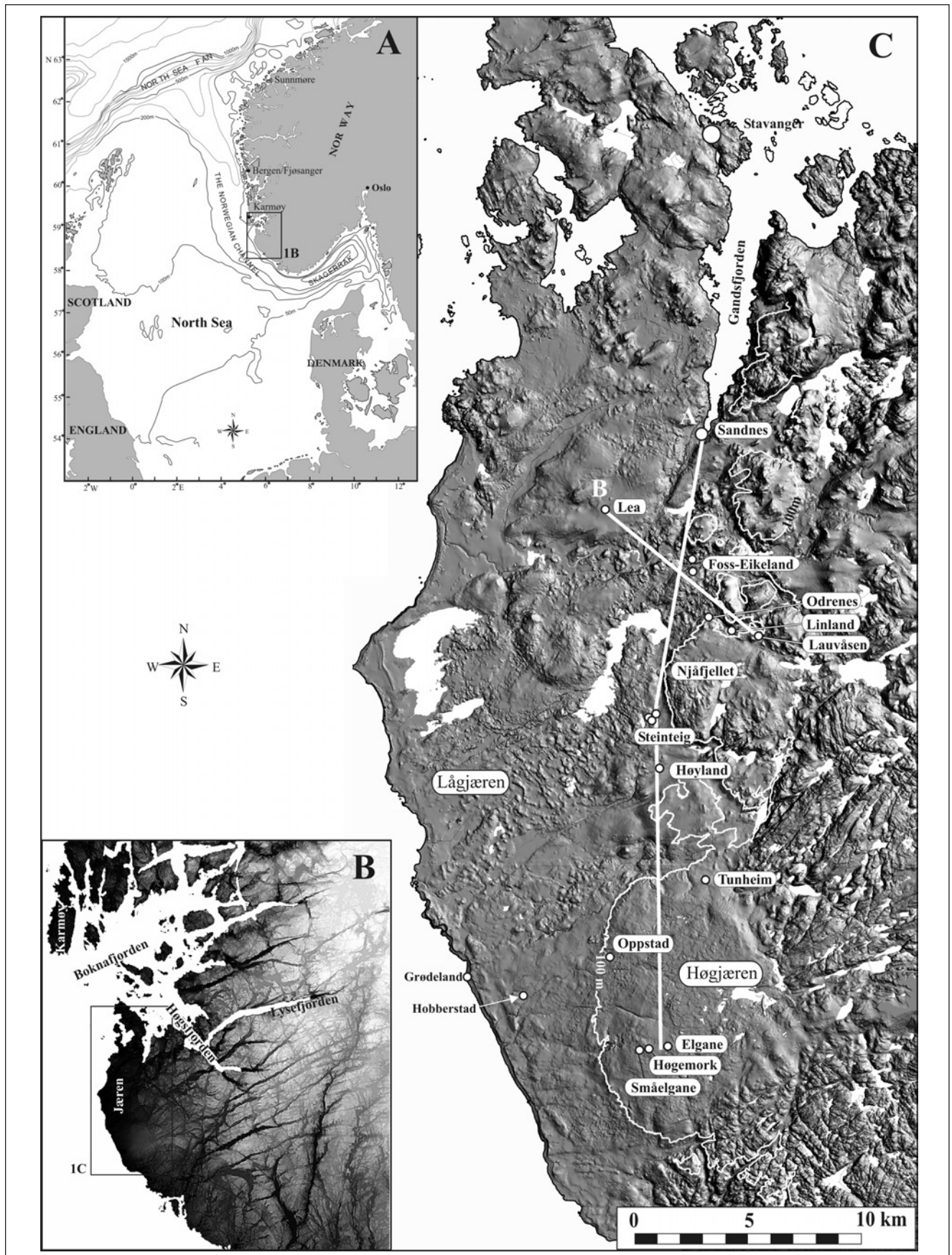


Fig. 1. A. Overview. B. Map of Rogaland, showing the orientation of valleys and fjords east and northeast of the Jæren area. C. Detailed map of Jæren presented as a 2D hill-shaded map with light from northeast. Sections have been investigated along two profiles. Profile A stretches from Sandnes in the north to Høgemork in the south, and profile B extends from Lea in the northwest to Lauvåsen in the southeast.

sites show large variations within a limited geographical area, e.g. at Steinteig (Figs. 2B-D). This may be due to differences in age or degree of glacial deformation and erosion, and to the great thickness of the sediments which prevents exposure of the whole units. Three main facies of subglacial glaciomarine sediments have been identified: Facies A) laminated silt and clay, facies B) homogenous silty clay and facies C) clayey diamict. In addition, stratified diamictos and massive silt and sandy silt are reported from cores at Elgane (Janocko et al. 1998) and Høgemork (Andersen et al. 1991, Fig. 1).

A review of early analyses of foraminifera from till and marine sediments at Jæren was given in Andersen et al. (1987), and several new analyses have been presented during the last decades (Fugelli 1987; Janocko et al. 1998; Sejrup et al. 1999; Stalsberg et al. 1999; Larsen et al. 2000; Raunholm et al. 2002). The glaciomarine sediments are commonly dominated by *Cassidulina reniforme* and *Elphidium excavatum* f. *clavata*. Other frequently occurring species are *Nonion labradoricum*, *Islandiella norcrossi* and *Stainforthia loeblichii*. The foraminifera assemblages in the new sections investigated in this study are similar to those of the Sandnes interstadial sediments at Sandnes (Table 2, Feyling-Hanssen et al. 1971). There are no significant differences in faunal composition between the different facies investigated in this study.

The distinction between clay-rich tills and glaciomarine diamictos can be difficult, especially if the diamictos lack any diagnostic structures (Hart & Roberts 1994; Licht et al. 1999). All glaciomarine diamictos described in this work have been overridden by glacial ice, and deformation related to this may complicate the distinction further. The rock fragments in both the glaciomarine diamictos and the tills at Jæren are dominated by gneisses and granites, but the glaciomarine diamictos have a higher proportion of far-travelled erratics such as flint and rhomb porphyry. These clasts originate in the Skagerrak and the Oslo area, respectively, and have been deposited from drifting icebergs. As shown in Figure 2 and 3, both glaciomarine diamictos and tills are dominated by subrounded and angular clasts, but sediments interpreted as tills often have a higher content of cobbles and boulders than the glaciomarine diamictos. Stratification has not been observed except for a faint shear banding interpreted to be due to glacial deformation, e.g. at the contact between glaciomarine diamict and overlying sandy till at Tunheim (Fig. 2F) and along some of the clastic dikes at Foss-Eikeland (Fig. 3B). The glaciomarine diamictos at Jæren have a higher content of foraminifera than the laminated and homogenous clays, indicating that these are primary deposits and not facies A and B mixed with coarse material. Clay-rich diamictos interpreted as till are commonly barren, or contain very few microfossils, and they have a lower CaCO₃ content than

glaciomarine diamictos. Only sediments interpreted to be of marine or glaciomarine origin are included in the following discussion.

Facies A - Laminated silt and clay

Laminated silt and clay has been found at Foss-Eikeland, Steinteig, Linland, Odrenes and Oppstad (Figs. 2 & 3). The laminated silt and clay is composed of normally graded couplets with 0.3-2.5 cm thick white silt layers and 0.5-2.5 cm thick dark, blue-grey clay layers (Fig. 5, Table 3). The couplets of silt and clay do not show any regional variations in thickness between the different sites. From the laminated clay at Steinteig, detailed analyses of different layers have been performed (Fig. 5A). Two layers of homogenous silt (1 and 2 in Fig. 5A) consist of 65.2% silt and 34.8% clay. Samples from the lower and upper part of an overlying clay layer (3 and 4 in Fig. 5A) have a clay content of 89.6 and 95.6%, respectively. The analysed samples weighing a total of 633 g contained only six foraminifera, and these were found in the silt layers.

The silt layers are usually composed of several upward fining laminae of silt, and rip-up clasts of clay and lenses of diamict material. Dropstones are occasionally found in the silt layers (e.g. Fig. 3D). No IRD have been found within the clay layers, and they lack visible laminae of silt. Fragments of molluscs are rare in facies A, and the content of foraminifera is less than 1 per gram sediment. The foraminiferal fauna is dominated by the arctic species *Elphidium excavatum* and *Cassidulina reniforme*, but other arctic species also occur (Table 1). Small, synsedimentary faults are common in the laminated silt and clay layers, and the laminated clay is usually also deformed by post-depositional processes (Fig. 5B). The degree of deformation varies from open folds and small faults (Unit F₁ in Fig. 3C) to brecciated lumps of laminated clay in a matrix of homogenous clay (Unit F₁ in Fig. 3B).

The laminated silt and clay are interpreted as having been deposited from sediment-laden meltwater, and the sparse arctic foraminifera fauna indicates a glaciomarine environment. The lack of IRD and silt lamina in the clay layers, and the very fine-grained composition of which up to 95.6% is less than 4 µm indicates deposition in a sheltered environment free from melting icebergs. Lumps of diamict material in the silt layers indicate ice rafting in an open marine environment. The cyclicity points to a rhythmical sedimentation process, and the silt-clay couplets are interpreted as having been annually deposited. The laminated silt layers are interpreted to have been deposited during the melting seasons, while the clay layers may have been deposited during winter, below seasonal sea ice (Dowdeswell et al. 2000). The release of sediments from icebergs is not likely to stop during the winter season, but the lack of

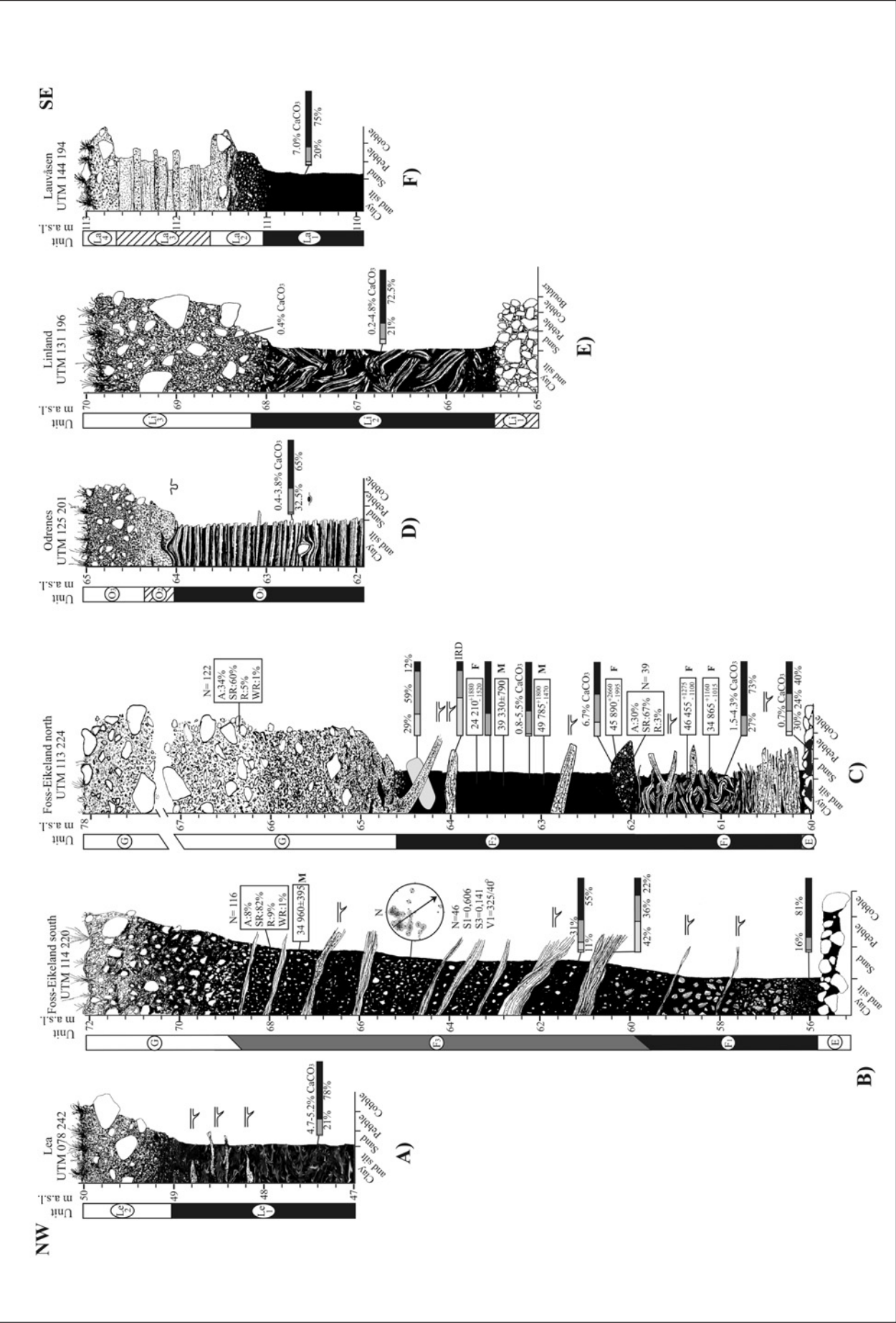


Fig. 3. Logs from sections with glaciomarine sediments in a northwest-southeast profile at Iæren (profile B in Fig. 1C). The logs from Foss-Eikeland (Figs. B & C) are modified from Raunholm et al. (2002).

IRD in the clay layers may be explained if the area was largely cleared of icebergs before freeze-up (Syvitski et al. 1996). An interpretation of the silt/clay couplets as annual, indicates a fairly high sedimentation rate, and with an average thickness of the couplets of 2–3 cm, 20–30 m of laminated sediment can be deposited in 1000 years. Folded and brecciated silt and clay in which the primary structures are still visible is interpreted to have been deformed by an overriding glacier. The deformation has not been pervasive, and the laminated sediments have probably been transported for relatively short distances.

Facies B - Homogenous silty clay

Homogenous silty clay is exposed at Sandnes, Foss-Eikeland, Lea and Lauvåsen (Fig. 3). Where both facies A and facies B is observed in the same section, facies B is found above facies A. The homogenous clay is similar to the laminated clay regarding grain size distributions, fossil content and carbonate content (Figs. 2 & 3, Table 3). In facies B at Foss-Eikeland (unit F₂ in Fig. 3C), deformed lumps of laminated clay can be found within the homogenous clay (Raunholm et al. 2002).

Powell & Molnia (1989) observed in a study from Alaska that deposition of laminated silt and clay is progressively replaced by homogenous clay at distances greater than a few kilometres from the efflux point. It is possible that the homogeneity of facies B is partly primary, due to increasing distance to a recessive glacier margin. However, the small lumps of laminated silt and clay found in some sections of the homogenous clay may indicate that the homogeneity could be a result of intense deformation of laminated silt and clay. At Foss-Eikeland, unit F shows increasing deformation upwards (Raunholm et al. 2002), and the homogeneity may be due to a combination of post-depositional glaciotectionic deformation of laminated clay and primary deposition of homogenous clay.

Facies C - Clayey diamicton

Clayey diamictons with a richer foraminifera fauna than facies A and B are found at Sandnes, Foss-Eikeland, Steinteig, Tunheim, Smålgane, Elgane and Høgemork. Facies C contains c. 1.5–34 foraminifera per gram sediment and is dominated by sandy clay with scattered pebbles (Table 3). The pebbles include far-travelled clasts such as flint, rhomb porphyry and anorthosite. In most places the clayey diamicton is several meters thick and homogenous, and primary bedding or stratification has not been observed in any of the new sections presented in this study. However, some stratification has been observed at Elgane and Høgemork (Andersen et al. 1981; Andersen et al. 1987; Andersen et al. 1991; Janocko et al. 1998).

The homogenous diamictons in facies C indicate that sedimentation from meltwater plumes was reduced and deposition from melting icebergs increased. Ploughing icebergs and post depositional glaciotectionic deformation may also have contributed to the homogeneity. At Foss-Eikeland, facies C overlies glaciotectionically deformed laminated silt and clay, indicating that also facies C has been subjected to glaciotectionic deformation. Fabric measurements at Foss-Eikeland (Fig. 3B) show that the clasts have an average dip of 40°, indicating deposition by ice-rafting (Domack & Lawson 1985). Facies C was most likely deposited in a glaciomarine environment with sediment-laden icebergs, but with more favourable conditions for marine life than during deposition of facies A and B.

Chronology and local correlation

Previously reported as well as new radiocarbon dates from the uppermost sub till glaciomarine sediments on Jæren are presented in Table 4. Only 6 of the sections have been dated, and the dates show some scatter (Figs. 2 & 3, Table 4). Some of the dated foraminifera samples contain more than 3000 tests, and mixing of re-sedimented and in situ fossils may result in an average age. Only single fragments of molluscs are used for dating in this study, but also these may be re-sedimented. Up to 300 ka old sediments with a glaciomarine fauna similar to that of the Sandnes interstadial are found at Jæren (Andersen et al. 1987; Janocko et al. 1998; Sejrup et al. 1998; Sejrup et al. 1999; Stalsberg et al. 1999; Sejrup et al. 2000). In addition, the Norwegian Channel ice-stream (NCIS) may have supplied the Jæren area with reworked material from the Norwegian Channel, and a third source for re-sedimented fossils is from fjords in the area east of Jæren (Fig. 1B).

Facies A and B contain less than 1 foraminifer per gram sediment, and the diverging dates may be explained by a high and varying proportion of reworked material. The date of 45890 yrs BP from Foss-Eikeland is from a clast of ice-rafted diamicton (Raunholm et al. 2002), and is interpreted to be reworked material. The clayey diamicton at Smålgane has been dated to 41950 and 42850 yrs BP (Larsen et al. 2000, Table 3). Larsen et al. (2000) indicated that the shell fragments were re-sedimented, and correlated the clayey diamicton to the Sandnes interstadial based on its stratigraphic position and short distance to Elgane and Høgemork. However, the unit may also be an older interstadial. Excluding the dates from the laminated and homogenous clays, as well as the dates from Smålgane, the nine remaining ¹⁴C dates from the glaciomarine diamictons are concentrated between c. 30 and 38.5 ka BP (Table 4). Facies C has a higher abundance of foraminifera per gram sediment than facies A and B (Table 2), but the three

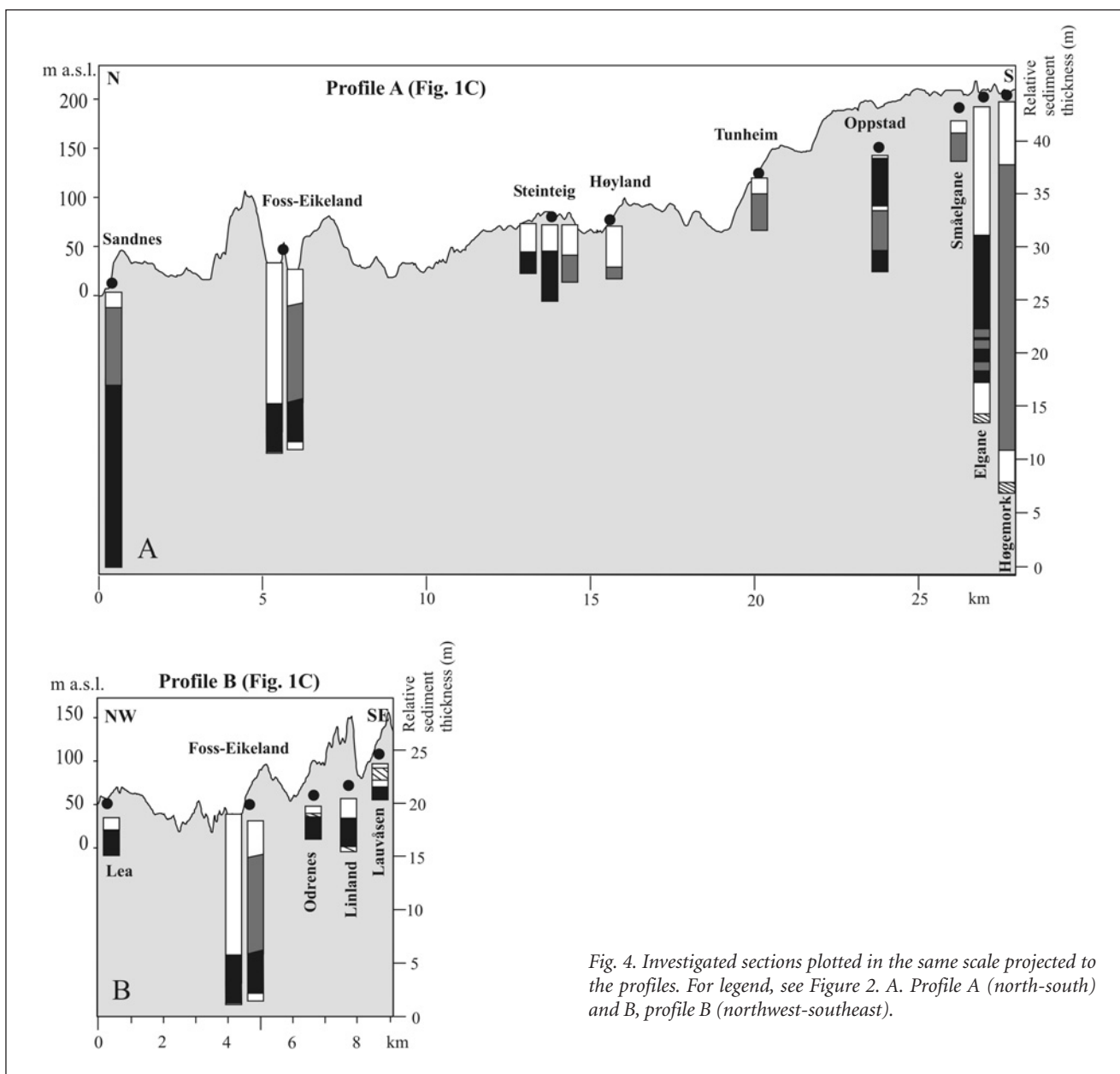


Fig. 4. Investigated sections plotted in the same scale projected to the profiles. For legend, see Figure 2. A. Profile A (north-south) and B, profile B (northwest-southeast).

dates from Tunheim varying from 34.8 to 38.5 ka BP are from the same sample, suggesting that reworking could be a problem also with the glaciomarine diamictos. Therefore, we tend to favour the younger dates from the glaciomarine diamictos, at 35–30 ka BP as the most likely interval for deposition of the sediments.

Amino acid analyses on *E. excavatum* from the uppermost glaciomarine units at Foss-Eikeland, Elgane, Oppstad and Høgemork have alle/Ile ratios between 0.044 and 0.071 (Tellemann 1986; Fugelli 1987; Janocko et al. 1998; Larsen et al. 2000; Raunholm et al. 2002), supporting a mid Weichselian age for the sediments (Sejrup et al. 1999; Larsen et al. 2000).

Feyling-Hanssen (1974) defined the Sandnes interstadial as "the Weichselian interstadial during which zone

1, the *labradoricum-norcrossi* assemblage, of the Sandnes Clay was deposited". Zone 3 at Sandnes was assumed to represent a stadial (Feyling-Hanssen 1974), but as both zones 4, 3, 2 and 1 represent a glaciomarine environment, we suggest that these sediments were all deposited during the same interstadial. The type locality for the Sandnes interstadial has previously only been dated on mollusc fragments, giving a minimum age of 30 ka BP (Feyling-Hanssen et al. 1971). A shell fragment from zone 1 at 7.8 meters depth in core no 1 at Sandnes is now dated to 38100 ± 1600 BP (Fig. 2A, Table 4). Based on the available dates, we cannot exclude the possibility that the investigated sediments represent more than one interstadial. However, similarities in fauna, structure, grain size composition and stratigraphic position below the uppermost till, and their position above the postglacial marine limit, sug-

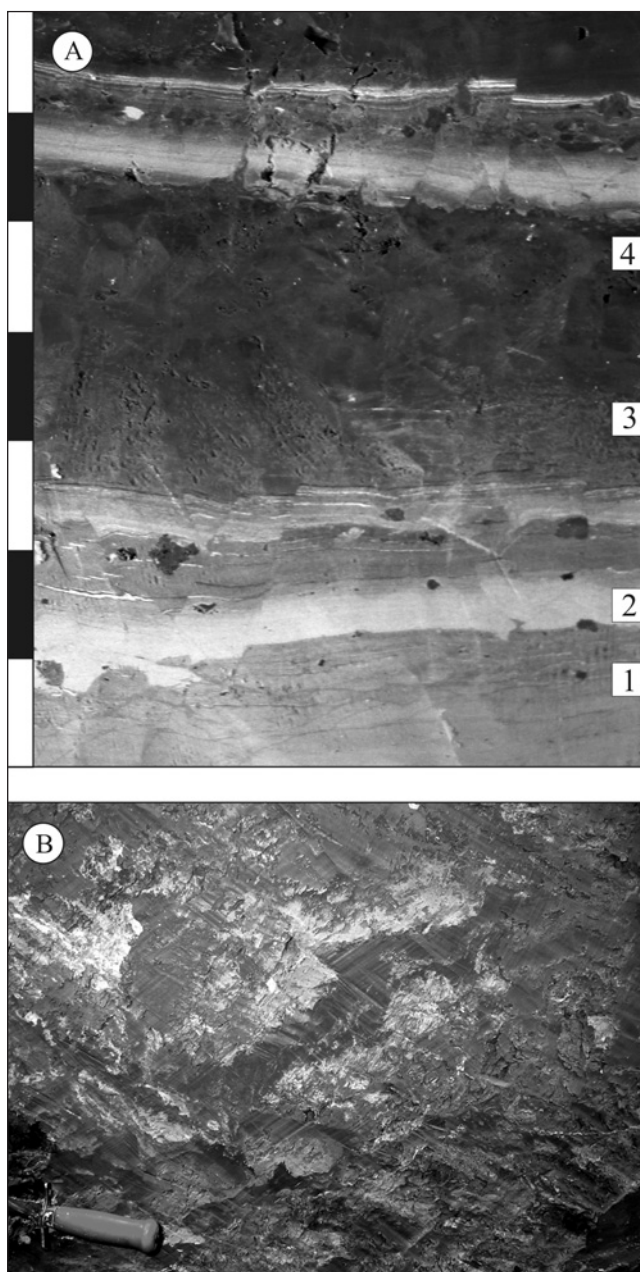


Fig. 5. A. Laminated clay from unit S1 at Steinteig. Scale in cm. Numbers 1-4 refer to samples analysed for grain size distribution, see text for discussion. B. Deformed, laminated clay from unit S1 at Steinteig. Knife for scale.

gest that they most likely represent one single ice-free period.

Larsen et al. (2000) suggested that three Weichselian interstadials are recorded in the sediments of the southern part of Jæren. The two youngest of these relate to a sea level of c. 200 m above that of the present day, while the oldest has a slightly lower sea level. The division into the two younger interstadials was based on a reinterpretation of the Oppstad and Høgemork sections (Andersen et al. 1991) by Larsen et al. (2000). We admit that this reinterpretation is uncertain, and it

might only be one Middle Weichselian interstadial (the Sandnes interstadial) in addition to an Early Weichselian interstadial (Larsen et al. 2000).

Regional correlation

As discussed above, we favour the interval between 35 and 30 ka BP as the most likely period for the Sandnes interstadial, and we correlate it to the Ålesund interstadial defined by Mangerud et al. (1981a). The glaciomarine sediments at Jæren were probably deposited relatively rapidly in an ice-proximal environment, and they most likely represent the early parts of an interstadial when the Jæren area was below sea level as a result of glacioisostasy. No sections with datable terrestrial sediments have been encountered from the Sandnes interstadial at Jæren, and the glaciomarine sediments may only represent a limited part of the Ålesund interstadial during which glaciomarine conditions prevailed at Jæren. Based on nearly 50 AMS ^{14}C dates on bones from caves in the Ålesund area (Fig. 1), the Ålesund interstadial is dated to 35–28 ka BP (Larsen et al. 1987; Valen et al. 1995; Valen et al. 1996; Mangerud et al. 2003). The assemblage of bones found in the caves indicates that the climate during Ålesund interstadial was similar to the climate of western Svalbard today, i.e. some 7–8°C colder than at present. The presence of reindeer in the caves indicates a continuous ice-free coast southwards, as the reindeer probably migrated from the south (Larsen et al. 1987; Mangerud et al. 2003).

AMS dates from till and sub till sediments on the North Sea Plateau indicate that the North Sea was ice-free in a period around 30 ka BP, and that an extensive glaciation of the North Sea took place after 29.4 ka BP (Sejrup et al. 1994). These data support the delimitation of Sandnes interstadial to be somewhere between 35 and 30 ^{14}C ka BP.

Ice configuration

The regional distribution of the glaciomarine sediments of Sandnes interstadial age is used to infer the ice configuration and sea levels prior to and during this interstadial (Fig. 6). Laminated silt and clay and homogenous silty clay dominate in the northern part of Jæren, while the southern part is dominated by glaciomarine diamictos and homogenous silt and sandy silt (Figs. 2–4, Table 1). There is also a vertical transition from facies A and B to facies C, indicating that sedimentation from meltwater was reduced and deposition from melting icebergs became dominant. The stratified glaciomarine sediments in the southern part of Jæren

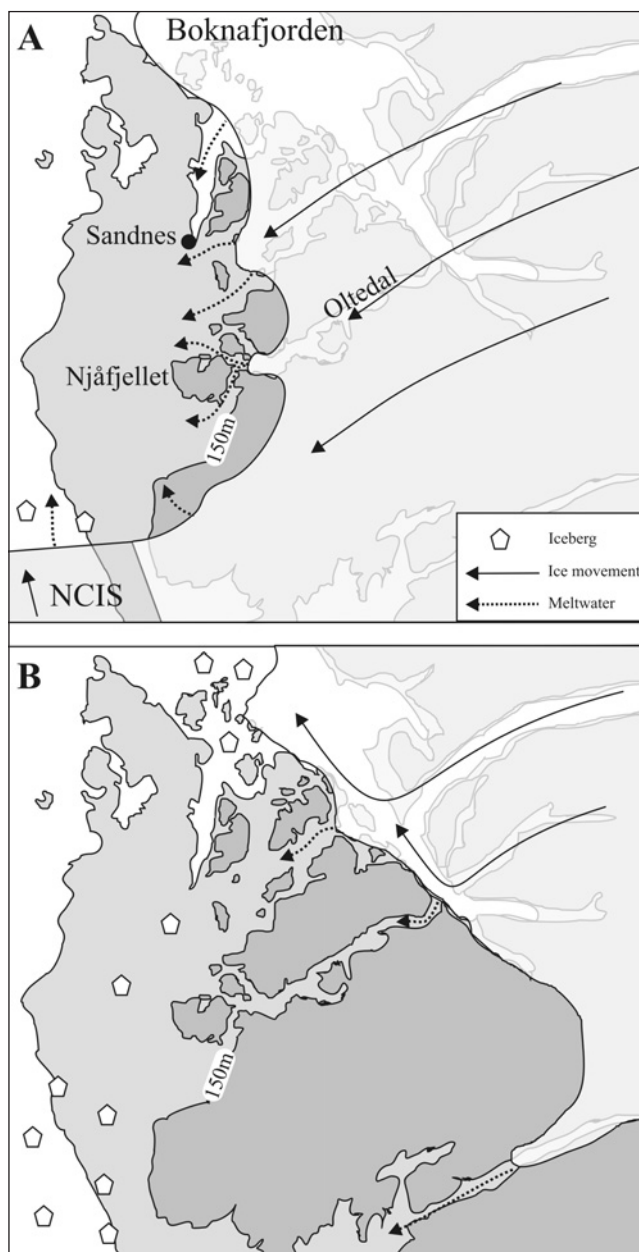


Fig. 6. Different scenarios of ice configuration during the Sandnes interstadial. The areas below c. 200 m in the southern part of Jæren and c. 150 m in the northern part were probably below sea level during the early parts of the Sandnes interstadial. A. Early part of the Sandnes interstadial with the front of the Norwegian Channel Ice Stream situated outside Jæren. The inland ice crosses Høgsfjorden and sediment-laden meltwater is supplied to Jæren through two large valley systems. Fine-grained glaciomarine sediments are deposited across Jæren. B. The inland ice does not cross Høgsfjorden, and the supply of sediment-laden meltwater to Jæren is reduced. Sedimentation on Jæren changes from deposition of laminated silt and clay to deposition from melting icebergs. The icebergs probably originate both from Boknafjorden and from the disintegrating ice stream in the Norwegian Channel.

may be due to more ice-proximal conditions with alternating deposition from debris flows, melting icebergs and meltwater plumes.

To the east of Jæren, several large valleys are oriented NE-SW (Figs. 1B & 6). This is parallel with the ice-movement of the inland ice during the last deglaciation (Andersen et al. 1987; Raunholm et al. 2003), and probably also parallel to ice-movement prior to the Sandnes interstadial. As long as glaciers from the Lysefjorden area were large enough to cross Høgsfjorden, meltwater could be channelled through two valleys between Høgsfjorden and Jæren (Figs. 1B & 6) resulting in an input of meltwater to the shallow sea on Jæren and deposition of laminated glaciomarine sediments (Fig. 6A). As discussed above, seasonally sea ice probably prevailed during the early part of the Sandnes interstadial. The vertical transition from laminated glaciomarine sediments to glaciomarine diamictos may be linked to the final break-up of the Norwegian Channel ice stream (Fig. 6B). Far-travelled clasts such as flint, rhomb porphyry and coal fragments occur in the glaciomarine diamictos (Janocko et al. 1998; Larsen et al. 2000). Such clasts have their origin in the Oslo and Skagerrak area, and can be deposited from ice-bergs from the Norwegian Channel Ice Stream.

Glaciomarine sediments up to 200 m above the present sea level imply glacioisostatic loading of at least 600 m of ice on Jæren. This can be achieved with an ice stream in the Norwegian Channel as suggested by Sejrup et al. (1998). New data from the southeastern Nordic Sea continental margin may suggest that during the Weichselian, the Norwegian Channel Ice Stream only reached the margin in periods between 28 and 15 ka BP (Sejrup et al. 2003; Hjelstuen et al. in press). However, it is possible that the Norwegian Channel Ice Stream had an intermediate extent prior to the Sandnes interstadial, with the front somewhere between Jæren and the North Sea Fan. A plateau on the eastern flank of the Norwegian Channel outside Jæren rises to c. 200 m below sea level, and marks a threshold between the 700 m deep Skagerrak basin and the northern part of the channel, sloping down from 200 m water depth outside Jæren to more than 400 m in the north (Fig. 1A). As indicated by Sejrup et al. (1998), the surface gradient of the ice stream is likely to have been highest where the Norwegian Channel has its steepest gradients, i.e. southwest of Jæren. Even if the Norwegian Channel Ice Stream did not reach all the way to the margin, it may still have been thick enough southwest of Jæren to cause significant glacioisostatic depression. During the early phase of Sandnes interstadial, the front of the ice stream may have been situated on the threshold in the Norwegian Channel, outside Jæren (Fig. 6A). A frontal position outside Jæren would probably not cause any further depression of the land, but it may have delayed the glacioisostatic recovery.

The glaciomarine sediments correlated with the Sandnes interstadial rise from north to south and from west to east (Figs. 2-4). It is uncertain if this trend represents

the primary distribution of the sediments, or if the lack of glaciomarine sediments at higher altitudes in the northern part of Jæren is due to erosion and lack of suitable places for deposition in the more rugged bedrock topography there. Larsen et al. (2000) suggested that the rising, north-south trend could be caused by glacioisostatic depression from an ice stream in the Norwegian Channel thickening towards the south. Stalsberg et al. (2003) estimated the average gradient of the Norwegian Channel Ice Stream between the shelf edge to Jæren to be 1-1.3 m/km based on a maximum scenario for the ice stream and 500-700 m of ice on Jæren. The distance between Sandnes and Høgemork is c. 30 km, and with a gradient of 1.3 m/km the difference in ice thickness would be approximately 40 m. Since the weight of ice is approximately 1/3 of bedrock, the difference in glacioisostatic loading would be 10-15 m. However, the gradient of an ice stream varies along its profile (Bentley 1987), and it may have been steeper in the Jæren area. The maximum gradient of ice stream B in Antarctica is c. 3-4 m/km (Bentley 1987). Applying the same gradient to the ice stream outside Jæren, the difference in ice thickness between Sandnes and Høgemork would be 90-120 m, and the difference in glacioisostatic loading would amount to 30-40 m. This is still far from explaining the observed difference in sediment distribution of c. 170 m. Differential loading by an ice stream may have contributed to the distribution of the Sandnes interstadial sediments, but deposition in different water depths seems to be a more plausible explanation.

In the introduction, five different explanations for the distribution of high-lying glaciomarine sediments were presented. The interpretation of all the glaciomarine sediments as tills was rejected by (Andersen 1964), and Sejrup et al. (1998) and Larsen et al. (2000) argued that the present elevation of the glaciomarine sediments could not be explained by regional tectonic movements. The model presented by Anundsen (1990) with a coastal ice sheet over western Norway and parts of the North Sea harmonizes poorly with present knowledge of the Norwegian Channel ice stream. We support the theory presented by Sejrup et al. (1998) that glacioisostatic loading by an ice stream in the Norwegian Channel best explains the high elevation of the glaciomarine sediments across Jæren.

Conclusions

Based on excavations across Jæren, glaciomarine sub-till sediments have been divided into three main facies: A) Laminated silt and clay, B) Homogenous silty clay and C) Clayey diamicton. The two first facies were deposited by sediment laden meltwater plumes, while facies C is mainly composed of ice-rafted detritus.

In the southern part of Jæren, the glaciomarine sediments are found up to 204 m a.s.l., while they occur up to c. 30 m in the north. An ice stream in the Norwegian Channel thickening towards the south may have resulted in larger glacioisostatic depression in the southern part of Jæren than in the northern part. This may explain up to c. 25% of the differences in altitudes, the rest can be explained by deposition in different water depths.

The glaciomarine deposits are thought to represent a deglaciation phase into a middle Weichselian interstadial. Radiocarbon dates are not conclusive, but we suggest that the sediments were deposited between 35 and 30 ¹⁴C ka BP, and that they correlate with the Sandnes interstadial.

The glaciomarine sediments may have been deposited with input from both the Norwegian Channel Ice Stream and the inland ice.

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Table 1. Brief description of investigated sections and previously published sites used in this paper. Locations of the sites are shown in Figs. 1 & 4.

Section/ Fig. number	Description and references
Sandnes 2A	In 1963, six sediment cores were retrieved from an old clay pit in Sandnes, and these were described by Feyling-Hanssen (1966) and Feyling-Hanssen et al. (1971). The numbering in Figure 2A represents a foraminiferal zonation where zone 4 and 2 are almost barren, whereas zone 3 and 1 contain an arctic foraminifera fauna. Zone 4, 3 and 2 are composed of 18 m of silty clay, and zone 1 is a 7.5 m thick sandy clay with small stones. The clay content in zone 1 is 50-55%, and it contains up to 34 foraminifera per gram sediment (Feyling-Hanssen et al. 1971). The upper 2 m are composed of a sandy till. The Sandnes interstadial was defined by Feyling-Hanssen (1974) as "the Weichselian interstadial during which zone 1, the <i>labradoricum-norcrossi</i> assemblage, of the Sandnes Clay was deposited".
Steinteig 2B-D	Three excavations have been performed at Steinteig west of Njåfjellet. The distance between the excavations presented in Figure 2B and 2D is approximately 200 m. Bedrock was not exposed. Unit S ₁ is a laminated, partly deformed silty clay with clastic dikes of laminated sand, Unit S ₂ a clay-rich diamicton with c. 14 foraminifera/g sediment, and small pieces of flint and rhomb porphyry are common. Unit S ₃ is a sandy diamicton with boulders interpreted as till.
Høyland 2E	Unit H ₁ is a 1 m thick grey, sandy diamicton with shell fragments and an arctic foraminifera fauna dominated by <i>Elphidium excavatum</i> . Some of the specimens are abraded or crushed. The diamicton is interpreted as glaciomarine, but the abraded and crushed specimens indicate deformation and/or resedimentation. Unit H ₂ is a light brown, silty and compact diamicton with boulders interpreted as a till.
Tunheim 2F	Unit Tu ₁ is a homogeneous clay-rich diamicton with shell-fragments and an arctic foraminifera fauna. Tu ₂ is a sandy and gravelly diamicton with large boulders interpreted as a till. Up to 1 cm large clasts of flint and rhomb porphyry occur in unit Tu ₁ , but none have been found in the overlying sandy and gravelly diamicton (unit Tu ₂). Diffuse shear banding has been observed at the contact between the two units.
Oppstad 2G	The section at Oppstad was described by Andersen et al. (1981), Fugelli (1987) and Andersen et al. (1991), and the nomenclature used in Figure 2G is from Andersen et al. (1991). A laminated silt and clay (K) is overlain by 4 m of unstratified silty clay with dropstones interpreted as a glaciomarine diamicton. Unit M is a one m thick bouldery clay interpreted as a till. Unit N and P are composed of inversely graded silt and clay beds and unit Q is a gravelly and clayey sediment interpreted as a till (Andersen et al. 1991).
Småelgane 2H	A 4 m deep excavation at Småelgane was described by Larsen et al. (2000). The uppermost 3 m of a glaciomarine diamicton was exposed below a 1.1 m thick till. The glaciomarine diamicton has a silty matrix and contains frequent shell fragments (Larsen et al. 2000).
Elgane 2I	A 30 m deep coring at Elgane was described by Janocko et al. (1998) and Larsen et al. (2000). Unit 1 is a coarse sediment interpreted as glaciofluvial and Unit 2 is a diamicton interpreted as a subglacial till. Unit 3 consists of silt and sandy silt with frequent outsized clasts and coal fragments. Thin diamicton beds occur in the lower part, and the unit is interpreted as having been deposited from suspension and by gravity flows in an ice-proximal, glaciomarine environment. Some of the beds in unit 3 are strongly bioturbated. Unit 4 is dominated by massive sandy silt with outsized clasts, and is interpreted as a subglacial till (Janocko et al. 1998).
Høgemork 2J	A 37 m long core from Høgemork was presented by Andersen et al. (1981), Andersen et al. (1987), Fugelli (1987) and Andersen et al. (1991). Unit S ₁ is a coarse glacial or glaciofluvial sediment, and Unit S ₂ is a gravelly diamicton interpreted as a till. The 27 m thick T-unit at Høgemork consists of stratified, in part laminated, glaciomarine clay, silt and sand with some gravel beds. The clayey beds dominate, and some of them are very gravelly with several large clasts. They could be till beds, possibly deposited as flow-till (Andersen et al. 1991). Unit U is a clayey sediment with large boulders interpreted as a till.

Lea 3A	A 100 m long and 3-4 m deep trench at Lea exposed dark grey, deformed silty clay overlain by 1-2 m clayey diamicton with boulders. Unit Le ₁ contains an arctic foraminifera fauna and is interpreted as glaciomarine, while Unit Le ₂ is interpreted as a till.
Foss-Eikeland 3B-C	The stratigraphy at Foss-Eikeland has been described by Bergersen and Follestad (1971), Østmo (1971), Feyling-Hanssen (1974), Andersen et al. (1981), Bakken and Dale (1986), Tellemann (1986), Andersen et al. (1987), Andersen et al. (1991) and Raunholm et al. (2002). The logs in Figure 3C and D are modified from Raunholm et al. (2002), and the lower part of the stratigraphy is not shown here. Unit F ₁ is deformed, laminated silt and clay, F ₂ is homogenous silty clay, and F ₃ is a clayey diamicton interpreted as glaciomarine. A fabric analysis from Unit F ₃ indicates stress from NW, but it is barely significant (S ₁ of 0.6). Unit G is a gravelly diamicton interpreted as till (Raunholm et al. 2002).
Odrenes 3D	2 m of laminated, undeformed silt and clay (O ₁) is overlain by c. 20 cm of sorted gravel interpreted as glaciofluvial (O ₂) and capped by 50 cm of sandy diamicton interpreted as till (O ₃).
Linland 3E	Coarse, open-work gravel (Li ₁) is overlain by deformed, laminated silt and clay (Li ₂) and capped by a gravelly diamicton interpreted as till (Li ₃).
Lauvåsen 3F	A homogenous clay (La ₁) is overlain by a till (La ₂) with a lower silty and sandy diamicton, and an upper sandy and gravelly diamicton. Unit La ₃ is composed of stratified sand interpreted as glaciofluvial and capped by a thin, gravelly diamicton with limited lateral distribution (La ₄) interpreted as a debris flow deposit.

Table 2. Selected taxa of benthic foraminifera from glaciomarine sediments at Jæren. Only specimens occurring at a frequency of 1% or higher are included. Numbers are in percent. X marks the presence of a species, but detailed fauna analyses have not been performed.

Species (%)	Foss-Eikeland (F1)	Foss-Eikeland (F2)	Foss-Eikeland (F3)	Foss-Eikeland (IRD)	Foss-Eikeland i)	Foss-Eikeland i)	Tunheim (T1)	Steinteig (S1)	Gann, zone 1 ii)	Elgane (3) iii)	Lea (Le1)	Linland (Li2)	Lauvåsen (La1)
<i>Cassidulina reniforme</i>	48	51	34	48	33	29	45	41	13-22	35-55	x	x	x
<i>Elphidium excavatum</i>													
<i>f. clavata</i>	37	43	54	36	56	52	42	29	35-73	32-50		x	
<i>Nonion labradoricum</i>	2	2	1	1	2	3	1	1	3-10	x		x	
<i>Islandiella norcrossi</i>	8	2	1	6	2	5	5	10	1-12	x			
<i>Islandiella spp.</i>			2	2			1	2	1-3			x	
<i>Stainforthia loeblichii</i>	3		1	3	2		1	5		x			
<i>Elphidium spp.</i>	1	1	2	1	2	3	1	2	1-4	x			
<i>Cibicides spp.</i>			1				1		0-7	x		x	
<i>Noniella spp.</i>				2				3					
Other	1	1	4	1	3	8	3	7	4-14				
Individs per gram	0.3	0.1	1.6	15	1.8	1.8	14	<1	<34		<1	<1	<1

i) Middle part of Unit F at the southern side of Figgjo, from Feyling-Hanssen (1974)

ii) Three samples from zone 1 (glaciomarine diamicton) in Sandnes (Feyling-Hanssen et al. 1971)

iii) Analyses from Unit 3 at Elgane were presented by Janocko et al. (1998) and Larsen et al. (2000)

Table 3. Characteristic features of sedimentary facies A-C

Facies	Bulk grain size	Foraminifera per g sediment	% CaCO ₃	Interpretation
<i>Facies A – Laminated silt and clay</i>	65-81 % clay 20-30 % silt 1-5 % sand and gravel	<1	0 - 4.8	Annually deposited couplets of glaciomarine silt and clay
<i>Facies B – Homogenous silty clay</i>	66-75 % clay 20-31 % silt 3-5 % sand and gravel	<2	0.8 - 7	Glaciomarine, may result of homogenous clay and from both primary deposition glacitectonic deformation of laminated silt and clay
<i>Facies C – Clayey diamicton</i>	40-55 % clay 20-30 % silt 10-30 % sand and gravel	1.5-34	7-15	Glaciomarine diamicton deposited from melting icebergs

Table 4. AMS radiocarbon dates from marine sediments at Jæren found below the uppermost till. All samples are corrected for a reservoir effect of 440 years (Mangerud & Gulliksen 1975). Samples with prefix TUa were prepared at the Norwegian University of Science and Technology (NTNU) in Trondheim and analysed at Tandem accelerator laboratory at the University of Uppsala. The sample with prefix ETH is analysed at the Institute of Particle Physics in Zurich, Switzerland, and the sample with prefix AAR in Aarhus, Denmark. Results are presented in radiocarbon years with one standard deviation. The dated material is from different sedimentological facies: Laminated silt and clay (A), homogenous silty clay (B) and clayey diamicton (C).

Locality/ Unit	Material/ Sample No.	Facies	¹⁴ C-age BP	Lab. No.	References
Elgane	<i>E. excavatum</i>	B	34820 $\frac{+1165}{-1020}$		c)
Elgane	<i>E. excavatum</i>	B	33480 $\frac{+1520}{-1280}$		c)
Foss-Eikeland F ₂	<i>E. excavatum</i>	B	24210 $\frac{+1880}{-1520}$	TUa-2168	b)
Foss-Eikeland F or G	<i>Mya truncata</i>		27900 $\frac{+850}{-776}$	T-3423A	a)
Foss-Eikeland F or G	<i>Mya truncata</i>		31300 $\frac{+700}{-640}$	T-3423B	a)
Foss-Eikeland F ₁	<i>E. excavatum</i> , <i>Islandiella</i> spp.	A	34865 $\frac{+1160}{-1015}$	TUa-2167	b)
Foss-Eikeland F ₃	<i>Arctica islandica</i>	C	34960±395	TUa-2102	b)
Foss-Eikeland F ₂	<i>Macoma calcarea</i>	B	39330±790	TUa-2103	b)
Foss-Eikeland F ₂	<i>Arctica islandica</i>	B	49785 $\frac{+1800}{-1470}$	TUa-2450	b)
Foss-Eikeland F	<i>E. excavatum</i>	C	45890 $\frac{+2660}{-1995}$	TUa-2169	b)
Foss-Eikeland F ₁	<i>E. excavatum</i> , <i>Islandiella</i> spp.	A	46455 $\frac{+1275}{-1100}$	TUa-2451	b)
Sandnes	Shell fragment	C	38100±1600	AAR-6695	*)
Småelgane	Shell fragment	C	41950±690		d)
Småelgane	Shell fragment	C	42850±820		d)
Steinteig	<i>E. excavatum</i>	C	31455±520	TUa-2994	*)
Steinteig	<i>E. excavatum</i>	C	30160±330	ETH-25563	*)
Tunheim	3100 <i>E. excavatum</i>	C	34820±575	TUa-3064	*)
Tunheim	1200 <i>Islandiella</i> spp. + 900 <i>E. excavatum</i>	C	38540±775	TUa-3145	*)
Tunheim	Shell fragment	C	36450±635	TUa-3065	*)

References: a) Andersen et al. (1981), b) Raunholm et al. (2002), c) Janocko et al. (1998), d) Larsen et al. (2000), *) This study.

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