Sedimentology and stratigraphy of two glacial–deglacial sequences at Skorgenes, western Norway

EILIV LARSEN & BRENT WARD


Two complex sequences of diamictons and associated waterlain deposits were investigated with respect to processes of formation. The lower unit, a highly variable deposit ranging from clay to diamicton and with an overall upward coarsening trend, is interpreted as a series of subaqueous flows from a glacial source. Based on a number of characteristics, such as rip-up clasts and deformed sand lenses, the overlying diamicton is interpreted as a result of a combination of processes between melt-out and lodgement till. Ice flow directions change from regional to local up the unit. Between this till and the next diamicton unit, bottomset and foreset beds of a delta, most likely glaciomarine, and deposited when sea level was minimum 84 m. The upper diamicton is also interpreted as a combination of melt-out and lodgement, but is probably closer to the melt-out end member than the lower diamicton. Only local ice flow directions are recorded in till fabrics, but thrust faults and strong overconsolidation of underlying sediments evidence thick ice independent of topography overriding the site. The entire section is capped by a glaciomarine delta deposited up to the marine limit (90 m) during the last deglaciation. Thermoluminescence and optical stimulated dates were obtained from the waterlain sediments. The results from parallel dating are highly variable. However, based on these dates and correlations with a well-dated sequence in the cave Skjonghelleren, it is proposed that the upper diamicton was deposited during the Weichselian maximum, the underlying delta during the Ålesund interstadial (ca. 30 ka BP), and the lower diamicton during a glacial advance some 40 ka to 50 ka BP. The lowermost interstadial sediments may be some 50 ka to 70 ka old. In addition, the deposition of these marine sediments up to 50 m above present sea level may indicate a preceding glaciation not recorded by deposits at the site.

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Ice sheet related depositional processes often result in complicated sedimentary sequences. Tills, mass flow deposits, ice rafted material, and sorted, waterlain sediments may be deposited simultaneously within a few tens of metres of the glacier margin, leaving a complex record that varies greatly both laterally and vertically. Where the glacier terminus was located in the sea the record is further complicated by marine influence. Even though the amount of palaeoenvironmental information stored in such records is potentially large the exact interpretation of such records can be hampered by the potential of many different processes to produce similar sediments.

On the coast of western Norway several sections with stratigraphies covering large parts of the last glacial cycle have been reported (reviews in Larsen & Sejrup 1990, Mangerud 1991). Still, many questions related to this timespan are unresolved, including timing and extent of glacier advances and retreats. This paper adds to the understanding of this glacial cycle by presenting the results of sedimentological and stratigraphical investigations in several closely spaced sections through the same sedimentary units. The main aim of this study is to elucidate the depositional processes for each individual unit, concentrating on the diamictons present. This information is used to construct a local stratigraphic framework and to correlate this with other records. The studied sections are located at Skorgenes in western Norway (Fig. 1).

Regional and local setting

Most valleys and fjords in the region are oriented perpendicular or parallel to the coast. Long stratigraphic sequences may be preserved in the valleys and fjords which parallel the coast, since these are generally perpendicular to regional ice movements (Landvik & Hamborg 1987; Follestad 1990) and were protected from glacial erosion. Several Weichselian advances and retreats of the ice sheet are documented on the outer coast (Mangerud et al. 1981a; Landvik & Mangerud 1985; Larsen et al. 1987; Larsen & Mangerud 1989). During two early interstadials (ca. 70–80 ka and 90–100 ka), the entire region is believed to have been deglaciated (Larsen & Sejrup 1990), whereas the extent of deglaciation during the Ålesund interstadial (ca. 30 ka) is more uncertain. At its maximum, the Late Weichselian ice sheet extended to the continental shelf edge (Rokoengen 1980; Rise & Rokoengen 1984). Its vertical thickness, however, is less clear; Nesje et al. (1987) conclude that widespread nunataks occurred, while Follestad (1990) presents evidence of the summits having been overrun by ice at this time.
Skorgenes is situated at the eastern mouth of a small east–west trending tributary valley (Skorgedalen) to the fjord Tresfjorden (Fig. 1). Tresfjorden is a tributary to the main fjord system, Romsdalsfjorden. At its western end, Skorgedalen is a tributary to the southern main fjord system, Storfjorden. The orientation of these fjord systems, together with the generally alpine topography, led to a complicated pattern of deglaciation of the last ice sheet (Larsen et al. 1991). Following the Late Weichselian maximum, Romsdalsfjorden was deglaciated earlier than Storfjorden, resulting in glacier outlets flowing through tributary valleys between the two fjords (Larsen et al. 1991). Skorgedalen contained such an outlet glacier. Marine limit during the last deglaciation is represented by the surface of a terrace at 90 m asl, and is interpreted as a delta (Fig. 2). Subsequent to the delta formation, numerous cirque glaciers formed during Younger Dryas (Reite 1967; Larsen et al. 1984). Meltwater from such glaciers drained through Skorgedalen depositing a terrace seaward of the marine limit terrace (Fig. 2).

Unit description and interpretations
The sections are located in natural exposures (mainly river cuts), gravel pits and road cuts on both sides of the river Skorgeelva (Fig. 2). Some of the exposures were excavated further by machine. Although the present river bed is at or very close to bedrock, the lowest part of the sequence is inaccessible. This problem was partly overcome by making a ca. 8 m deep excavation at site 2b (Fig. 2), but bedrock was not reached. The base of this excavation was, however, very close to the elevation of bedrock in the nearby river. Elevations and thicknesses of the units on the south side of the valley are shown in Fig. 3. Stratigraphic logs of the described sections are shown in Fig. 4.

Unit 1 – Sands, gravels and diamictons
This unit is exposed at sites 1, 2a, 2b and possibly 2d (Figs. 3 and 4). It is at least 11 m thick, but the lateral extent of the unit is unknown because of the limited exposures. It could extend horizontally for approximately 250 m if the correlation to the sediments at the base of 2d is correct. At 2b the upper elevation is 50 m asl.

Description. – The lower contact of this unit was not observed. Correlation of the unit from site 2b to site 1 is tentative, based on stratigraphic position and elevation.
Fig. 2. Location of the studied sections (1, 2a, etc.) at Skorgenes. For reference, the main road and smaller roads (stippled) are indicated. The marine limit and Younger Dryas terraces are also shown.

At site 1, a strongly overconsolidated, laminated silt, very rich in trace fossils, was found. The best exposure of the unit, at 2b, shows a complex, generally coarsening upward trend from clay to gravel. The lower ca. 5 m consists mainly of alternating sand and gravel beds with frequently occurring silt/clay beds in between. Both the sand beds and the silt beds are overconsolidated and show normally graded lamina with common small-scale faults and water escape structures. Two diamictons occur in this lower portion. Both have lower contacts that exhibit loading features. A thick bed of sand with gravel in the upper part constitutes the rest of the unit (Fig. 5).

Interpretation. – Unit 1 is interpreted as material deposited into a subaqueous environment in front of a glacier. Most of the material was deposited by mass flows as evidenced by normal grading and presence of rip up clasts. The fine-grained diamictons have loaded lower contacts typical of a flow in a subaqueous environment when the density of the flow is higher than that in the substratum (Middleton & Hampton 1976). In addition, the much finer grain size of these sediments compared to diamictons from overlying units (Fig. 6) reflects a different depositional process. The wide range of grain sizes, from cobbles to clay, indicates highly variable energy levels. Whether this represents glaciomarine or glaciola-custrine sedimentation is unknown. Deposition in a marine environment, which is most likely, would indicate an isostatic depression of at least 50 m.

Unit 2 – Diamicton

Unit 2 is a diamict exposed at sections 2a, b and d (Figs 3 and 4). The lower contact is exposed at 2a, 2b and possibly at 2d. The thickness is 10–12 m.

Description. – The lower contact is well exposed at sections 2a and 2b (Fig. 5). At 2a the contact is sheared with blocks of underlying material incorporated into the diamicton. At 2b the contact is sharp and horizontal. Associated with this contact is a 1–5 cm thick, fine-grained layer that parallels it with branches extending downward into unit 1 (Fig. 5). The structure of this feature is complex, with zones that dip at 50° and some that are horizontal. The orientation of the dipping portions varies between 135° and 110°. The entire feature thins and fines with depth. The lower contact of the diamicton was tentatively defined at 2d, where it appeared to truncate fine-grained sediments, but since the exposure is poor, this could simply be a lens within the diamicton.

Overall, the diamicton is crudely stratified, as defined by eastward-dipping concentrations of boulders (Fig. 7). Further weak stratification is seen as slight changes in clast concentration and grain size of the matrix, as well as by the presence of thin, elongate, sorted bands, especially near the top of the unit. Clast concentration ranges from 20 to 30%, with most being subangular cobbles. Some striations were observed on clasts. Average clast size is from cobbles to boulders, some being in excess of 1 m (Fig. 7). The matrix is silty sand (Fig. 6).

Sand lenses of various sizes and shapes occur throughout the unit, as do minor gravel lenses. Sand lenses are most numerous and largest at the base of section 2a where they can be more than 1 m long and 30 cm thick, many preserving primary stratification (Fig. 8). In some cases these lenses are disturbed, possibly by shearing. Sand lenses in the upper portion of the unit are generally smaller and range from elongate to highly irregular with no primary stratification preserved (Fig. 9).

A total of six pebble fabrics were obtained from this unit. Their locations are shown in the stratigraphic logs (Fig. 4) and principal eigenvector and eigenvalues in Table 1. At the base and central part of the unit they are oriented approximately S–N to SSW–NNE with weak to moderate strengths, while in the upper 2 m they are all weak and oriented SE–NW. The two strongest fabrics (2 and 3) are located in the central part of 2a, where there
Fig. 3. Distribution of the sediment units on the south side of the valley and a photograph of the indicated portion of the exposure.
is an obvious visible fabric in the large clasts protruding from the unit (Fig. 7).

**Interpretation.** – Unit 2 is interpreted as a proximal glacial diamicton consisting mainly of basal till. This interpretation is based on the nature of the lower contact and the associated injection feature, fabric data, and characteristic lenses. The feature that extends from the till down into unit 1 (Fig. 5) is interpreted as a clastic dike that was injected downwards. This indicates a near margin position (Larsen & Mangerud in press) and a steep hydraulic gradient (Mangerud et al. 1981b). The presence of striated clasts indicates a period of basal transport.

Fabric data alone are not sufficient to differentiate between different types of tills (Mills 1991). Lodgement and basal melt-out tills which are the two end members of basal tills have a wide range of strength values (e.g. Lawson 1979; Shaw 1982; Dowdeswell et al. 1985; see Mills (1991) for further references). Thus, we will mainly use the fabric data as an ice flow indicator. Fabric 1, obtained 5–20 cm above the lower contact (Fig. 4), has a rather low eigenvalue, but it has a bimodal distribution. This could indicate a reoriented fabric (Broster & Dreimanis 1981). The two strongest fabrics (2 and 3), which are located above fabric 1, indicate ice flow towards the NE. The dike cutting through the area of fabric 1 is striking at approximately 120°, which is perpendicular to the latter ice flow direction. This supports an initial ice flow during deposition of unit 2 towards NNW with a subsequent NE ice flow resulting in the S–N trend of fabric 1. In the upper portion of the unit the fabrics (4, 5 and 6) are very weak. The low eigenvalues are due to large scatter rather than to bimodal distribution, and thus no preferred flow direction could be determined.
The largest sand lenses preserving primary stratification in the lower portion of exposure 2a are interpreted as rip-ups from the underlying sand. Deformation of these lenses would indicate some basal movement during deposition. Similar lenses are reported in lodgement tills (Krüger 1979; Rappol 1987), but this precludes a particle by particle process. Sand lenses above this are smaller and do not appear to preserve primary stratification. They could represent rip-ups incorporated to a higher stratigraphic level or primary melt-out lenses that were
Two glacial–deglacial sequences, western Norway

Table 1. Principal eigenvector and eigenvalues for the pebble fabrics obtained from diamictons.

<table>
<thead>
<tr>
<th>Number</th>
<th>Section</th>
<th>Unit</th>
<th>Number of clasts</th>
<th>Principle vector</th>
<th>Eigenvalues</th>
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<tr>
<td>1</td>
<td>2b</td>
<td>2</td>
<td>45</td>
<td>178</td>
<td>0.528</td>
</tr>
<tr>
<td>2</td>
<td>2a</td>
<td>2</td>
<td>25</td>
<td>189</td>
<td>0.662</td>
</tr>
<tr>
<td>3</td>
<td>2a</td>
<td>2</td>
<td>25</td>
<td>197</td>
<td>0.619</td>
</tr>
<tr>
<td>4</td>
<td>2a</td>
<td>2</td>
<td>25</td>
<td>325</td>
<td>0.536</td>
</tr>
<tr>
<td>5</td>
<td>2a</td>
<td>2</td>
<td>25</td>
<td>344</td>
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</tr>
<tr>
<td>6</td>
<td>2a</td>
<td>2</td>
<td>25</td>
<td>319</td>
<td>0.531</td>
</tr>
<tr>
<td>7</td>
<td>2c</td>
<td>5</td>
<td>25</td>
<td>179</td>
<td>0.674</td>
</tr>
<tr>
<td>8</td>
<td>2c</td>
<td>5</td>
<td>45</td>
<td>170</td>
<td>0.700</td>
</tr>
<tr>
<td>9</td>
<td>3a</td>
<td>5</td>
<td>25</td>
<td>213</td>
<td>0.671</td>
</tr>
<tr>
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<td>3a</td>
<td>5</td>
<td>25</td>
<td>166</td>
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</tr>
<tr>
<td>11</td>
<td>3a</td>
<td>5</td>
<td>25</td>
<td>219</td>
<td>0.624</td>
</tr>
</tbody>
</table>

subsequently disturbed. Sand lenses associated with clasts from this area (Fig. 9) have generally been considered to be indicative of basal melt-out (Shaw 1982, 1983). However, similar lenses have also been demonstrated to occur as a result of shearing due to overriding ice (Rappol 1987). Thus, these lenses could be taken to indicate both rip-up and basal melt-out. In either case, deformation of the lenses (Fig. 9) demonstrates active ice.

There is no evidence of particle by particle lodgement. Conversely, the deformed lenses and the injected dike preclude melt-out from stagnant ice. Thus, the main body of unit 2 is interpreted as a combination of processes between the two commonly used basal till end members. The uppermost 2 m of the section is more problematic. Here there are abundant sorted sediments forming relatively continuous layers in addition to diffuse lenses. Taken together with the weak fabrics, this could be interpreted in several ways: subaqueous flow in front of the retreating ice; melt-out from debris poor ice; or subsequent remobilization of previously deposited material.

Units 3 and 4 – Delta bottom- and foresets

Unit 3 is exposed at sections 2a, b and d, and unit 4 at sections 2a, b, c, d and 3a (Figs. 3 and 4). The lower boundary of both units dips to the east. The boundary between the two units ranges from gradational to erosional, resulting in a large variation in the thickness of unit 3 (2–5 m). The upper contact of unit 4 also dips to the east, more steeply in the eastern part. Observed thickness of this unit is up to 11.5 m.

Description. – Unit 3 is draping the underlying diamicton. The grain size varies (Fig. 6) and coarsens upward from clay and silt at the base to silt and fine sand at the top. The structure ranges from massive (rare) to laminated normally graded beds with well-sorted layers. Minor convolute folding and abundant flame and small loading structures are present. Dropstones occur throughout the unit, decreasing in abundance upward. Trace fossils are very rare and restricted to occasional horizontal burrows. The unit is overconsolidated, and six oedometer tests gave effective stress from 10 to 15 MPa (Heyerdahl 1991).

Two distinct types of deposits occur in unit 4. At 2a and d the unit is well bedded. Bed thickness is from 5 to 50 cm (rare) with most being 20 to 30 cm. Grain size is highly variable, but in general coarsens upward, ranging from fine sands to cobbles gravels, but individual beds are moderately to well sorted. Normal grading is most common although some display inverse grading. Clusters of pebbles exist in the lower sands. Contacts between individual beds range from gradational, through conformable, to erosive. Dip increases upward to about 25° consisting of large-scale asymmetric crossbedding.

At 2c and 3a a coarse, normally-graded gravel is supported in a fine-grained matrix (Figs. 10 and 11) which is composed almost entirely of silt and clay (Fig. 6). The best exposure is at 3a where there are four fining upward packages from very coarse boulder gravel up to pebble gravel. The sequences consist of a very coarse lower layer which abruptly fines after 1.5 to 2.0 m to cobbles; this then continues to fine upward to small

Fig. 10. Units 4, 5 and 6 at site 2c with contacts indicated by dashed lines. Gravel lens mentioned in the text occurs at the base of unit 5 above the pick. In this position unit 4 is composed of a fine-grained, matrix-supported gravel. The pick is 0.8 m long.
pebbles with some oscillations in grain size defining internal bedding. These sequences are up to 14 m (perpendicular to bedding) thick. The matrix of the first and fourth of these sequences is dominated by silt and clay, while the two in between mainly have a matrix of small pebbles or coarse sand with clay coating. Laminations are rarely preserved in the matrix, and are disturbed adjacent to boulders, in some cases folded. In the lowest coarse layer the boulders are up to 1.2 m in size with long axis parallel to bedding and trending down dip. Most of these deposits are matrix supported although zones of clast support are present.

**Interpretation.** – On the basis of fine grain size, stratification, lack of ripples, general lack of trace fossils, occurrence of dropstones and stratigraphic position, unit 3 is interpreted to have formed in a harsh marine environment by suspended sediment deposition in front of a prograding delta. The fine grain size indicates a dominance of deposition from suspension. The well stratified, mainly normally graded nature of the unit, especially in the upper portion, indicates oscillatory energy conditions which increased upward. Deposition likely occurred in relatively deep water, below wave base. Convolute fold-

Measurements and Interpreted Fields of Activity

**Unit 4** – Former Delta

This unit is exposed in section 2a, b, c, d, and e as well as in gravel pits and in road cuts (Figs. 3 and 4). The lower contact dips gently to the east until about section 2c and then more sharply eastward, possibly truncating the underlying units. At section 3a the unit dips steeply eastwards. This unit is generally less than 2 m thick, except at 2d where it thickens to more than 9 m.

**Interpretation.** – On the basis of fine grain size, stratification, lack of ripples, general lack of trace fossils, occurrence of dropstones and stratigraphic position, unit 3 is interpreted to have formed in a harsh marine environment by suspended sediment deposition in front of a prograding delta. The fine grain size indicates a dominance of deposition from suspension. The well stratified, mainly normally graded nature of the unit, especially in the upper portion, indicates oscillatory energy conditions which increased upward. Deposition likely occurred in relatively deep water, below wave base. Convolute fold-

**Unit 5 – Diamicton**

This diamicton is exposed at 2a, b, c, d, and e as well as in gravel pits and in road cuts (Figs. 3 and 4). The lower contact dips gently to the east until about section 2c and then more sharply eastward, possibly truncating the underlying units. At section 3a the unit dips steeply eastwards. This diamicton is generally less than 2 m thick, except at 2d where it thickens to more than 9 m.

**Description.** – The lower contact of the diamicton is sharp, distinct and most likely erosive at 2b, 2d and 3a (Fig. 10). Associated with the lower contact at 3a there was a lodged elongate clast and striated clasts anchored in the underlying gravel. The lodged clast's trend and plunge was 018° at 20° and the striations on the clasts were oriented at 020°-200°. At 2a, compressive deformation in underlying sands, a zone of mixing, and a clastic dike are associated with the lower contact. Here, two thrust faults have dip directions and dips of 155° at 22° and 135° at 31°. The zone of mixing (ca. 50 cm thick) that occurs between the sands and the diamicton is cut by a small clastic dike. A larger clastic dike is also present and has a more irregular outline than that below unit 2, but a similar grain size.

The diamicton is generally massive with some minor, weak stratification, as evidenced by changes in matrix and by sandy zones. Clast content ranges from about 25–40%, clast size up to boulders with most clasts being subangular. The matrix is generally silty sand (Fig. 6). Although more massive than unit 2, several apparently undeformed gravel lenses were observed. The best exposed lens was at section 2c (Fig. 10). It is approximately
7 m long and slightly concave up. Maximum thickness is 30 cm at the centre and it tapers laterally. The lens at 3a is less well defined, having an indistinct contact with the lower gravels and a convex-up upper surface. This lens was not fully excavated, but is more than 3 m long and approximately 70 cm high.

The diamicton exposed at section 2d is much thicker and has a higher clast concentration than at other sites. The exposure was poor, so detailed descriptions are lacking. The matrix appears similar to the rest of the unit, although no samples were taken. It appears to have abundant diffuse sandy zones and sand lenses throughout. The diamicton at this site appears similar to diamictons observed further up the Skorgedalen valley.

A total of five pebble fabrics were measured in this diamicton. Their locations are given in the logs (Fig. 4) and statistical data in Table 1. With the exception of fabric 10, they are all moderately strong with a principal eigenvalue ranging from 0.624 to 0.700. The orientation of the strongest fabrics varies slightly between the two sites with those from 2c being approximately S–N and those from 3a SW–NE.

**Interpretation.** – On the basis of the nature of the lower contact, moderately strong fabric and lateral extent unit 5 is interpreted as a proximal glacial diamicton consisting mainly of basal till. Overriding of the site by glacial ice is indicated by the sharp lower contact and associated striated and lodged clasts, and by the compressive deformation, interpreted as glaciotectonics. The mixed zone cut by a clastic dike at 2a indicates that some material was lodged and subsequently cut by a clastic dike.

The fabric strengths are moderately strong except for fabric 10. This fabric was obtained directly above the gravel lens described at 3a, which may have affected clast orientation. The observed striated and lodged clasts at 3a correspond well with fabrics 9 and 11, indicating glacier flow towards the NE. A slightly different orientation was obtained from fabrics 7 and 8 from section 2c, indicating flow towards the north. The thrust faults at 2a indicate ice flow towards the NW.

The presence of apparently undeformed gravel lenses precludes particle by particle lodgement. Based on this and the relatively strong fabrics, we infer that the style of deposition of the majority of this unit is closer to basal melt-out than to lodgement. The different nature of the unit at 2d could reflect a change in the style of sedimentation as we shift from more marine to more terrestrial environment up valley.

**Units 6, 7 and 8 – Delta bottom-, fore- and topsets**

Units 6, 7 and 8 are identified at sections 2a, b, c and 3a (Figs. 3 and 4). These units are also exposed in the surrounding gravel pits and road cuts. Unit 6 drapes unit 5 and is thus gently dipping eastward to exposure 2c and then more steeply. It has a thickness of 0.5–1.5 m at the measured sections, but was observed to be thicker in a road cut on the south side of the valley. The lower contact of unit 7 ranges from erosive at 3a to conformable at 2d and the thickness varies from 8 m at 2a to 25 m at 3a. Unit 8 forms the upper surface of the well-defined terrace, which has a maximum elevation of 90 m asl (Fig. 2). The terrace dips gently towards Tresfjorden. The unit has a uniform thickness of about 2 m.

**Description.** – The lower contact of unit 6 is everywhere conformable, draping the underlying gravel or diamicton. It is finest grained at the base, where couplets of fine and very fine sand are either normally graded to or abruptly capped by clayey silts. The unit is well laminated throughout and gradually coarsens upward. Many of the contacts between laminations have minor soft sediment deformation features such as loading and flame structures. In addition, some minor folding was observed. Dropstones occur throughout the unit and appear to decrease in abundance upward. Trace fossils are much more abundant than in unit 3, appearing to increase in occurrence upward.

Unit 7 has only been described at 2a and 3a. It consists of asymptotic bedded sands and gravels dipping towards the east, indicating flow out of Skorgedalen. The unit contains abundant normal grading with some soft sediment loading and slump features in the lower portion. There are, however, some differences between the two sections. At 3a there are several packages in an overall coarsening upward sequence. This type of internal variation is very different from exposure 2a, where one basically continuous coarsening upward sequence exists. The lower contact with unit 6 is gradational and the unit coarsens upwards as the dip increases to about 25–30°.

Unit 8 was only described at 2a. The gravel has a sharp erosive lower contact and is coarse grained with cobbles and occasional boulders. The matrix is coarse sand with granules and small pebbles. Bedding is poorly defined, but appears to be approximately horizontal.

**Interpretation.** – Unit 6 is very similar to unit 3 and therefore has a similar interpretation; deposition in a glaciomarine environment in front of a prograding delta. However, the much more common occurrence of trace fossils in unit 6 indicates more favourable conditions for benthic organisms. In addition, unit 6 is not as overconsolidated as unit 3, demonstrating less post-depositional loading (Heyerdahl 1991).

On the basis of similarity to unit 4, geomorphic expression and relative stratigraphic position, unit 7 represents foresets of a prograding delta. The lower contact is variable, but reflects an increase in energy levels as the delta prograded. Unit 8 is interpreted as delta topsets.
from the TL measurements that the zeroing of the TL signal at the time of deposition was very poor and it was not possible to obtain a TL age for this unit (Mejdahl, pers. comm. 1991). OSL measurements yielded two different OSL ages: 41 ka with the added-dose technique and 73 ka with the regeneration technique (mean of three runs). Thus, both by geological evaluations and judgement of the dates, the sample from this unit appears unsuitable both for TL and OSL dating.

Abundant evidence suggests that the till (unit 5) separating the two delta units indicates thick ice overriding the site: first, the strong overconsolidation of underlying sediments indicates that ice thickness was at least 1100 m (Heyerdahl 1991); second, the orientation of thrust faults indicates regional ice movement direction towards the NW rather than local movements out of the valley, although all fabrics may be explained in terms of thin ice influenced by topography; and third, this till probably correlates with a till unit found on seismic records in Tresfjorden (Larsen & Longva 1989) and to an upper till unit found further up the valley Skorgedalen. Furthermore, a restricted, local readvance with deposition of till (unit 5) is contradicted by the succession itself; shallow marine foresets directly underlying the till, and deeper marine bottomsets directly overlying the till. The age of unit 5 cannot be securely estimated on the basis of TL and OSL dates of underlying and overlying sediments (Fig. 12). However, the stratigraphic position and the inferred thick and regional ice sheet suggest that it was deposited at some time during the Late Weichselian maximum glaciation.

The TL age of unit 4 was taken as the mean value of two ages with rather large difference (65 ka and 81 ka) and is, therefore, somewhat dubious even though the age plateaus were satisfactory. The OSL age is the mean value of an added-dose and a regeneration result (39.7 ka and 38.6 ka, respectively). Because these results are identical, the OSL age is regarded as the most reliable. One possible explanation for the discrepancy between the TL and the OSL ages is that the light exposure during the latest transport of the material was insufficient to bleach the TL signal. In this case, the TL age might reflect earlier depositional events. The obtained OSL age is close to radiocarbon and U/Th ages obtained for the Ålesund interstadial (Mangerud et al. 1981a; Larsen et al. 1987). Thus, we suggest that this delta (units 3 and 4) was deposited during the Ålesund interstadial

**Chronology, correlations and glacial history**

**Chronology and correlations**

Thermoluminescence (TL) and optically stimulated dates (OSL) were obtained from units 1, 4 and 7. The locations of the dated samples are given in Fig. 4, and ages in Table 2 and Fig. 12. TL ages were obtained by the differential bleach technique of Mejdahl (1988), which combines the regeneration technique with an age plateau criterion. OSL ages were obtained by the classical added-dose technique (Aitken 1985) or regeneration using single aliquots (Duller, in press). The infrared diode system developed by Better-Jensen et al. (1991) was used for optical stimulation of the luminescence signal. It should be emphasized that, so far, the experience with OSL dating is rather limited. It is evident from these results (Table 2, Fig. 12) that the absolute chronology of the sediment sequence is highly uncertain. However, by evaluation of the dates and by comparisons with other sequences some assumptions can be made (Fig. 12).

The uppermost units (6, 7 and 8) comprise a complete, undisturbed glaciomarine delta, and we feel confident that it was deposited as the Late Weichselian ice sheet withdrew from the area, i.e. some 12 ka BP (Mangerud, Larsen, Henningsen & Hovden in prep.). It was clear

**Table 2. Results of thermoluminescence (TL) and optically stimulated dates (OSL).**

<table>
<thead>
<tr>
<th>Section/unit</th>
<th>Sample no.</th>
<th>Lab. ref.</th>
<th>TL age (ka)</th>
<th>OSL age (ka)</th>
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<td>el 90052</td>
<td>R-913808</td>
<td>51 ± 5</td>
<td>28 ± 3</td>
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<tr>
<td>2B/1</td>
<td>el 90020</td>
<td>R-903801</td>
<td>63 ± 6</td>
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<tr>
<td>2A/4</td>
<td>el 90075</td>
<td>R-913809</td>
<td>73 ± 10</td>
<td>39 ± 5</td>
</tr>
<tr>
<td>2A/7</td>
<td>el 90076</td>
<td>R-913810</td>
<td>73 ± 10</td>
<td>41 ± 5</td>
</tr>
</tbody>
</table>

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![Fig. 12. Inferred correlations of ice-free versus ice-covered conditions between Skorgenes and the Skjonghelleren cave with dates obtained at the two sites. Boundaries between events are not synchronous. The stratigraphy of Skjonghelleren was reported by Larsen et al. (1987) and Larsen & Mangerud (1989).](attachment:image_url)
Glacial history

The deposition of unit 1 marine sediments up to 50 m asl (Mangerud et al. 1981a; Larsen et al. 1987), probably during deglaciation of the previous glaciation, to account for the high sea level. This age estimate is supported by the interpretation given for the overlying till.

The lower till unit (2) was deposited during a large-scale glaciation, as indicated by ice flow independent of topography towards the NNW (Fig. 4). The age of this unit cannot be confidently established from the obtained TL and OSL dates below and above, but we suggest that this glaciation corresponds with the glaciation recorded by beds I and J in the Skjonghelleren cave on the outer coast (Fig. 12; Larsen et al. 1987). Based on palaeomagnetic correlations of the beds in Skjonghelleren with the Lachamp-Olby excursion (Larsen et al. 1987; Løvlie & Sandnes 1987), this would suggest that the unit is a little older than 40 ka.

Based on the obtained TL and OSL ages the absolute age of unit 1 is as problematic (Fig. 12). Both samples for TL dating (Table 2) had long age plateaus, and the TL ages are considered reliable. The two ages nearly overlap within one standard deviation, and the best age estimate for the unit would be the mean value of 57 ± 6 ka. The OSL date (Table 2) was based on four measurements, one added-dose (28.5 ka) and three regeneration (28.8, 28.3 and 27.8 ka). The mean value of the four results is 28.4 ka with a standard deviation of 1.4%. The OSL age is, therefore, well defined. There is thus a real discrepancy between the TL and OSL ages, and the significance of this is unclear at the present time. If it is correct, as concluded above, that both till units represent separate, regional scale glaciations interrupted by an interstadial, the OSL dates must be too young. The two TL dates may be approximately correct as the inferred correlations with the cave Skjonghelleren suggest (Fig. 12), but this contention cannot be tested further at present. We will, however, reiterate that these TL dates were performed on sediments deposited as subaqueous mass flows as opposed to the foreset beds dated further up sequence.

According to Mejdahl (pers. comm. 1991) it is unusual to find such large discrepancies between TL and OSL ages (Table 2). It was found important, however, to include both sets because such differences might contain information that may be possible to interpret as more experience with the OSL method accumulates. We would also like to point out that sampling for TL and OSL in the uppermost delta (unit 7) and the underlying delta (unit 4) was done in sedimentologically very similar foresets, so that obtained ages of the delta with known age (ca. 12 ka) could be compared with obtained age of the underlying delta. Unfortunately, this sedimentological approach did not ensure sampling of sediments with similar exposure to light during deposition, as indicated by both TL and OSL dates.

Glacial history

The deposition of unit 1 marine sediments up to 50 m asl may indicate an isostatic depression caused by a pre unit 1 glacier advance over the area. This being the simplest explanation for this high sea level stand. If the high sea level was caused by a preceding glaciation, this could correlate to the glaciation evidenced by bed L in Skjonghelleren (Fig. 12; Larsen et al. 1987; Larsen & Mangerud 1989). The bed in Skjonghelleren is undated, but regional correlations (Larsen & Sejrup 1990; Mangerud 1991) suggest a Lower Weichselian age.

The unit 1 sediments are all proglacial. At least the upper part was deposited in front of an advancing glacier and thus reflects the end of an interstadial. Erosional contact between the uppermost gravel and underlying sand could indicate a major hiatus, but the overall appearance of the succession suggests rapid sedimentation. High sea level towards the end of the interstadial may indicate that it was rather short-lasting, or deglaciation was restricted, since crustal compensation was incomplete, given the high sea level stand was caused by a preceding glaciation. However, this poses problems with regard to regional correlations; the most likely correlation being with a Lower Weichselian interstadial during which extensive deglaciation of the entire Scandinavia is inferred (Olsen 1988; Larsen & Sejrup 1990; Mangerud 1991). Considering both the uncertainty in absolute age and the assignment of the sediments to the end of an interstadial, we will not speculate further, except to mention that this may be a hitherto unrecognized interstadial.

The lower diamicton (unit 2) clearly indicates a large, regional glacier overriding the area. If the correlation with Skjonghelleren is correct (Fig. 1), the glacier extended at least to the outermost coast. Near the base of the unit a regional ice movement towards NW is recorded, whereas N to NNE ice movement is recorded further up section (Fig. 4, fabrics 1–3). The latter ice movement direction probably reflects influence by local topography due to thinning of the ice during deglaciation. This contention is supported by the clastic dikes related to the N–NNE ice movement direction, since such dikes are easiest explained as forming in a near margin position (Larsen & Mangerud in press). Thus, the lower part of the till unit, where abundant rip-ups, erosion and regional ice flow are evident, reflects deposition when the ice margin was at or beyond the coastline, whereas the rest was deposited during deglacial stages. In this way, the large thickness of the unit may be explained in terms of near margin deposition during deglaciation, possibly caused in part by accumulation on the lee side of a near-by bedrock knob.

The subsequently deposited delta sequence (units 3 and 4) was most likely fed by water from an ice lobe in Skogedalen, similar to what occurred during the last deglaciation. This delta indicates a relative sea level at the start of this interstadial of at least 84 m asl, and is comparable to the Upper Weichselian marine limit of 90 m asl. If this delta was deposited during the Ålesund interstadial, as inferred above, this is the first sea level
observation from that period. The extent of deglaciation and the duration of the Ålesund interstadial is unknown. So far this site is the innermost location on the west coast with possible Ålesund interstadial sediments.

As discussed above, the upper diamict unit (5) was most likely deposited by the ice that reached the Weichselian maximum extent. However, all ice movement directions deduced from fabrics in this unit may be explained in terms of thin ice influenced by topography. Only the orientation of thrust faults indicates a regional ice flow direction to the NW. Thus, it may be inferred that most of the unit was deposited during deglaciation.

The three uppermost units (6, 7 and 8) comprise a delta deposited up to the marine limit (90 m asl) during the deglaciation after the Weichselian maximum. This delta was deposited by water from an ice lobe in Skorgedalen as evidenced by the dip of the strata, glacial striations up-valley from the site (Henningsen & Hovden 1984), and the style of deglaciation of the area (Larsen et al. 1991).

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References