Weichselian stratigraphy and palaeoenvironments at Bellsund, western Svalbard

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A coastal cliff facing the ocean at the west coast of Spitsbergen has been studied, and seven formations of Weichselian and Holocene age have been identified. A reconstruction of the palaeoenvironment and glacial history shows that most of the sediments cover isotope stage 5. From the base of the section, the formation 1 and 2 tills show a regional glaciation that reached the continental shelf shortly after the Eemian. Formation 3 consists of glaciomarine to marine sediments dated to 105,000-90,000 BP. Amino acid diagenesis indicates that they were deposited during a c. 10,000-year period of continuous isostatic depression, which indicates contemporaneous glacial loading in the Barents Sea. Foraminifera and molluscs show influx of Atlantic water masses along the west coast of Svalbard at the same time. Local glaciers advanced during the latter part of this period, probably due to the penetration of moist air masses, and deposited formation 4. A widespread weathering horizon shows that the glacial retreat was succeeded by subaerial conditions during the Middle Weichselian. Formation 5 is a till deposited during the Late Weichselian glacial maximum in this area. The glaciation was dominated by ice streams from a dome over southern Spitsbergen, and the last deglaciation of the outer coast is dated to 13,000 BP. A correlation of the events with other areas on Svalbard is discussed, and at least two periods of glaciation in the Barents Sea during the Weichselian are suggested.

The present-day understanding of the Late Quaternary palaeoclimate of the Northern Hemisphere is based on the geological record from deep-sea cores, the continental shelves, and stratigraphical sequences found on land. Although the main pattern of glacial/interglacial cycles is correlated between mid- and high latitudes, and from east to west, a less detailed picture exists of the dramatic palaeoclimatic changes that occurred within each cycle. In particular, little is known of the growth and decay of ice-sheets, and glacial margin fluctuations that reflect changes in oceanic and atmospheric circulation as well as sea level.

The purpose of this paper is to present a study from a section with glacial and marine sediments of Weichselian age, and to contribute to the understanding of the glacial development of Svalbard during the last glacial cycle. Even though this archipelago is situated at a high latitude, it is sensitive to climatic changes as it was reached by Atlantic water during periods of oceanic circulation similar to that of the present day (Fig. 1). Many of the key sections where the Quaternary stratigraphy of Svalbard is preserved were studied several decades ago (Lavrushin 1967, 1969; Semevik 1967). However, the introduction of better dating methods and lithostratigraphic techniques has led to a reinvestigation of many of these areas (e.g. Boulton 1979; Lindner et al. 1983; Miller 1982; Miller et al. 1989; Fæling-Hansen & Ulleberg 1984; Landvik & Salvigsen 1985; Lonne & Mangerud 1991; Mangerud et al. 1992; Mangerud & Svendsen 1992).

At the south shore of Bellsund there is a large section of Quaternary sediments at the bay of Skivika (Figs. 1 and 2). A 1000-m-long and up to 42-m-high section in the eastern part of the bay is formed by coastal erosion of the underlying low-consolidated Tertiary bedrock, while a 700-m-long section to the west is underlain by more resistant metamorphic Hekla Hook rocks and exhibits less fresh exposures (Fig. 2).

The sections and mollusc fauna have been described previously by Semevik (1967). Sim-
Fig. 1. Map showing the central part of Spitsbergen and the main localities mentioned in the text. Shaded areas are covered by glaciers. The insert shows the position of Svalbard and the present-day surface circulation with warm currents (solid lines) and cold (stippled lines) (after Miller et al. 1989).

plified stratigraphies, including some dates, have been presented by Troitsky (1975), Troitsky et al. (1979) and Punning & Troitsky (1981). Some amino acid data were given by Boulton et al. (1982) and the foraminiferal stratigraphy was described by Łużinska (1974) and Lycke et al. (1992). A synthetic profile of the deposits in the area, including several thermoluminescence (TL) dates, was presented by Pekala & Repelewska-Pekalowa (1990).
We have carried out detailed field studies on these sections during the period from 1983 to 1985, and propose new interpretations of the formation and age of several of the sedimentary units. A history of glaciation in the Barents Sea during the Early Weichselian is proposed.

Methods

Horizontal distances were measured from a zero point where the high tide reaches the bedrock cliff at Renardodden, and locations along the section refer to metres from this point (Fig. 3). Excavated sites were numbered in roman numerals (see Fig. 3). The sections are characterized by laterally continuous lithological units which we have divided into informal formations, named formation I to formation 8 (Figs. 3 and 6). The sediments exhibit several sedimentary facies (Walker 1984). Different facies are found in vertical and lateral successions, and will be discussed in stratigraphic order.

Till fabric analyses were performed on the diamict units. Clasts with the longest axis between 2 and 6 cm, and a/b axis ratio >2, were measured. The results have been plotted on a Schmidt net, lower hemisphere, and as mirror image rose diagrams by a computer program, which also calculated the statistical parameters (e.g. Fig. 4).

The foraminiferal stratigraphy (Fig. 6) through the sequence has been presented in detail by Lycke et al. (1992). In the present paper we use these results in our interpretation of the geological history. The Foraminifera were grouped into four assemblage zones, which generally coincide with the boundaries of the lithologic formations described below. A molluscan zonation (Fig. 7) is based on both identification and counting in the field, and on bulk sediment samples brought to the laboratory.

Amino acid diagenesis on molluscan shells was used to obtain age estimates, detect possible hiatus, and estimate the duration of the ice-free
periods. We use the epimerization of isoleucine to alloisoleucine in *Mya truncata* and *Hiatella arctica* (Miller 1982). The analytical procedure follows Miller & Mangerud (1985). The results are expressed as the alle/Ile ratio in the total fraction (Fig. 13). For most stratigraphic levels, three or more samples were analysed. The individual analyses were presented by Bolstad et al. (1992).

The thermoluminescence (TL) dates were produced at the Nordic Laboratory for Thermoluminescence Dating, using the plateau method (Mejdahl 1988) and assuming a water content of 14%. An underestimate of the water content to, for example, 2% would reduce the ages by only 4% (Mejdahl 1991). However, recent studies (Mejdahl et al. 1992) suggest that the ages may have been underestimated because sediments absorb more irradiation under laboratory conditions than in nature. Such an underestimate may explain why assumed Eemian deposits (125,000 BP) from Denmark obtained TL ages of 80,000–90,000 BP (Mejdahl et al., 1992).

**Description of the sections:**

**Formations 1 and 2 (tills)**

*Description.* – The two diamictons interpreted as subglacial tills are best exposed at the base of site III (50–60 m), but have also been studied between 400 and 600 m (Figs. 3 and 4).
Formation 1 is a matrix-supported diamicton with a matrix of poorly sorted, well consolidated, dark grey silt. Some sandy inclusions from the underlying bedrock occur. No boulders, and only scattered striated cobbles are found. Of these clasts, 80–90% are Hecla Hoek rocks and some are quartzitic sandstones. Abraded shell fragments, mainly thick-walled *Mya truncata*, *Hiatella arctica* and *Astarte* sp., occur throughout the formation.

At site III (0–100 m) formation 1 interfingers with formation 2, whereas at site VII (450 m) there is a 1.9-m-thick sediment lens at the boundary. The lens consists of tectonically deformed sand overlain by gravel with both sandy infill and openwork structure. The sorted character of the sediment indicates that it has been exposed to water action, while numerous striated clasts suggests a glacial origin.

At site III, formation 2 differs from formation 1 by its more light-grey coloured matrix, caused by less silt and clay and an increase in the gravel content. Shell fragments are found throughout the formation. At site IV, formation 2 has a higher silt content, and a higher content of cobbles and boulders, most with glacial striae. The petrographic composition resembles that of the underlying formation 1.
Till fabric. — Fabric analyses from two sites show a remarkable correspondence (Fig. 4). The stereographic plots supported by the rose diagrams show a preferred orientation, initially towards the NW followed by WNW in formation 1. From the symmetry of the plots we assume the long axes to be parallel with the ice movement, and thus that ice streams ran across the mountain area between Recherchefjorden and Van Keulenfjorden (Fig. 1). This interpretation is strongly supported by the close correspondence between till fabrics at the same stratigraphic levels at the two sites, which are 400 m apart (Fig. 4).

Till fabrics at the base of formation 2 (Fig. 4) show a slightly more northerly direction than the uppermost one in formation 1. The analysis in the middle of the formation at site III demonstrates a transitional movement towards the north (i.e. out Recherchefjorden), which grades into a NE movement from the local glacier Scottbreen. The clasts in the middle analysis have a maximum dip towards the north. Assuming an up-glacier dip, this would imply a glacier coming directly from Bellsund. However, this is the least likely direction of ice movement at the site.

Interpretation. — We interpret the two diamictons as subglacial tills and the till fabric as showing ice-flow directions towards the NW and WNW during deposition. This flow direction indicates that the glacier extended to the shelf west of Svalbard (Fig. 1). Formations 1 and 2 are the only units in the section that show such an extensive glaciation. We consider it most likely that the tills were deposited during different phases of the same glaciation, even though the possibility that they represent two glaciations cannot be excluded.

Formation 3 (marine silt and sand)

Formation 3 is the most extensive unit within the sections and can be traced everywhere, except between 150 and 450 m (Fig. 3), where formation 5 till has discordantly cut the older strata. Detailed studies of formation 3 were carried out at sites IV and IX (Fig. 3), with careful reconnaissance between the sites. The altitude difference of 6 to 8 m within a distance of only 250 m gives an excellent opportunity for a three dimensional reconstruction of the depositional environment (Fig. 5).

The sediments of the formation can be divided into four rather broad facies which succeed each other both stratigraphically and laterally. In stratigraphic order, these are: pebbly silt, massive sand, cross-bedded sand, and cross-bedded gravel. The genetic interpretation of the sediments is closely linked to an understanding of the well-preserved coarsening-upward sequence at site IX (Fig. 5), which represents a complete prograding beach sequence (Harms et al. 1982).

Aided by the presence of the formation-4 bouldery beds, sediments correlated to formation 3 can also be found in the slumpcd sections in the eastern part of the Skilvika bay (Fig. 2). This correlation is supported by similar amino acid ratios (Bolstad et al. 1992: Table 1). At site XXIV (Fig. 2), a piece of whale rib 90 cm long was found in the sediment. Unfortunately, the rib was weathered and no collagen could be extracted for radiocarbon dating (S. Guliksen, pers. comm. 1990).

Pebby silt facies

Description. — This facies always occurs at the base of the formation, normally with a sharp boundary to the underlying till. At site III, however, the till and the pebbly silt are so texturally similar that only the presence of molluscs in living position within the latter can be used to locate its lower boundary. The sediment consists of a dark grey sandy silt containing dispersed subangular pebbles and some scattered cobbles. Several clasts are striated, and abundant molluscs in living position and shell fragments occur in the sediment. It includes beds with minor textural and structural differences. At sites IV and IX (Fig. 5) the beds A—E and A—C, respectively, belong to this facies. The fine-grained sediments drape the surface relief of the underlying formation.

Locally (i.e beds 3B and 3D at site IV, Fig. 5), thin diamicton beds are embedded within the pebbly silt. Amino acid analyses show that the shell fragments within the lower diamicton bed have a pre-formation-3 age, with alle/llc (total) as high as 0.207 (Fig. 14) (Bolstad et al. 1992). Despite their diamicton character, we are confident that they are not primary tills, but probably derived from stratigraphically underlying tills that have slid from higher topographic positions, or been transported by icebergs.
Fig. 5. Correlation and inferred sedimentary facies of formation 3 at sites IV and IX. Logs are shown at their correct altitudes.
Fractured, but well preserved, paired mollusc shells are found. The fauna is dominated by *Hiattella arctica* and *Nuculana pernula* and a total of 19 molluscan and gastropod species are present (Fig. 7).

**Interpretation.** - The pebbly silt is interpreted as a glaciomarine sediment. This is based on the high degree of deposition from suspension, the content of drop stones, several of them striated, and the position above a till. The foraminiferal assemblage is typical for shallow arctic and arctic-boreal water masses, and indicates moderate to high salinities and water depths of more than 5–10 m, possibly as much as 50 m (Lycke et al., 1992).
### Bivalves

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### Gasteropods

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**Fig. 7.** Mollusc stratigraphy at sites located in Fig. 1.
The mollusc *Chlamys islandica* indicates influx of warmer water. The influx of oceanic water masses is probably explained by the position of the site close to open ocean to the west (Fig. 1), and the deposition of the glacimarine mud may have occurred in an area at some distance from the retreating glacier.

**Massive sand facies**

**Description.** This facies constitutes homogeneous fine-grained sand with scattered pebbles. Thin beds enriched in gravel occur at the lower boundary, and at irregular intervals through the sand (Fig. 5). At both sites IV and IX, a series of thin pebbly beds occur in the lower part (Fig. 5). There are numerous molluscs in living position. This facies is found undisturbed from 450 to 1050 m (Fig. 3), being thicker at low altitudes. It interfingers with formation 4 where it is not overlain by other formation-3 sediments (i.e. site IV, Fig. 5). At Renardodden (0–200 m) (Figs. 2 and 3), the sand facies occurs only as glacitectonically displaced slices, mixed with sediments of the pebbly silt facies.

**Foraminifera and molluscs.** The *Astarton honigboreus* zone comprises the lower gravelly part of the sand facies, while the *Cassidulina reniforme–Elphidium excavatum* zone comprises the upper more homogeneous sand (Fig. 6). Throughout the sand facies, some very low percentages of boreo-arctic foraminifera were found (Lycke et al. 1992), and there are a greater number of species than in the underlying pebbly silt. The number of foraminifera per 100 g, however, declines markedly from the *Astarte borealis* and *Serripes groenlandicus*, which indicate water depths less than 30 m (Ockelmann 1958, Odhner 1915), and by the current-tolerant foraminiferal species *Cibicides lobatus* (Oxbry & Nagy 1981; Sturrock & Murray 1981).

Nutrient-rich, open sea conditions are indicated by the presence of the mollusc *Yoldia hyperborea* (Thorson 1934), which lives in the outer Isfjorden today but is not observed in the inner part. Also, the relatively high number of foraminiferal species and low dominance indicate penetration of saline water masses into Bellsund (Lycke et al. 1992). A high content of *E. excavatum* is typical for environments close to glacier fronts (Osterman 1982, 1984), and the upwards increase of this species is compatible with the progradation of a glacial system (formation 4) into the open sea environment.

**Cross-bedded sand facies**

**Description.** This facies comprises fine to medium cross-bedded sand. The sets are 0.5 m thick, medium to steeply inclined, and minor erosional scours occur. There are no signs of bioturbation but shell fragments are enriched in gravel horizons. The facies is well exposed in the uppermost part of formation 3 near site IX (Figs. 3 and 5), but it also occurs further west. The foraminifera and molluscs have not been studied in detail.

**Interpretation.** We postulate that the cross-bedded sand facies was deposited on the shoreface, below the wave base (Harms et al. 1982). This is based on the fine-grained character and large lateral extension of the sandy cross-bed sets. Erosional scours with lags of pebbles and shell fragments show sporadic high-energy conditions, probably storm induced.
**Cross-bedded gravel facies**

*Description.* - This is a clast-supported gravel with a matrix of coarse sand and small shell fragments. The gravel is subangular to rounded. The cross-beds alternate stratigraphically with 1–2-m-wide sandy lenticular beds containing very low-angle or subhorizontal lamination. The gravel cross-beds have a uniform dip of 10° to 15° within a 50° sector towards the south. Seaweed mats occur. The foraminifera and molluscs have not been studied in detail.

The facies occurs at site IX at 800 m (Figs. 3 and 5), where it was studied in detail. Between 800 and 1000 m, it interfingers locally with formation-4 sediments. In the western section, well-preserved sediments of this facies are found in the upper part of formation 3 (site XI, Fig. 2).

*Interpretation.* - The facies is interpreted to have been deposited in a foreshore environment, thus, close to the contemporaneous sea-level (Harms et al. 1982). This is based on the coarse-grained aspect, the angle and the uniform dip direction of the cross-stratification (Bourgeois & Leithold 1984), and the deposition of seaweed mats (Landvik et al. 1987).

**Formation 4 (bouldery diamicton)**

Formation 4 (Fig. 8) occurs throughout the eastern section, except between 150 and 450 m, where it is discordantly cut by the overlying formation-5 till (Fig. 3). It is also found in the upper part of the partly scree-covered cliffs of the western section and is well exposed at site XI (Fig. 2). The thickness varies between 4 and 10 m. The deposition of formation 3 and formation 4 was genetically related and the interpretation of their depositional environments will be dealt with together. Within formation 4, three different facies are distinguished, on the basis of clast composition and bed orientation.

**Bouldery foreset facies and sorted gravel facies**

*Description.* - The bouldery facies is a strongly bimodal sediment with dipping (20°–30° NW) strata of sandy gravel that contain boulders of mean diameter from 0.6 to 1 m and scattered boulders up to 2 m in diameter (Fig. 8). Boulder size increases with increasing dip. Most boulders are tabular and oriented parallel to the bedding surfaces. The larger clasts are mainly angular, while the smaller ones have a subangular character. As noted by Troitsky et al. (1979), nearly all boulders and gravel derive from the Hecla Hoek bedrock that make up the mountains immediately southwest of Skilvika, for example, underlying Scottbreen (Figs. 1 and 2). The foresets have a well-developed tangential lower contact and interfinger with individual sand laminae in formation 3 (Fig. 8).

The sorted gravel facies consists of sorted, sandy gravel with scattered cobbles and shell fragments. The beds dip at a low angle (10°–12°) in the same direction as the bouldery foresets.
The two facies alternate along the sections with their main occurrence between 500–800 m and 950–1050 m (Fig. 3). They can also be distinguished in the western half of the western section (Fig. 2).

**Foraminifera and molluscs.** — Fossils are found in the interfingering laminated sand which occurs as a transition between the bioturbated sand facies of formation 3 and the bouldery foresets of formation 4 (see above). The top of the *Cassidina reniforme*–*Elphidium excavatum* zone comprises the boundary foresets (Fig. 6) and this is the part where *C. reniforme* and *E. excavatum* f. clarata are most abundant (Lycke et al. 1992). Abundant molluscs are found in living position within the sand. The assemblage (Fig. 7) is dominated by *Macoma calcarea* and *Mysa truncata*. *Axinopsis orbiculata* and *Serripes groenlandicus* are also present.

**Interpretation.** — A marine depositional environment is concluded from the large-scale cross-bedding, the sorted gravel and the fossils present. The size of the boulders and the diamict character indicate a glacial sediment source, and the dip direction of the beds reflects deposition by a larger Scottbreen glacier (Figs. 1 and 2). The bouldery foreset-bedded sediment body show a considerable progradation, which can only have been caused by a glacial advance where the glacier overran the previously deposited foresets. The primary source for the boulders must have been rockfall from the mountain walls (Fig. 2) on to the glacier surface. An englacial transport explains the large number of angular boulders that have not been abraded during the glacial transport (Boulton 1978; Eyles et al. 1985).

We assume that the boulders avalanched periodically directly from the glacier snout and formed the foresets in the sea. The sorted gravel represents periods of less glacial deposition and marine reworking of the sediments in a foreshore or shoreface environment. The interfingering sand laminae probably suggest deposition by longshore currents and, thus, represent the normal background sedimentary environment which was interrupted by the blocky flows. Sea level during deposition must have been above the top of the foresets and the alternation with foreshore sediments indicates shallow depths.

The increase in the content of *E. excavatum* f. *clarata* is typical for environments close to glacier fronts (Osterman 1982, 1984). However, the high number of species (Fig. 6) and low dominance indicate open sea conditions during deposition at the site (Lycke et al. 1992). We conclude that this facies represents the advance of a local glacier, ancestral to Scottbreen, into a coastal marine environment with a longshore current system.

**Deformed diamict facies**

**Description.** — This facies was not studied in detail because of its inaccessibility. It comprises a silty sandy diamicton with scattered cobbles and boulders and its texture varies between matrix supported and clast supported. Irregular subparallel structures resulting from grain-size differences can be traced for tens of metres. The structures dip slightly towards the south, while locally they seem to be overfolded and thrusted. The clasts consists mainly of Hecla Hoek conglomerates.

This facies is found only in a near vertical outcrop at 0–100 m (Figs. 2 and 3) and it is separated from the rest of the formation-4 body by an erosional depression between 130 and 500 m (Fig. 3). The correlation across the depression is based on the altitude of the sediments, the stratigraphic position and petrographic composition.

**Interpretation.** — We see two possible genetic interpretations for this facies: either it is a subaqueous ice marginal deposit subjected to downslope gravity flows (Eyles et al. 1989) or a glacitectonically sheared sediment of glacial origin. Due to the paucity of observations, we are not able to differentiate between these two models. We can only conclude that the Scottbreen glacier, during formation-4 time, advanced to or beyond the present point of Renardodden (Fig. 2).

**A weathered horizon**

A careful search along the unconformity between formations 4 and 5 revealed an upper zone of formation 4 which we interpret as having been subject to pedogenic processes. The geochronological studies (see below) indicate that this unconformity represents a major hiatus. At site IV (Fig. 3) there is a sharp boundary between formation 4 and the overlying formation-5 till (Fig. 9). The uppermost 0.5 m of formation 4 consists of a clast-supported cobbly
gravel, with subrounded clasts. All clasts of the uppermost 0.2 m are fractured and shattered in situ. The conglomerate clasts are fragmented without any preferred zones of weakness being visible, while the shales are split along the bedding planes. Both the primary and secondary formed oblate particles are rotated to an almost vertical position, which we interpret to be the result of frost-related processes.

A continuous cover of carbonate precipitate (Forman & Miller 1984) occurs on the base of the clasts and its presence on the sides of sub-vertically oriented particles demonstrates reorientation after carbonate precipitation. The upper 15–20 cm of formation 4 is also characterized by both a vesicular silt matrix and the formation of silt bridges between the clasts. Forman & Miller (1984) classified carbonate precipitation and silt infiltration of open-work conglomerates as time dependant pedogenic processes. The rate of these processes is largely controlled by the source material, e.g. the local bedrock, and climate. Due to differences between the Bellsund region and Brøggerhalvøya, studied by Forman & Miller (1984), we cannot compare their age estimates directly. However, we find that the pedogenic products formed on the top of formation 4 are of the same order of magnitude as Forman & Miller (1984) described for the Holocene. This may indicate that a long period elapsed between the deposition of formations 4 and 5.

The weathered horizon is not found west of 800 m (Fig. 3). However, at the same stratigraphic level, at 1030 m (section XXI, Figs 2 and 3), there are lenses of a reddish-brown coarse sand, which contain shattered cobbles. Upwards, the weathered horizon grades into a dark grey, matrix-supported gravel with a vesicular sandy silt matrix. A content of 1.1% organic carbon is found in the matrix. The bed has a maximum thickness of c. 30 cm. The lower boundary is sharp, while the upper boundary is disturbed by reworking. All clasts are angular and shattered and some of them have completely disintegrated. They are of Heda Hoek origin and cobbles comprise more than 50% of the sediment volume. The bed is underlain by a 15-cm-thick homogeneous, gravely silty sand which contains the bouldery foreset beds of formation 4. This erosional boundary can be traced from 850 to 1050 m (Fig. 3) and, considering the total shattering of the clasts in the overlying beds, suggests a phase of terrestrial erosion and redeposition.

**Formation 5 (till)**

**Description.** – Formation 5 consists of a 0.5–1-m-thick diamicton that can be traced continuously from 30 to 550 m (Fig. 3). Further westward, only remnants of the diamicton have escaped littoral reworking during the Holocene regression. To the south (Fig. 2), a correlated bed is found in the Scottelva river section (sites XVIII and XIX, Fig. 2). The diamicton has a sharp lower boundary. It is mainly matrix-supported with a matrix of sandy silt to silty sand, and contains glacially striated pebbles and cobbles. At some sites the matrix colour grades from brownish grey in the lower part of the bed, to more brownish in the upper part. Petrographically, the bed is characterized by up to 50% rocks derived from the underlying Tertiary beds. The clasts are comprised of poorly consolidated sandstones and even striated stones of coal. Shell fragments are found throughout the bed. The diamicton drapes the gentle NNW–SSE oriented valley that is cut almost at right angles by the sections between 100 and 500 m (Figs. 2 and 3). Based on the texture, geometry and stratigraphic position of the formation, the diamicton is interpreted as a subglacial till.

**Till fabric.** – Several till fabric analyses (Fig. 10) show two main directions. In the lower part of the formation (sites VII, XIV, XVII and XXII, Fig. 10) there are very strong concentrations that show movement towards the NNW to N. There is a clear contrast between this direction and the movement towards the NW that is found at higher stratigraphic and topographic positions.
Interpretation - The till fabric, the high content of Tertiary rocks, which could only have been incorporated by the ice movement indicated by the fabric, and the orientation of the erosive valley draped by the till, show that the lower part of formation 5 was deposited by a glacier that drained out of Recherchefjorden, probably towards a calving bay in Bellsund (Fig. 1). In contrast, the top of the till was deposited from a local glacier situated in the same basin as the present-day Scottbreen (Figs. 1 and 2).

Formation 6 (clay)

Description. The formation consists of a well-laminated clay. The clay content (<2 μm) varies between 32 and 60%, the remaining sediment being silt. Scattered fine-grained gravel particles are found. Laminae are 2–10 mm thick (Fig. 11), and occur in sets of greenish grey and brownish colour, respectively, which can be followed for long distances. Generally, the laminae drape the lower boundary. The brownish sets are slightly more clay-rich and may contain tiny shells of Nuculana pernula (Fig. 7). The Foraminifera (Fig. 6) show a total dominance of Elphidium excavatum f. clava, reflecting an extremely stressed environment (Lycke et al. 1992).

The laminated clay conformably overlies formation 5 from site XVIII at Scottelva (Fig. 2) to site XXII at 500 m (Figs. 2 and 3), i.e. over a distance of 1200 m. The bed has a maximum thickness of 5 m in the depression at site XIII, and wedges out at the higher elevations towards the east and west (Fig. 3). Along its lower boundary, we searched for signs of a possible hiatus, but found only laminations draping irregularities of the underlying till surface.

Interpretation. As shown by radiocarbon dates of about 12,700 BP (Table 1), the bed must have been deposited immediately after the last deglaciation. The very high clay content, lack of dropped particles and sparse foraminiferal and molluscan fauna (Figs. 6 and 7) indicate a very low energy and ecologically severe depositional environment. Such an environment could be expected under yearly sea-ice cover, as suggested by Vorren et al. (1983) in their study of a sediment with the same textural characteristics in the fjords off northwest Norway. The ridge at Renardodden (Fig. 2) has been partly removed by coastal erosion. A previous extension into the bay may have contributed to a sheltered environment in the topographic depression where the facies is well developed.

Formation 7 (Holocene sand and gravel)

Separated from the formation-6 clay by an erosional contact (Fig. 3) is a formation grading from a thick-laminated yellow sand to a more homogeneous, bioturbated sand, with a sandy silt on top. All parts of this formation contain in situ molluscs. Locally, the sequence is capped by a thin, discontinuous beach gravel.

Fig. 10 Till fabric analyses within formation 5. At each site, the analyses are arranged in columns showing their stratigraphic order within the formation. Plotted as in Fig. 4.
Other sites

Site XXIII

At site XXIII (Fig. 2) is a section exposed in a gully cut into a Holocene beach ridge reaching 43 m a.s.l. The significance of the section lies in the ages obtained, which deviate from the dates in both the over- and underlying sediments (Fig. 12). A thin sandy bed with a TL date of 52,000 BP (Table 2) and an amino acid ratio of 0.027 on a shell fragment was found between a bouldery diamicton capped with a soil profile, which in the field can be correlated with formation 4 and the Holocene beach sediments. These analyses indicate a considerably younger age than those from formation 3 (see below). From the lithostratigraphy, the studied bed may have been deposited as a lower part of the beach ridge complex, which would imply that the shell fragments are deposited and the TL signal was not zeroed. However, similar ages were reported by Pekala & Repelewska-Pekalowa (1990) who obtained TL dates of 43,000 and 45,000 BP from sediments that overlie what we assume to be formation 4.

Chronology

The chronology of the sediment sequence is based on amino acid diagenesis, $^{14}$C and TL dates (Fig. 13). Both the radiocarbon dates and the amino acid ratios clearly divide the sequence into an older and a younger part.

Shells older than formation 3. – Amino acid ratios higher than those of formation 3 were obtained from shell fragments in the lowermost tills (formations 1 and 2) and from the thin beds of diamicton in formation 3 (Fig. 14). The glacier must have incorporated shells from older deposits. The presence of such old deposits in the area is confirmed in a section at the creek immediately south of Calypsoyen (Fig. 2), where sorted sand is overlain by a diamicton with glacially striated clasts. In the field the sand was assumed to be of formation 3 age, but amino acid analyses on Mya truncata gave 0.134 and 0.149 (Bolstad et al. 1992), which compare with the ratios obtained from the tills (Fig. 14).

Formation 3 and 4. – Most of the $^{14}$C dates show infinite ages (Table 1, Fig. 13). We obtained two finite dates of 47,500 and 43,600 BP from sites III and IX, respectively. Troitsky et al. (1979) reported $^{14}$C ages of 30,750 and 31,910 BP on mollusc shells from a unit which is clearly our formation 3. However, these are interbedded in the sequences with infinite ages, and we conclude that formations 3 and 4 are older than 50,000 BP.
Troitsky et al. (1979) also reported a TL date of 26,000 BP on quartz grains extracted from the unit we correlate with formation 4 and which interfingers with formation 3. We obtained four TL dates from formation 3 and 4 sediments (Table 2, Fig. 13). Three dates from formations 3 and 4 range from 89,000 to 105,000 BP, while a strongly deviant date of 169,000 BP (Table 2), obtained from the same level at site XXI (Fig. 2), is discarded. Pekala & Repelewska-Pekalowa (1990) reported similar TL dates from the area. The dates are located on a diagrammatic profile which can be compared with the stratigraphy presented in this study. Three dates from formation 3 sediments are in the range of 102,000–76,000 BP. However, taking into account a recent re-evaluation of the dating method (Mejdahl et al., 1992).
liblc /. Radiocarbon dates from Skilvika in stratigraphic order. Non-finite ages are given with two standard deviations. The samples are corrected for isotopic fractionation to -25 per mil \( ^{13} \text{C} \) PDB, and a marine reservoir age of 440 years (Mangerud & Gulliksen 1975) has been subtracted for all samples. The dates were performed at the Trondheim Laboratory (prefix T-) and the The Swedberg Laboratory, Uppsala University (prefix Ua). Mollusc species: Ha = Hiatella arctica. Mt = Mya truncata, Mc = Mactra edulis. Np = Nucula pernula.

<table>
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<tr>
<th>Laboratory no.</th>
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<th>Site</th>
<th>Fm/bed</th>
<th>Species</th>
<th>Comments</th>
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<td>84-576</td>
<td>10,260 ± 110</td>
<td>VII</td>
<td>7C</td>
<td>Ha</td>
<td></td>
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<td>7A</td>
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<td>6</td>
<td>Np</td>
<td>Slide at the base of Fm. 8</td>
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<tr>
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<td>VII</td>
<td>6</td>
<td>Np</td>
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<td>3M</td>
<td>Mc</td>
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<tr>
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<td>LAN 83280</td>
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<td>2100</td>
<td>III</td>
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<tr>
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<table>
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<td>4</td>
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<tr>
<td>R-882503</td>
<td>85-244</td>
<td>52 ± 10</td>
<td>XXIII</td>
<td>10% water</td>
<td></td>
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</table>

Table 2. Thermoluminescence dates from Skilvika.

Formation 6 to 7. - Several shells of Nucula pernula from the laminated clay in formation 6 (Fig. 13) were dated by the conventional radiocarbon method, whereas a single valve was dated by accelerator mass spectrometry (AMS) (Table 1). The dates average 12,700 BP, which is a minimum age for the last deglaciation. We conclude that deglaciation occurred in this area around 13,000 BP. This is supported by ages of 10,000-11,000 in the overlying formation 7 (Table 1, Fig. 13), suggesting that the deglaciation of Bellsund occurred earlier than in the Van Mijenfjorden basin to the northeast (Fig. 1) (Mangerud et al. 1992). No comparable amino acid analyses could be obtained from formation 6, as only Nucula pernula and Pecten groenlandicus were found. In all, 20 analyses on fragments from a slide deposit at the base of formation 7 (Bolstad et al. 1992) yielded a mean allele ratio of 0.16 ± 0.03 (Fig. 13). The shells were \(^{14} \text{C} \) dated to 11,230 BP (Fig. 13, Table 1). This is equal to the allele ratio reported by Mangerud et al. (1992) for shells of molluscs that lived in the area shortly after the deglaciation. A slightly lower mean ratio (0.14 ± 0.004) was obtained from 19 analyses from formation 7, and this compares with the \(^{14} \text{C} \) date of around 10,000 BP (Fig. 13, Table 1).

Discussion and correlation with other Svalbard sites

A glaciation curve for Spitsbergen and the Barents Sea, as suggested from the Skilvika sec-
We will here discuss the glacial history and the correlation with other stratigraphic records from Svalbard and the adjacent Fram Strait.

**Formation 1 and 2 glaciation: regional ice advance**

Formation 1 and 2 tills were deposited by the only regional ice advance positively recorded in...
this sequence. The ice flow was topographically independent and we assume that the western ice-margin was situated at the shelf edge. The age of the tills can be estimated only from the age of the overlying formations 3 and 4. From the correlation (see below) of formation 3 to the Early Weichselian interstadial episode B on Brøggerhalvøya (Fig. 1) (Miller et al. 1989), it follows that formations 1 and 2 are younger than the last interglacial. Thus, the formation 1 and 2 glaciation is bracketed between the Eemian and the onset of formation-3 deposition (Fig. 15), TL dated to 105,000–90,000 BP.

Miller et al. (1989) found an extensive ice advance early in their episode B, which they interpreted to have occurred late in isotope stage 5. From Kapp Ekholm (Fig. 1), Mangerud & Svendsen (1992) reported a glacial advance that occurred immediately after the Eemian interglacial. A topographically independent glacier over Skilvika must reflect such a large ice-cap over Spitsbergen so that the Kapp Ekholm site was overrun at the same time. If a correlation is correct, the amino acid ratios at Kapp Ekholm indicate a very short-lived glaciation (Mangerud & Svendsen 1992).

Sediment cores from the Fram Strait (Fig. 1) have been analysed with respect to input of ice-rafted detritus (IRD) during the last 130,000 years (Hebbeln 1992). The major IRD input was probably triggered by glacial advances on Svalbard. No peak of IRD was found in isotope stage 5 (Fig. 15), which indicates that glaciers did not reach the west coast of Svalbard during this time (Hebbeln 1992). At Skilvika, however, we show that the formation 1 and 2 glaciers did reach the coast during an extensive ice advance, and the lack of IRD in the cores is thus enigmatic. A possibility that formations 1 and 2 represent a pre-Eemian glaciation exists, but so far cannot be supported by our data.

Formation 3 interstadial: open marine conditions

From our data, we propose an Early Weichselian age for formation 4, even though an Eemian age cannot be completely ruled out. Neither the foraminiferal (Lycke et al. 1992) nor the mollusc fauna requires sea-surface temperatures as warm as at present. Sejrup & Larsen (1991) suggest that a biostratigraphical distinction between interglacial and interstadial periods at this latitude may be difficult. The foraminiferal assemblage and its high abundance in the lower part of the sequence (Fig. 6) suggests relatively open and saline conditions, while the foraminifera in the transition to formation 4 indicate less stable water masses with more variations in temperature and salinity. This reflects conditions similar to or slightly colder than today, and does support an interstadial age for the sediments (Lycke et al. 1992). However, an interglacial age cannot be excluded as the raised sediments must have been formed during isostatic depression and they probably do not represent the interglacial climatic optimum.

Based on the three consistent TL dates (Table 2), we suggest, as a first approximation, that formations 3 to 4 were deposited somewhere between 105,000 and 90,000 BP. This is supported by three dates in the range of 76,000–102,000 BP, obtained for the same sediments by Pekala & Reposewska-Pekalowa (1990).

The mean aHe/Ile ratio of formations 3 to 4 is 0.037 ± 0.08, which lies between the mean ratios of episode B (0.031 ± 0.003) and C (0.044 ± 0.004) at Brøggerhalvøya (Miller et al. 1989). One should expect to find time-equivalent sediments in both areas, as the sequences are found at approximately the same elevations, and the areas lie on the same isobase with respect to the last glaciation (Forman 1990). Episode C is correlated with the Eemian, whereas episode B is assumed to be of late isotope stage 5 age (Miller et al. 1989). As there are no conclusive indications that the sediments at Skilvika are of interglacial age, we propose a correlation between formation 3 and episode B at Brøggerhalvøya. Episode B was the first ice-free period after the last interglacial, and, like formation-3 deposition, it succeeded an extensive glacial advance. The small difference in amino acid ratios may be explained by different effective diagenic temperatures due to differences in the local glacial history.

The most probable correlative unit at Kapp Ekholm is formation D (Mangerud & Svendsen, 1992), which represents the first marine episode after the last interglacial. However, this correlation, also proposed by Mangerud & Svendsen (1992), ignores the higher mean aHe/Ile ratio of 0.063 of formation D at Kapp Ekholm.

The duration of the formation-3 ice-free period was probably less than 18,000 years and perhaps closer to 10,000 years. As indicated by the sea-
level curve (Fig. 15), a high relative sea level persisted from the time of deglaciation, during the whole interstadial period, and during the formation 4 readvance. The isostatic adjustment after the late Weichselian deglaciation was very rapid (see Forman 1990). With a global eustatic sea level lower than present (Shackleton 1987), this high sea level can be explained only by isostatic subsidence due to continued glacial loading in the Svalbard or Barents Sea area (Fig. 15).

Formation 4 glaciation: local ice-advance

Formation 4 was deposited by a local advance of the Scottbreen glacier. As suggested above, it started c. 90,000 BP. We have no dates or amino acid ratios that constrain the duration of that glaciation (Fig. 15). However, there must have been enough time available to produce, transport and deposit the large volume of sediment in the prograding bouldery foresets.

The high relative sea level during the deposition of formation 3 to 4 (Fig. 15) indicates contemporaneous isostatic depression by glaciers over eastern Svalbard and the Barents Sea. Thus, this occurred at a time when Atlantic water masses reached the west coast of Svalbard. The growth of local glaciers, as recorded here, may thus reflect increased precipitation due to penetration of moist air masses north to this latitude.

The glacial retreat was followed by a period of low relative sea level and subaerial weathering at Skilvika. Sea level must then have been below c. 20 m above the present and, by comparison with the studies of Forman & Miller (1984), the duration of the weathering could have been as long as the Holocene interglacial, i.e. about 10,000 years.

A Middle Weichselian isostatic event?

The indications of a marine event at c. 50,000 BP at site XXIII (Fig. 12) comply with the 40,000–50,000-year-old raised marine formation B at Kapp Ekholm (Mangerud & Svendsen 1992). Such a high sea level during isotope stage 3 can be explained only by glacioisostatic loading. A glacial event at this time is also suggested by a peak of IRD (Fig. 15), probably derived from Svalbard, in the deep-sea cores from the Fram Strait (Hebbeln 1992).

Formation 5 glaciation: the Late Weichselian glacial maximum

The till (formation 5) shows that the Skilvika site was inundated by a glacier that flowed out of Recherchejorden (Fig. 10). An implication of the flow direction is that the glacier probably calved in the Bellsund basin. However, from a regional consideration, Mangerud et al. (1992) point out that this reconstruction may represent only a deglaciation phase. We find this suggestion reasonable, as continuous deposition without any phases of erosion is unlikely during the build up and retreat of a glacier.

Based on the dates in the overlying formation 6, a deglaciation at around 13,000 BP is inferred. The whole duration of the glacial advance, as shown in Fig. 15, is based on the time estimates presented by Mangerud et al. (1992). This glacial advance correlates with an IRD peak in the Fram Strait cores (Hebbeln 1992) (Fig. 15).

Sea-level change and glaciations in the Barents Sea

During the entire Weichselian, the eustatic sea level was significantly lower than today (Chappell & Shackleton 1986; Shackleton 1987). Thus, all parts of the sequences that reflect high relative sea-level stands must have been deposited during periods of glacioisostatic depression of the crust, as shown by the rebound after the last glaciation (see Forman 1990). Two alternatives are then possible: either a high sea level during the deglaciation of an overriding isostatically depressing glacier, or a high sea level due to persistent glacial loading in eastern Svalbard and the Barents Sea, possibly without any glaciers overriding the west coast of Spitsbergen.

Reconstructed sea-level changes. – The Scottbreen progradation into the sea at the end of formation-3 deposition is revealed by two sets of stratigraphic records which possess a considerable time-stratigraphic overlap: (1) the vertical sequence of formation 3, and (2) the lateral accretion of formation 4 from west to east.

By considering the lithofacies of the two formations, we have constructed a sea-level curve for the ice-free period (Fig. 15) which probably shows the correct trends with a precision of ±10 m.
The minimum sea level, immediately after deglaciation after the deposition of formation 2, is given by the uppermost occurrence of the pebbly silt facies at the base of formation 3. The general coarsening-upwards sequence of formation 3 (Fig. 5) may be explained either by a falling sea-level or an increased input of sediments due to the advancing glacier front. The foreshore deposits (Fig. 5) indicate a sea level close to 30 m a.s.l. during the final period of deposition of formation 3 at this site. The bouldery foresets on top of the foreshore indicate a relative sea-level rise during or before deposition of formation 4 (Fig. 5). The oldest beds of formation 4 were deposited up to at least 40 m a.s.l. (site XXI, Fig. 3). The lateral alternation between bouldery foresets and sorted gravel facies indicates that the rest of formation 4 was deposited at a sea level close to 30–35 m, before the deposit was overridden by the glacier. The total lack of any marine deposits below the post-formation-4 weathering horizon indicates a sea-level lowering prior to the final retreat of Scottbreen.

Barents Sea glaciations. - From this reasoning, the interpretations of the Skilvika sections indicate that eastern Svalbard and the northern Barents Sea were ice-covered at least two, maybe three times during the last interglacial/glacial cycle (Fig. 15).

1) During a continuous period of glaciation and high relative sea level from the last interglacial/glacial transition (118,000 BP) until c. 80,000 BP, i.e. during isotope stage 5.
2) During the Late Weichselian maximum between c. 20,000–13,000 BP.
3) Perhaps also during a period of high sea level which we have indications of at around 50,000 BP.

In the intervening intervals, other periods of glaciation could have existed without leaving evidence in the form of marine deposits associated with the relatively high sea levels. For example, during the period after 80,000 BP, the significant eustatic sea-level lowering (Shackleton 1987) may have compensated for any regional glacio-isostatic loading, so that no marine deposits were formed above present-day sea level.

The model outlined in Fig. 15 indicates that the northern Barents Sea was ice-covered during at least 40% of the Weichselian.

Conclusions

1) The sequence at Skilvika post-dates the last interglacial, and covers at least three Weichselian glacial advances.
2) Two extensive ice advances overran the site, the first one shortly after the last interglacial, the second during the Late Weichselian.
3) Most of the sediments were deposited during a period of influx of Atlantic water masses, coinciding with an ice-sheet over the Barents Sea. This period, dated to 105,000–90,000 BP, was followed by the growth of both local and Barents Sea glaciers, and was succeeded by eustatic sea-level lowering.
4) A long period of low relative sea level during the Middle Weichselian is suggested by weathering and soil development.
5) In all, the sequence reflects two, perhaps three, periods of glaciation of eastern Svalbard and the northern Barents Sea, and indicates that the northern Barents Sea was ice-covered during at least 40% of the Weichselian.

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References


Troitsky, L. S. 1975: Oldeneniye Spivbergena (Sval'bard). (The glaciation of Spitsbergen (Svalbard)). English translation in *Polar Geography and Geology 5,* 57–81.


