Middle and Late Quaternary depositional history reconstructed from two boreholes at Lågjæren and Høgjæren, SW Norway

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Two boreholes drilled in the lowland (Lågjæren) and upland (Høgjæren) area of the Jæren region of SW Norway, revealed sedimentary successions of various ages. The Auestad borehole at Lågjæren, closer to the coast, contained only Saalian sediments. The 35-m-long sedimentary succession comprises till (unit 1), glaciofluvial and fluvial sediments (unit 2), glaciomarine sediments (unit 3), till bed (unit 4) and glaciofluvial sediments (unit 5). The Elgane borehole at Høgjæren contained 30 m of Weichselian sediments. The lower part of the succession consists of coarse-grained, probably glaciofluvial sediments (unit 1) and till (unit 2). This is overlain by in situ glaciomarine silts (unit 3), deposited before about 33,000 years ago. The Elgane sedimentary succession is capped by clayey till (unit 4). The difference in stratigraphy between the drilling sites suggests intensive erosion at Lågjæren probably by a north-flowing glacier. The two successions indicate four glacial episodes ranging in age from Saalian to Late Weichselian. The glacial phases are separated by marine intrusions. When at its highest, sea level was at least 200 m above the present level during the Middle Weichselian Sandnes Interstadial.

Introduction

The long stratigraphic successions of the Quaternary deposits in the Jæren area have been known since the turn of the century (Bjørlykke 1908; Grimnes 1910; Feyling-Hanssen 1964, 1966, 1971, 1974; Wangen 1968; Østmo 1971; Andersen et al. 1981, 1987; Fugelli 1992; Fugelli & Riis 1992). Jæren (Fig. 1) has a lowland character, with a slightly undulating relief rising from the coast towards the east where elevations reach about 250 m a.s.l. A pronounced step, generally trending north–south, divides the region into two morphological levels. The lower, flat-lying Lågjæren (lower Jæren) extends from the coast up to ca. 80–100 m a.s.l. The upper level, Høgjæren (upper Jæren), extends from about 180 m towards a mountain fringe in the east at some 240 m (Fig. 1).

An up to 125-m-thick sedimentary succession, consisting mainly of till and glaciomarine sediments, records deposition from the middle Pleistocene onwards (Andersen et al. 1987; Janocko et al., in press). Clayey fine-grained sediments were found at elevations up to 200 m a.s.l., and their origin has been debated in the literature (Reusch 1895; Bjørlykke 1908; Grimnes 1910; Hansen 1913; Feyling-Hansen 1964; Andersen et al. 1987, 1991; Fugelli 1992; Fugelli & Riis 1992). The basement consists of Palaeozoic and Precambrian granites, phyllites, mica schists and mica gneisses (Birkeland 1981; Jorde et al. 1995). Palaeozoic and Precambrian granodiorites and phyllites are upthrusted onto Precambrian granites and granitic gneisses along a boundary approximately identical with the boundary between Høg- and Lågjæren in the studied area (Fig. 1).

The presented cores from the two boreholes, at Auestad and Elgane, were collected in 1994 as a part of a renewed study of the Quaternary stratigraphy in the Jæren area (Larsen et al. 1992) in addition to a coring at the coastal site of Grødeland (Fig. 1) (Janocko et al., in press). The Auestad borehole was located in the yard of the old Auestad schoolhouse (UTM 32VLL072011) east–southeast of Varhaug. The site is at 75 m a.s.l., and only 100 m west of the foot of the morphological step separating Låg- and Høgjæren (Figs. 1, 2). The Elgane borehole was located next to a barn at Skreting farm (UTM 32VLL101017) at an altitude of 208 m in the Høgjæren area, east of Varhaug (Figs. 1, 6). A flat area comprising clayey and gravelly till prevails from the borehole towards the west. The transition zone between Høg- and Lågjæren, consisting here of a step-like morphology, lies about 1 km west of the borehole locality (Figs. 1, 9). East of the Elgane site, the relief becomes more dissected and surface sediments consist mostly of till and glaciofluvial deposits. The drilling site is located only 250 m from the Hegemork borehole, described by Andersen et al. (1981, 1987). Two sections at Høgjæren were described earlier: Oppstad (Feyling-Hanssen 1971; Andersen et al. 1981) and Bjorheim (Vistnes in Feyling-Hanssen 1964).
Fig. 1. Localization of Auestad and Elgane boreholes and other sites discussed in this paper. In the close-up, the morphological step between Lågjåren and Høgjåren is shown. The distribution of Quaternary sediments and bedrock is after Andersen et al. (1987).
The objective of the two new corings is to obtain a detailed sediment stratigraphy from both Lågjæren and Høgjæren. The drilling sites were located in the proximity of an existing seismic profile (Andersen et al. 1987), the old borehole at Høgemork (Fig. 1) (Andersen et al. 1987) and a sediment section at Skretting (Fig. 1) (Stalsberg 1995).

In this paper we present a stratigraphic description and interpretation of the sedimentary successions at Lågjæren and Høgjæren including some results of biostratigraphical and chronological work. These data were used for interpretation of depositional environments and palaeoenvironmental reconstructions.

Methods

The boreholes were drilled using a truck-mounted rotary drilling rig with a wire-line device for sampling, described in more detail by Janocko et al. (in press). The general run interval during sampling was 150 cm, but in some intervals it was reduced to 75 cm in order to improve recovery. Core recovery in some units was low (see Figs. 3, 7) due to loss of sorted sediments from the core catcher, or because large clasts blocked the opening in the drill bit during penetration. Usually, a small amount of sediment held in the core catcher was recovered even if the sampling tube was empty. Bouldery diamict units were penetrated without sampling using a hard metal drill bit. In intervals with no sediment recovery, sediment flushed up by the drill mud was caught on a screen (drill cuttings), and drill penetration rate was logged.

In order to gain higher recovery from the sorted sedimentary units, parallel corings were made at both sites ca. 3 m north of the first boreholes. The individual boreholes are named A1, A2 (Auestad) and E1, E2 (Elgane), respectively (see Figs. 3, 7).

After the cores were split and a macroscopic description carried out, about 1-cm-thick sediment slices were transferred to plexiglass trays and X-rayed. The cores were sampled for grain size, water content, total carbon (TC), total organic carbon (TOC), carbonate content (CaCO₃), foraminifera and pollen. Undrained shear strength was measured by fall-cone test. For outsized clast counting, X-radiographs were placed on a light table and particles larger than 2 mm in diameter were counted at 2 cm intervals (Grobe 1987). Using the thickness of X-rayed sediment, a calculation for outsized clast frequency per 10 cm³ of sediment was made. The microstructure of the sediment was studied in thin sections following procedures described by Merkt (1971) and Murphy (1986). Foraminifera were prepared and analysed following procedures by Meldgaard & Knudsen (1978). Amino-acid samples were prepared according to Miller et al. (1983) and analysed on an automatic ion exchange amino-acid analyser at the Bergen Amino Acid Laboratory. Two shell fragment samples from Elgane were AMS radiocarbon dated at the Laboratory for Radiological Dating in Trondheim.

Sedimentary successions

The sediments recovered at both drilling sites are mainly related to glacigenic environments. Lithofacies and lithofacies associations (Figs. 3, 7) suggest glacial, glaciomarine, glaciofluvial and fluvial environments.

Glacial sediments are represented by two distinct facies. Diamictic facies (Dmm) consists of matrix-supported gravelly and bouldery diamicton. The matrix is unsorted and consists of a clay-silt-sand mixture. Gravelly and bouldery clasts are usually subangular sometimes with secondary fractures. Diamicton beds have an erosive base. Glacial origin is ascribed to massive silt (facies Fm) with outsized clasts recovered in the upper part of the Elgane borehole. The deposit shows deformation typical of subglacially formed sediments (see detailed description below).

Glaciomarine sediments are mostly represented by massive silt (facies Fm) and laminated silt (facies Fl) containing outsized clasts interpreted as dropstones. Both facies are thought to have been deposited by suspension fall-out. Lamination in Fl facies is probably caused by fluctuation in suspension concentration due to irregular sediment supply. Thin beds of sandy silt clasts (facies Fe) occasionally interfinger with Fm and Fl facies.
The origin of this facies is interpreted to have resulted from iceberg grounding and gravity flows (see a more detailed description below).

Glaciofluvial and fluvial sediments consist mostly of gravel and sand. The gravel is matrix-supported (facies Gmm), and the sand is mostly massive (facies Sm). Some of the gravel beds contain roots in subvertical position and pollen of local origin, strongly suggesting subaerial deposition.

**Auestad**

The borehole penetrated 35.5 m of sediments before encountering a large block of crystalline rock, hampering its continuation (Fig. 2). Refraction seismic profile performed at the drilling site suggested bedrock at about 50 m (Rye, written comm. 1994). The sediment succession was divided into five units (Fig. 3).

**Unit 1**

**Description.** – Unit 1 comprises the lowermost part of the borehole. The unit is more than 4.5 m thick, but only a 15-cm-long core was recovered before the large boulder was hit. The core sample shows massive, matrix-supported diamicton of facies Dmm. Angular and subangular, rarely subrounded, crystalline clasts of variable size with secondary fractures are supported in a matrix consisting of a poorly sorted mixture of silt and sand. A few foraminifera of *E. excavatum*, *C. lobatulus* and *C. reniforme* were found in the sediment.

**Interpretation.** – Dmm facies with variable clast size and roundness, secondary fractures of clasts and poorly sorted matrix suggest that the diamicton is a subglacial till. The few foraminifera are interpreted as having been redeposited from older, glaciomarine sediments.

**Unit 2**

**Description.** – Unit 2 extends from 31 m to 21.1 m and is composed mostly of gravel and sand (Fig. 3). The lower boundary is placed between the core containing unit 1 diamicton at 31.5 m and the core-catcher sample from 30.6 m showing sandy gravel (Fig. 3). The unit is separated from overlying silty sediments by a sharp boundary. The recovery in this unit was poor.

Two core-catcher samples in the lower part and a 25-cm-long core retrieved from 28.5 m show gravel (facies G) that consists of angular and subangular crystalline clasts up to 9 cm in diameter. Some clasts have secondary fractures. The gravel passes upward into light olive brown, massive, gravelly sand (facies Sm), recovered by a core catcher at 27 m and in the lower part of the core at 25.8 m, which, in turn, is overlain by a

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**Fig. 3.** Composite log of the Auestad borehole. Caption as in Fig. 7, facies codes shown in Table 1.
sharp-based, 5-cm-thick bed of matrix-supported gravel (facies Gmm). The subangular, crystalline clasts of pebbly gravel are supported by a matrix of medium sand to sandy silt. The gravel bed contains up to 10-cm-long plant roots in a subvertical position and pollen of *Betula pubescens*, *Pinus*, *Alnus*, *Salix herbacea*, *Betula nana*, *Empetrum*, *Antennaria*, *Rosaceae*, *Poaceae* and *Cyperaceae* (Table 2). A sharp boundary separates the gravel bed from a very fine (Md = 7.4), massive, clayey silt (facies Fm) with scarce outsized clasts. The silt is grey with black smudges from sulphides. The TC contact and TOC content are relatively high (Fig. 3). The upper boundary of the silt bed has not been recovered.

Light yellowish brown matrix-supported pebbly gravel is found in the lowermost part of the core at 24.1 m (Fig. 3). The crystalline clasts are mostly subangular. The gravel is overlain by sharp-based, horizontally laminated, normally graded sand (facies S) (Fig. 4). The light yellowish-brown sand is medium to fine grained with small clasts of crystalline rocks in the lower part of the bed. Laminae consist of alternating coarse and fine sand, 2–5 mm thick. The uppermost part of unit 2 consists of deformed sand (facies Sd) consisting of medium-grained sand and silty, poorly sorted sand separated by subvertical boundaries (Fig. 4). The sediment contains outsized clasts.

A few foraminifera were found in the gravel and sand layers in the lower part of the unit and in the sand layer in the upper part of the unit (Table 2, Fig. 3). No foraminifera were found in the silt.

### Table 2. Pollen analysis from the fluvial sediment of unit 2, Auestad borehole.

<table>
<thead>
<tr>
<th>Pollen family</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Betula pubescens</em></td>
<td>6</td>
</tr>
<tr>
<td><em>Salix herbacea</em></td>
<td>1</td>
</tr>
<tr>
<td><em>Betula nana</em></td>
<td>6</td>
</tr>
<tr>
<td><em>Empetrum</em></td>
<td>1</td>
</tr>
<tr>
<td><em>Antennaria</em></td>
<td>1</td>
</tr>
<tr>
<td><em>Rosaceae</em></td>
<td>1</td>
</tr>
<tr>
<td><em>Poaceae</em></td>
<td>84</td>
</tr>
<tr>
<td><em>Cyperaceae</em></td>
<td>11</td>
</tr>
<tr>
<td><em>Unidentified</em></td>
<td>21</td>
</tr>
<tr>
<td><em>Polypodiaceae</em></td>
<td>2</td>
</tr>
<tr>
<td>Total pollen &amp; spores</td>
<td>140</td>
</tr>
<tr>
<td>Charcoal</td>
<td>132</td>
</tr>
</tbody>
</table>

Fig. 4. Photograph and redrawn sketch of normal-graded and deformed sand (facies Sg, Sd) of unit 2. Transition to massive silt (facies Fm) of unit 3 is also shown. Auestad borehole, 21.1 m of depth.

Fig. 5. Photograph of glaciomarine massive silt overlain by sandy silt clasts. Auestad borehole, 15.0 m of depth.
The sediment contains 9–36 foraminifera/g. The fauna is almost totally dominated by *Elphidium excavatum* (ca. 50%) and *Cassidulina reniforme* (ca. 25%). Other species such as *Bulimina marginata*, *Elphidium albumblicatum* and *Bolivina skagerrakensis* are common, but do not exceed 10%. Several accessory species such as *Stainforthia loeblichii*, *Astrononion gallowayi*, *Haynesina orbicularis* and *Buccella frigida*, are also found. The sediment also contains some unidentified shell fragments.

**Interpretation.** – The massive and horizontally laminated silt containing outsized clasts interpreted as dropstones suggests deposition by suspension fall-out in a glaciomarine environment (Stevens 1990; Stewart 1991). The dropstones suggest calving of an ice sheet and melting of icebergs releasing entrained sediments. The origin of Fc facies is ambiguous and can be explained by iceberg grounding (Longva & Bakkejord 1990), gravity flow (slide) (Boulton 1990) or by ice rafting (Gilbert 1990; Goldschmidt et al. 1992). The stiffness of the silt clasts suggests that the sediment has been formed as a result of deformation due to iceberg grounding (Longva & Bakkejord 1990). The prevailing Fm facies suggests an absence of wave-generated currents during deposition, implying deposition below wave base.

**Unit 4**

**Description.** – Unit 4 (10.6 m to ca. 9.0 m) consists of a massive, erosive-based, gravelly diamicton (facies Dmm). The base of the unit was sampled by a core, and the top was only retrieved by a core-catcher sample. It is composed of subangular, crystalline clasts, up to 5 cm in diameter, supported by a silty and sandy matrix. The foraminiferal content is low (Fig. 3, Table 2). The upper boundary of the unit has been inferred from the cuttings.

**Interpretation.** – The matrix-supported structure of the diamicton, subangular clasts, poor sorting and lower erosional boundary suggest subglacial deposition as till. The few, scattered foraminifera are interpreted as redeposited from the underlying glaciomarine sediments.

**Unit 5**

**Description.** – Unit 5 extends from 9.0 m to 4.0 m and is composed of gravel and sand, inferred from drill cuttings and penetration rate during drilling. No cores were recovered. Continuous sampling of drill cuttings revealed an upward-fining gravel fraction with a maximum particle size decreasing from 7 to 4 cm and consisting of subangular and subrounded crystalline clasts. The loss of samples during drilling suggests that the gravel is sorted. However, being transported by the drill mud, the recovered clasts may only represent a single grain-size fraction of the *in situ* sediment.
Fig. 7. Composite log of the Elgane borehole. Facies codes shown in Table 1.
Elgane

The borehole at Elgane penetrated 30 m of sediments. It was abandoned at this depth owing to loss of drill mud, probably caused by penetration of sediments with high permeability. A refraction seismic profile made across the drilling site (N. Rye, written comm. 1995) suggests a depth to bedrock of ca. 40 m. The drilled sediments consist mainly of silt with abundant outsized clasts (Fig. 8), intermittently interlayered with thin diamicton beds. Based on lithology, the succession was divided into four lithological units (Fig. 7).

Unit 1

Description and interpretation. – Unit 1 extends from the base of the borehole (30 m) to about 29 m. No samples were retrieved from this interval, but abrupt loss of drill mud below 27.5 m in the E 1 borehole and at 30 m in the parallel E 2 borehole shows a change to a highly permeable sediment at this depth. We assume this to be an open-work gravelly sediment, probably of glaciofluvial or littoral origin.

Interpretation. – Owing to lack of recovery, we can only make assumptions about the genesis of unit 5. Sorted gravel such as this could be deposited either in coastal, fluviatile or glaciofluviatile environments. The setting, immediately above the till, may indicate a glacially related formation.

Unit 2

Description. – Core-catcher samples from 26.3 m and 27 m show a diamictic sediment (facies D). The lower boundary is assumed to lie at 29 m where drill mud was lost. The upper boundary is below the silt recovered by a core at 26.2 m. The diamicton consists of subangular pebbles of crystalline origin in a silty matrix.

Interpretation. – Low recovery makes interpretations difficult, but the diamictic character and the association with overlying glaciomarine sediments (see below) suggest deposition as a subglacial till.

Unit 3

Description. – Unit 3 extends from 26.2 m to 12.3 m. The upper boundary at 12.3 m is loaded and is also marked by abrupt change in grain size (Figs. 7, 8). The unit consists of silt and sandy silt with frequent outsized clasts and thin diamicton beds in the lower part. Occasionally, coal fragments <1 mm occur. The sediment comprises three facies.

The dominant facies is massive silt and sandy silt with scattered outsized clasts (facies Fm). It is arranged in thick beds exceeding the core length (75 cm). Grain size and frequency of outsized clasts vary slightly (Fig. 7). The sediment is often more clayey, less consolidated and contains less outsized clasts when situated underneath Dmm beds compared to other positions. Facies Fl, only found in the lower part of the unit, consists of horizontally and faintly laminated silt and sandy silt. The laminae, arranged into some 10-cm-thick beds with diffuse boundaries, are from 2 mm to 1 cm thick. Laminae are strongly bioturbated at some intervals.

Dmm facies is found in the lower part of the unit. It is composed of massive diamicton consisting of matrix-supported pebbles. The matrix is a mixture of clay, silt and sand or clayey sand. The diamicton comprises erosive based, 10–20-cm-thick beds.

The foraminiferal content varies between 1 and 20 foraminifera per gram sediment, with the highest values occurring between 18 and 14 m (Fig. 7). Elphidium excavatum and Cassidulina reniforme account for 70 to 90% of the total fauna, and the two species vary between 30 and 50% each. Other common species are Islandiella norcrossi, Stainforthia loeblichi, Nonion labradoricum and Elphidium albiumbilicatum. The last species is absent in the interval between 18 and 14 m.
Fig. 9. Sediment successions in the area surrounding the Auestad and Elgane boreholes and a cross-section from the coastline across the Auestad and Elgane boreholes showing correlation between sediments. The bedrock is adapted from reflection-seismic profiles by Andersen et al. 1987 and N. Rye (written comm. 1995)
Interpretation. – Thick beds of massive and horizontal laminated silt suggest deposition from suspension (Stevens 1990; Stewart 1991). Lamination of silt (facies Fl) is thought to be caused by pulsatory sediment supply. Diamictic facies Dmm comprising thin, erosive based beds, is thought to have been deposited by gravity flows (Powell 1984; Boulton 1990). They probably originated as a result of slope failures in areas near the glacier terminus during high sediment input. A change in the sediment supply indicated by facies Fl and the occurrence of diamictic facies in the lower part of the unit suggest an unstable sedimentary environment typical of an inner, ice-proximal glaciomarine zone (Boulton 1990). In contrast, the exclusive occurrence of Fm facies in the upper part of the unit and finer-grained sediment in the uppermost part of the unit suggest a more stable environment in a more distal position relative to the ice front. Proximal glaciomarine sedimentation is also indicated by the dominance of *Elphidium excavatum* and *Cassidulina reniforme*.

Unit 4

Description. – Unit 4 extends from 12.3 m to the top of the drilling. It is separated from the underlying unit by a loaded base at 12.3 m depth (Figs. 7, 8), and it is distinguishable from unit 3 by a higher sand content, occurrence of deformation microstructures and lower variance in foraminifera content (Fig. 7). The prevailing facies is massive sandy silt containing outsized clasts (facies Fm). This is arranged into erosive-based beds in some parts of the core. A thin section from 12.25 m depth shows the occurrence of soft sediment deformation structures and small shear planes. At 9.8 m depth, a sharp-based, 5-cm-thick bed of sandy silt clasts occurs (facies Fc, Fig. 7). A sharp colour boundary between olive brown and light brown, and a lower content of foraminifera, TC, TOC and CaCO₃ mark a transition to the uppermost 1.7 m of the unit. The foraminifera *Cassidulina neoteretis* and *Cibicides lobatulus*, occurring in this interval, are scarcely found downcore where *Elphid-
ium excavatum and Cassidulina reniforme prevail. Other common species are Islandiella norcrossi, Stainforthia loeblichii, Nonion labradoricum and Elphidium albumbilicatum.

Interpretation. – The erosive, internal boundaries, together with shear planes and soft-sediment deformations, identified in thin section, and the sandy silt clasts, probably formed by sediment shearing, suggest that the sediment has been redeposited from underlying glaciomarine deposits in a subglacial environment. Amino-acid analyses indicate reworking of older foraminifera (see below). This is also supported by the low variation in lithology and foraminifera content, probably caused by homogenization of the sediment during redeposition. A sharp change in colour and drop in TC, TOC, CaCO3 and foraminifera content in the uppermost part of the unit probably reflects leaching related to soil development. We conclude that the unit is a subglacial till.

Chronology and correlations

Chronology

Auestad. – Amino-acid analyses have been carried out on 38 samples of the benthic foraminifera Elphidium excavatum and on 3 samples of Bullimina marginata taken from the depth interval 10.6 m to 20.7 m in unit 3 (Fig. 3). The alle/Ile ratios from E. excavatum lie around 0.12 while the ratios for B. marginata are around 0.15. A comparison of values with ratios of known age (Sejrup et al. 1989) suggests oxygen-isotope stage 6 for the E. excavatum and probably stage 7 for the B. marginata. Testing the difference statistically (t-test) shows an 86.5% significance that the shells are of different age. Accordingly, the older forams (B. marginata) are interpreted as having been redeposited.

Elgane. – Both radiocarbon dating and amino-acid analyses have been performed on Elphidium excavatum taken from the cores. Two AMS 14C datings from 16.9 and 20.6 m (unit 3) yielded ages around 34,000 years BP (Fig. 7). Alle/Ile ratios of 11 samples of E. excavatum between 19.8 and 14.25 m showed relatively consistent ratios around 0.05. The results from the amino-acid measurements suggest a Middle Weichselian age (Sejrup et al. 1989), which is in accordance with the AMS dates. An amino-acid analysis of E. excavatum from unit 4 (3 m depth) yielded 0.071, indicating a significantly older age than that obtained in the underlying unit 3. This supports the interpretation of unit 4 as subglacially reworked marine sediments.

Radiocarbon and amino-acid analyses show that the successions at Auestad and Elgane represent a time-span from Saalian to Middle Weichselian (Fig. 10). The oldest recovered sediments are the lowermost Auestad till and glaciofluvial and fluvial sediments (Auestad units 1 and 2). The correlation of a succession of the overlying glaciomarine, till and glaciofluvial deposits between Auestad and a nearby locality Skretting (Stalsberg 1995, see below) suggests a Late Saalian age of till and glaciofluvial deposits at Auestad (units 4 and 5). The glaciomarine sediments at Elgane (unit 3) were dated by both amino-acid (mean Alle/Ile value 0.05) and radiocarbon (two datings around 34,000 years) to Middle Weichselian, which suggests that upper till was deposited during Late Weichselian time.

Correlation

In the following, we will discuss the correlation between our new corings and previously studied sites in the Varhaug–Høgjære area, and use this to outline the local Late Quaternary geological history. The localities at Høgemork and Oppstad on Høgjære (Fig. 1) were investigated by several authors (Feyling-Hanssen 1964; Andersen et al. 1981, 1987). In the lower part of the slope between the Elgane and Auestad sites, an extensive sediment succession in the Skretting gravel pit (Fig. 1) was studied by Stalsberg (1995).

At Høgemork, a 37 m deep borehole penetrated a sedimentary succession of (Fig. 9): (1) Gravelly and bouldery sediments interpreted to be of glaciofluvial origin; (2) Gravelly diamicton interpreted as till; (3) Partly laminated clay, silt and sand of glaciomarine origin containing a till-like bed; (4) Bouldery diamicton having a clayey matrix interpreted as till (Andersen et al. 1981, 1987, 1991). Three amino-acid analyses performed on Elphidium excavatum from the glaciomarine sediments yielded ratios of 0.051, 0.075 and 0.061 respectively (Fugelli 1987; Andersen et al. 1991). The 0.075 ratio is from a till-like bed that probably contains other fossils reworked from older strata (Andersen et al. 1991). Foraminiferal analyses show a dominance of Elphidium excavatum and Cassidulina reniforme. The faunal dominance is very high and diversity is low (Andersen et al. 1991). Pollen analyses from the glaciomarine sediments suggest an open-arctic or sub-arctic vegetation zone with a strong element of Artemisia (Andersen et al. 1987).

The succession at Oppstad was previously exposed in an 11-m-deep excavation at a site of the old clay pit, 175 m a.s.l. (Fig. 9) (Andersen et al. 1991). The succession consists of: (unit K) A laminated, partly sheared and folded, clayey silt interpreted to be deformed by glacio-tectonics; (unit L) A silty clay with outsized clasts, interpreted as glaciomarine; (unit M) Bouldery clay with well-developed clast fabric interpreted as subglacial till; (unit N) Stratified and partly laminated clay with sand and silt beds, interpreted to have been glaciotechnically inverted; (unit O/P) Strongly folded sand and silt of possible marine origin; (unit Q) A till, partly interpreted from large erratics on the surface. Supported by amino-acid analyses, radiocarbon dates and thermoluminescence dates (Fig. 10), Andersen et al. (1991) concluded...
that the whole succession was strongly tectonized, and that sheets of older sediments were folded into units of younger sediments.

At Skretting, the sediment succession shows (Stalsberg 1995) (Fig. 9): (1) A clayey silt with outsized clasts interpreted as glaciomarine; (2) A bouldery sandy till interfingering with (3) gravel, and (4) a sorted sand, both interpreted as glaciofluvial deposits; (5) Massive matrix-supported diamicton with boulders, interpreted as basal till. Dating and amino acid results are shown in Fig. 9.

Correlations are made on the basis of lithology, sediment genesis, lateral extent, stratigraphic succession, content of foraminifera and pollen, and age as suggested by amino-acid, TL/OSL and radiocarbon analyses. As chronology can be best established for marine units, these serve as sort of markers for correlations. In the following, we will discuss the correlation in stratigraphic order, mainly from the top towards the base.

The uppermost till recovered at Elgane (unit 4) is correlated with the uppermost till at Høgemork (unit 4), Oppstad (unit Q), Skretting (unit 5) and with till covering the area in the vicinity of the Auestad borehole. The correlation of the till between the localities at Høgjæren is supported by its position above glaciomarine sediments of similar age (see below and Fig. 10) at all localities. Downslope (Skretting, Auestad), the surface till covers older sediments (Fig. 9). The main criteria for correlating this to Høgjæren are its stratigraphic position and the conclusion that the youngest, westerly ice advance reached beyond the present coastline (Andersen et al. 1987).

The uppermost glaciomarine sediments at Elgane, Høgemork and Oppstad seem to be coeval (Fig. 9). Within unit 3 at Høgemork, a thin bed of diamictic character contains marine fossils having higher Alle/Ile ratio suggesting a higher age (Fig. 9). This may be correlative with the thin till bed (unit M) at Oppstad (Andersen et al. 1987). A higher amino-acid ratio was also obtained from the uppermost till at Elgane (Fig. 9) confirming erosion of older glaciomarine sediments. Although not confirmed, this is also taken to suggest that unit 2 till at Elgane and Høgemork is situated stratigraphically below these older glaciomarine clays. The older glaciomarine clays may be represented by bed L in the excavation at Oppstad (Andersen et al. 1987), but this cannot be confirmed owing to the low number of amino-acid analyses and the scatter of the data (Fig. 9). Following this, partly counting from-the-top procedure, units 1 and 2 at Elgane and Høgemork, respectively, may be correlative.

On and below the slope separating the Høgjæren and Lågjæren, the surface till is underlain by older sediments than at Høgjæren. This makes correlation even more difficult owing to incompleteness in the stratigraphic successions as well as problems with establishing an absolute chronology. The two glaciomarine units (1 at Skretting and 3 at Auestad) have identical amino-acid ratios and are thus taken as being correlative. This suggests that the overlying tills and glaciofluvial sediments at Skretting and Auestad can be correlated. All these units seemingly are older than any recorded sediments at Høgjæren (Fig. 9).

Discussion

The sediment stratigraphy, revealed by drilling at Auestad and Elgane, has implications for the interpretation of the geological and morphological evolution of the whole Jæren area. In particular, these new data contribute to the understanding of the origin of the silt and clays found at high elevations at Høgjæren. Based on the corings, we have also reconstructed a glacial and sea-level history for Jæren.

The in situ glaciomarine sediments at Høgjæren

The Elgane drilling recovered more than 13 m of glaciomarine sediments (unit 3) between two till beds (Fig. 7). The sediment consists mainly of sandy silt (facies Fm) with some layers of diamicton (facies Dmm) and laminated sandy silt (facies Fl) in the lower part of the unit. Both the Fm and Fl facies are interpreted to have been deposited from suspension. The diamicton facies is interpreted as gravity-flow deposits (see above). The facies succession suggests deposition with increasing distance from the glacier front. The lower part of the unit reflects an unstable proximal glaciomarine setting, where debris flows (facies Dm) were released and deposited in an environment with a continuous 'rain' of silt and clay (facies Fl) from the water column. The prevailing facies Fm in the upper part of the unit indicates more quiet, suspension sedimentation suggesting a more stable glaciomarine environment. This is supported by the foraminifera stratigraphy which shows a typical deglaciation succession. A normal glacial–deglacial succession is also supported by the position of the glaciomarine sediments immediately above a till (unit 2). Such systematic successions of glacial and glaciomarine sediments have been reported from many areas within glaciated continental margins (e.g. Mangerud & Svendsen 1992; Lyså & Landvik 1994).

The occurrence of these sediments has been known for a century, and the scientific discussion has focused on whether they are of an in situ marine or glaciomarine origin, or have been displaced from lower altitudes by glacial processes (Reusch 1895; Bjørlykke 1908; Hansen 1913; Fugelli-Hansen 1964; Andersen et al. 1987, 1991; Fugelli 1992; Fugelli & Riis 1992; see more detailed discussion of older literature in Fugelli-Hansen 1964). Our study of the glaciomarine sediments at Elgane clearly indicates that they have been deposited in situ. This is supported by:
Glaciation 1. – The oldest glaciation is recorded by the lowermost till bed in the Auestad borehole (unit 1). The pre-Eemian age of the glaciomarine sediments above (Auestad unit 3, Fig. 10) suggests at least a Late Saalian age for the till.

The glaciation was followed by an ice-free period recorded by coarse-grained sediments mostly of glaciofluvial and fluviatile origin (Auestad unit 2) and a glaciomarine silt (Auestad unit 3). The presence of till below correlative glaciomarine sediments at the nearby locality Auestad-jordet (Stalsberg 1995) implies a possible glaciation between the deposition of the fluviatile and glaciomarine sediments. This is supported by a change in the depositional depth from the fluvial to the glaciomarine sedimentation. This may reflect an isostatically induced relative sea-level rise (Fig. 10) caused by an advancing glacier. The thin layer of overconsolidated, poorly sorted silt at the base of the glaciomarine sediments and underlying deformed sand (Figs. 3 and 4) suggest a possible overriding of the Auestad site by this glacier.

Glaciation 2. – The second glaciation is indicated by the till of Auestad unit 4. The correlation with the till at the Skretting locality suggests a Late Saalian age for the glaciation.

During glacier retreat, glaciofluvial sediments of Auestad unit 5 were deposited. The succession from till to glaciofluvial sediments shows that isostatic depression during this glaciation was not large enough to cause local relative sea-level rise and glaciomarine deposition. This suggests a possible short duration of the glacier advance.

Glaciation 3. – The third glaciation is represented by the lowermost till in the Elgane borehole (Elgane unit 2). The radiocarbon dates from the overlying glaciomarine sediments give a minimum age of 34,000 years BP. The same till-to-glaciomarine succession was found in the nearby Høgemork drilling (Andersen et al. 1981, 1987, see correlation above), which suggests a correlation of the till with the Jæren stadial dated to some 40,000 years BP (Andersen et al. 1987).

Glaciation 4. – The last glaciation is recorded by the uppermost till in the Elgane borehole which has widespread occurrence at both at Høg- and Lågjæren. The age of the glaciomarine sediments at Elgane (unit 3) suggests that it was deposited after 33,000 years BP. Andersen et al. (1987) correlates this till with Late Weichselian Stavanger Stadial.
marine sediments of unit 3. Foraminifera assemblages show deposition in an arctic environment located in the vicinity of an ice front. We do not know the exact regime of sea ice and longshore currents in this depositional setting, and even though the sediments appear to have been deposited below wave base, we conservatively consider sea level to have been above the highest altitude where we found unit 3 sediments, i.e. > 200 m. Glacial erosion of the top of unit 4 during the subsequent glacier advance also suggests that 200 m must be considered a minimum altitude.

Glaciomarine deposits from Elgane unit 3 found around 200 m a.s.l. suggest an intensive uplift of the area during the last 32,000 years. This has been explained by isostasy and/or fault tectonics in literature. Andersen et al. (1981, 1987 and 1991) explains high elevation of these deposits by a strong isostatic rebound combined with tectonic uplift. Fugelli & Riis (1992) advocate the theory of tectonic uplift caused by reactivation of pre-Quaternary faults. Sejrup et al. (in press) showed that a large glacio-isostatic rebound after the glaciomarine deposition might be connected with the retreat of an ice stream following the Norwegian Channel. Because we did not find any direct evidence for tectonic faulting in the investigated area, we favour the hypothesis of an isostatic rebound as an explanation for high-elevated glaciomarine deposits at Elgane.

Different chronostratigraphy at Høg- and Lågjæren

The sedimentary successions recovered by Auestad and Elgane drillings show a different age. All lithological units recovered at Auestad were deposited before the Eemian. A similar sedimentary succession has been found at the Skretting gravel pit located on the slope between the Høg- and Lågjæren (Stalsberg 1995). As shown by the dates, the sediments recovered at Elgane have been deposited during the Weichselian. The absence of Weichselian deposits at Lågjæren, closer to the coast, can be explained by either a glacier covering part of the Lågjæren during the sedimentation at Høgjæren, or glacier erosion. The same glacier position at Lågjæren during the sedimentation of all Weichselian lithological units recovered at Elgane does not seem probable. Accordingly, we explain the absence of sediments at Lågjæren by a glacier erosion. The direction of the boundary between Høg- and Lågjæren suggests that the erosion was caused by a NNW flowing glacier. Recently, a NNW flowing ice stream (Norwegian Channel Ice Stream) partly covering the area of Lågjæren has been proposed by Sejrup et al. (in press). The morphological scarp between the Høg- and Lågjæren marks the easternmost boundary of this ice stream.

Conclusions

The sedimentary record from the Auestad and Elgane boreholes shows that the sediments at Lågjæren and Høgjæren have been deposited during different parts of the Middle to Late Quaternary. Most of the sedimentation is related to glacial conditions when sea level was considerably higher than at present. A total of four glacial phases are recorded in the sediments, the two older phases are probably of Saalian age and are represented in the Lågjæren sedimentary succession. The sedimentary succession on Høgjæren was deposited during the Weichselian and shows at least two glacial phases. The studies of the cored glaciomarine sediments found up to 200 m a.s.l. suggest that they were deposited in situ.

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References


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