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; Haflidason 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 glacial 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), subtill sediments containing marine fossils and far-travelled erratics have been known since the end of the 19th century (Helland 1885). These sediments are 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.
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 Hel-
land (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* glacioma-
rine sediments (Andersen 1964).
2) The eastern part of Jæren has been *tectonically uplif-
ted*. 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 pre-
sent 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 sug-
gested by Andersen et al. (1987) and Andersen et al.
4) On the basis of glacial striae, Anundsen (1990) post-
ulated 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 sub-
sidence of the Jæren area of 350-400 m, enough to
explain the high lying marine sediments (Anundsen
1990).
5) Based on morphological features, provenance stu-
dies and lithological, biostratigraphical and geo-
chronological investigations of a series of sediment cores
across Jæren, Sejrup et al. (1998) suggested that gla-
ioisostatic loading by an ice stream in the Norwegian
Channel could explain the high relative sea levels
during deposition of marine sediments. This inter-
pretation 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 radio-
carbon 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). Glacioma-
rine 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-environ-
ment 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
destruction work in the area and exposures are be-
 tween 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 mm fractions analysed by Micromeritics® Sedi-
Graph 5100. Roundness values of clasts were determi-
ined using the division of Olsen (1983). The eigenvalue
method (Mark 1973) was used to evaluate fabric anal-
ysis from clay-rich diamictons. The principal eigenvec-
tor $V_1$ 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 disaggrega-
ted in water and wet sieved. Foraminifera used for
radio carbon dating and fauna analysis were separated
from the fraction >125 µm by using tetrachloroethyle-
none ($C_2Cl_4$).

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 indi-
cate 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 pre-
sented for other published sections (Figs. 2 & 3). Some
Weichselian interstadial sediments on Jæren

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.
Fig. 2. Logs from sections with glaciomarine sediments in a north-south profile at Jæren (profile A in Fig. 1C). For sections not described by the author, only interpretations of the sediments are shown. Note the different scales between the simplified logs and Fig. B-F. The stratigraphy at Sandnes (A) is from Feyling-Hanssen et al. (1971), Oppstad (G) is from Andersen et al. (1991), Småelgane (H) is from Larsen et al. (2000), Elgane (I) is from Janocko et al. (1998) and Høgemork (J) is from Andersen et al. (1991). Not all previous publications have distinguished between laminated and homogenous clay. Facies A and B are therefore marked by the same colour in the unit column.
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 subjilt glaciomarine sediments have been identified: Facies A) laminated silt and clay, facies B) homogenous silty clay and facies C) clayey diamicton. In addition, stratified diamictons 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 Staintforthia loeblichi. 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 diamictons can be difficult, especially if the diamictons lack any diagnostic structures (Hart & Roberts 1994; Licht et al. 1999). All glaciomarine diamictons 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 diamictons and the tills at Jæren are dominated by gneisses and granites, but the glaciomarine diamictons 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 diamictons 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 diamictons. 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 diamicton and overlying sandy till at Tunheim (Fig. 2F) and along some of the clastic dikes at Foss-Eikeeland (Fig. 3B). The glaciomarine diamictons 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 diamictons interpreted as till are commonly barren, or contain very few microfossils, and they have a lower CaCO₃ content than glaciomarine diamictons. 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-Eikeeland, 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 diamicr 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 glacio-marine 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 season, 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 Jæren (profile B in Fig. 1C). The logs from Foss-Eikeland (Figs. B & C) are modified from Raunholm et al. (2002).
RD 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 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 Sandnes, Foss-Eikeland, unit F shows increasing deformation upwards (Raunholm et al. 2002), and the homogeneity may be due to a combination of post-depositional glaciotectonic deformation of laminated clay and primary deposition of homogeneous 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, Småelgane, 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 anor-thosite. 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 glaciotectonic deformation may also have contributed to the homogeneity. At Foss-Eikeland, facies C overlies glaciotectonically deformed laminated silt and clay, indicating that also facies C has been subjected to glaciotectonic 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 subglacial marine 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. 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 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 Småelgane 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 dated from the laminated and homogenous clays, as well as the dates from Småelgane, 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
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 diamictons. Therefore, we tend to favour the younger dates from the glaciomarine diamictons, 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 αIle/βIle 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-

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**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).**
suggest 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 glacioisostacy. 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 14C 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 subtilt 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 14C 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 diamictons 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...
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 diamictons 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 diamictons (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 $^{14}$C 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.

Acknowledgements: - We want to thank Karen Louise Knudsen and Rolf W. Feyling-Hanssen for providing material for $^{14}$C dating from the Sandnes core, and Dagfinn Bøe for foraminifera analyses. Stig Monsen has assisted with the laboratory work. Carita G. Knudsen has assisted during the field work and participated in many fruitful discussions, and Atle Nygård has contributed with comments to the manuscript. Several farmers and construction workers have been positive and helpful during fieldwork, and special thanks go to Finn Arve Undheim who carried out several of the excavations. The project has been supported by funding from the Norwegian Research Council and Enterprise Oil. Comments from the reviewers Lars Olsen and Jon Landvik are greatly appreciated.
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.

<table>
<thead>
<tr>
<th>Section/ Fig. number</th>
<th>Description and references</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sandnes 2A</strong></td>
<td>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 &quot;the Weichselian interstadial during which zone 1, the labradoricum-norcrossi assemblage, of the Sandnes Clay was deposited&quot;.</td>
</tr>
<tr>
<td><strong>Steinteig 2B-D</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>Høyland 2E</strong></td>
<td>Unit H 1 is a 1 m thick grey, sandy diamicton with shell fragments and an arctic foraminifera fauna dominated by <em>Elphidium excavatum</em>. Some of the specimens are abraded or crushed. The diamicton is interpreted as glaciomarine, but the abraded and crushed specimens indicate deformation and/or reedimentation. Unit H 2 is a light brown, silty and compact diamicton with boulders interpreted as a till.</td>
</tr>
<tr>
<td><strong>Tunheim 2F</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>Oppstad 2G</strong></td>
<td>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).</td>
</tr>
<tr>
<td><strong>Småelgane 2H</strong></td>
<td>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).</td>
</tr>
<tr>
<td><strong>Elgane 2I</strong></td>
<td>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 at 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).</td>
</tr>
<tr>
<td><strong>Hogemork 2J</strong></td>
<td>A 37 m long core from Hogemork 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 Hogemork 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.</td>
</tr>
</tbody>
</table>
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 Le1 contains an arctic foraminifera fauna and is interpreted as glaciomarine, while Unit Le2 is interpreted as a till.

The stratigraphy at Foss-Eikeland has been described by Bergersen and Follestad (1971), Østmo (1971), Feyling-Hansen (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 F1 is deformed, laminated silt and clay, F2 is homogenous silty clay, and F3 is a clayey diamicton interpreted as glaciomarine. A fabric analysis from Unit F3 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).

2 m of laminated, undeformed silt and clay (O1) is overlain by c. 20 cm of sorted gravel interpreted as glacio-fluvial (O2) and capped by 50 cm of sandy diamicton interpreted as till (O3).

Coarse, open-work gravel (Li1) is overlain by deformed, laminated silt and clay (Li2) and capped by a gravelly diamicton interpreted as till (Li3).

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.

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

i) Middle part of Unit F at the southern side of Figgjo, from Feyling-Hansen (1974)
ii) Three samples from zone 1 (glaciomarine diamicton) in Sandnes (Feyling-Hansen 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

<table>
<thead>
<tr>
<th>Facies</th>
<th>Bulk grain size</th>
<th>Foraminifera per g sediment</th>
<th>% CaCO₃</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Facies A – Laminated silt and clay</strong></td>
<td>65-81 % clay 20-30 % silt 1-5 % sand and gravel</td>
<td>&lt;1</td>
<td>0 - 4.8</td>
<td>Annually deposited couplets of glaciomarine silt and clay</td>
</tr>
<tr>
<td><strong>Facies B – Homogenous silty clay</strong></td>
<td>66-75 % clay 20-31 % silt 3-5 % sand and gravel</td>
<td>&lt;2</td>
<td>0.8 - 7</td>
<td>Glaciomarine, may result of homogenous clay and from both primary deposition glacial tectonic deformation of laminated silt and clay</td>
</tr>
<tr>
<td><strong>Facies C – Clayey diamicton</strong></td>
<td>40-55 % clay 20-30 % silt 10-30 % sand and gravel</td>
<td>1.5-34</td>
<td>7-15</td>
<td>Glaciomarine diamicton deposited from melting icebergs</td>
</tr>
</tbody>
</table>

### 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).

<table>
<thead>
<tr>
<th>Locality/ Unit</th>
<th>Material/ Sample No.</th>
<th>Facies</th>
<th>¹⁴C-age BP</th>
<th>Lab. No.</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elgane</td>
<td>E. excavatum</td>
<td>B</td>
<td>34820 ±1185</td>
<td>TUa-2168</td>
<td>c)</td>
</tr>
<tr>
<td>Elgane</td>
<td>E. excavatum</td>
<td>B</td>
<td>33480 ±1520</td>
<td>TUa-2168</td>
<td>c)</td>
</tr>
<tr>
<td>Foss-Eikeland F₂</td>
<td>E. excavatum</td>
<td>B</td>
<td>24210 ±1480</td>
<td>TUa-2168</td>
<td>b)</td>
</tr>
<tr>
<td>Foss-Eikeland F₂</td>
<td>Mya truncata</td>
<td></td>
<td>27900 ±2200</td>
<td>T-3423A</td>
<td>a)</td>
</tr>
<tr>
<td>Foss-Eikeland F₂</td>
<td>Mya truncata</td>
<td></td>
<td>31300 ±2000</td>
<td>T-3423B</td>
<td>a)</td>
</tr>
<tr>
<td>Foss-Eikeland F₁</td>
<td>E. excavatum, Islandiella spp.</td>
<td>A</td>
<td>34865 ±1260</td>
<td>TUa-2167</td>
<td>b)</td>
</tr>
<tr>
<td>Foss-Eikeland F₃</td>
<td>Arctica islandica</td>
<td>C</td>
<td>34960±395</td>
<td>TUa-2102</td>
<td>b)</td>
</tr>
<tr>
<td>Foss-Eikeland F₂</td>
<td>Macoma calcarea</td>
<td>B</td>
<td>39330±790</td>
<td>TUa-2103</td>
<td>b)</td>
</tr>
<tr>
<td>Foss-Eikeland F₂</td>
<td>Arctica islandica</td>
<td>B</td>
<td>49785 ±1480</td>
<td>TUa-2450</td>
<td>b)</td>
</tr>
<tr>
<td>Foss-Eikeland F</td>
<td>E. excavatum</td>
<td>C</td>
<td>45890 ±2660</td>
<td>TUa-2169</td>
<td>b)</td>
</tr>
<tr>
<td>Foss-Eikeland F</td>
<td>E. excavatum, Islandiella spp.</td>
<td>A</td>
<td>46455 ±1270</td>
<td>TUa-2451</td>
<td>b)</td>
</tr>
<tr>
<td>Sandnes</td>
<td>Shell fragment</td>
<td>C</td>
<td>38100±1600</td>
<td>AAR-6695</td>
<td>*)</td>
</tr>
<tr>
<td>Småelgane</td>
<td>Shell fragment</td>
<td>C</td>
<td>41950±690</td>
<td></td>
<td>d)</td>
</tr>
<tr>
<td>Småelgane</td>
<td>Shell fragment</td>
<td>C</td>
<td>42850±820</td>
<td></td>
<td>d)</td>
</tr>
<tr>
<td>Steinheig</td>
<td>E. excavatum</td>
<td>C</td>
<td>31455±520</td>
<td>TUa-2994</td>
<td>*)</td>
</tr>
<tr>
<td>Steinheig</td>
<td>E. excavatum</td>
<td>C</td>
<td>30160±330</td>
<td>ETH-25563</td>
<td>*)</td>
</tr>
<tr>
<td>Tunheim</td>
<td>3100 E. excavatum</td>
<td>C</td>
<td>34820±575</td>
<td>TUa-3064</td>
<td>*)</td>
</tr>
<tr>
<td>Tunheim</td>
<td>1200 Islandiella spp. + 900 E. excavatum</td>
<td>C</td>
<td>38540±775</td>
<td>TUa-3145</td>
<td>*)</td>
</tr>
<tr>
<td>Tunheim</td>
<td>Shell fragment</td>
<td>C</td>
<td>36450±635</td>
<td>TUa-3065</td>
<td>*)</td>
</tr>
</tbody>
</table>

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


Quaternary Research 5, 263-273.
Stalsberg, K., Larsen, E., Ottesen, D. & Sejrup, H. P. 2003: Middle to Late Weichselian Norwegian Channel Ice Stream deposits and morphology on Jæren, south western Norway and the eastern North Sea area. Boreas 32, 149-166.