Glaciation development and interstadial sea-level on central Spitsbergen, Svalbard

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Above the marine limit in Gangdalen, Nordenskiöld Land, a 20 m thick sequence of unconsolidated sediments occurs. On the top of striated bedrock it is composed of a 2 m thick till bed, 15 m gravel interpreted to be deposited as a sandur, and another till bed on the top. A solifluction deposit is capping the section. Fabric analyses and erratics in the two tills indicate a similar development in glacial transport directions during the two glaciations, starting with a local glaciation which subsequently turns into a larger glaciation centred over the eastern part of Svalbard. Co-existence of different ice domes over Spitsbergen is suggested. The sandur was deposited during an ice free period with a sea-level 40–80 m higher than at present. The section is undated.

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Introduction

Glaciation models for Svalbard and in particular the Late Weichselian models have for a long time been heavily disputed. In recent years an extensive glaciation of the Barents Sea and Svalbard has been suggested by several authors (Schytt et al. 1968; Hughes et al. 1977; Grosswald 1980; Andersen 1981). Others quote a more limited glaciation of Svalbard and the Barents Sea (Salvigsen 1977; Troitsky et al. 1979; Boulton 1979a, b; Boulton et al. 1982; Salvigsen & Nydal 1981; Miller 1982).

Shoreline displacement curves from the eastern parts of Svalbard (Schytt et al. 1968; Salvigsen 1978, 1981; Jonsson 1983) and studies of sediment distribution and stratigraphy in the Barents Sea (Elverhøi & Solheim 1983) strongly indicate that a grounded Late Weichselian ice sheet existed in its shallow northern parts east of Svalbard. The main islands Spitsbergen and Nordaustlandet had a more extensive glaciation than that of today, probably with several local ice centres. However, large parts of the northern and western coastal areas were ice-free during the Late Weichselian maximum (Miller 1982; Salvigsen & Österholm 1982).

In this paper we present a lithostratigraphical study from a site situated above the late glacial marine limit on central Spitsbergen (Fig. 1). The stratigraphy shows the development of at least two regional glaciations and an intermediate ice free period with a relatively high sea-level. Taken into account other available data on pre-Holocene glaciations in adjacent areas, a model for the style of these glaciations is suggested.

Methods

Elevations within the studied section was levelled with a hand leveller. The elevation above sea level was determined by a Paulin altimeter which was brought from sea level into Gangdalen by helicopter on three occasions.

All directions are given in 360°. For till fabric studies 100 particles were measured within each stratigraphic interval of c. 20 cm. A computer programme after Kalkani & Frese (1980) modified by J. K. Michelsen, University of Bergen, was used for contouring (Fig. 4).

Grain-size analyses of material less than 19 mm were carried out by sieving on screens with whole ϕ-intervals. The fine fraction was analysed by the pipette method. Grain-size classes are according to Doeglas (1968), see Fig. 4, and all calculations were done by a computer programme modified after Myhre (1974). The fraction less than 2 mm is considered as matrix.

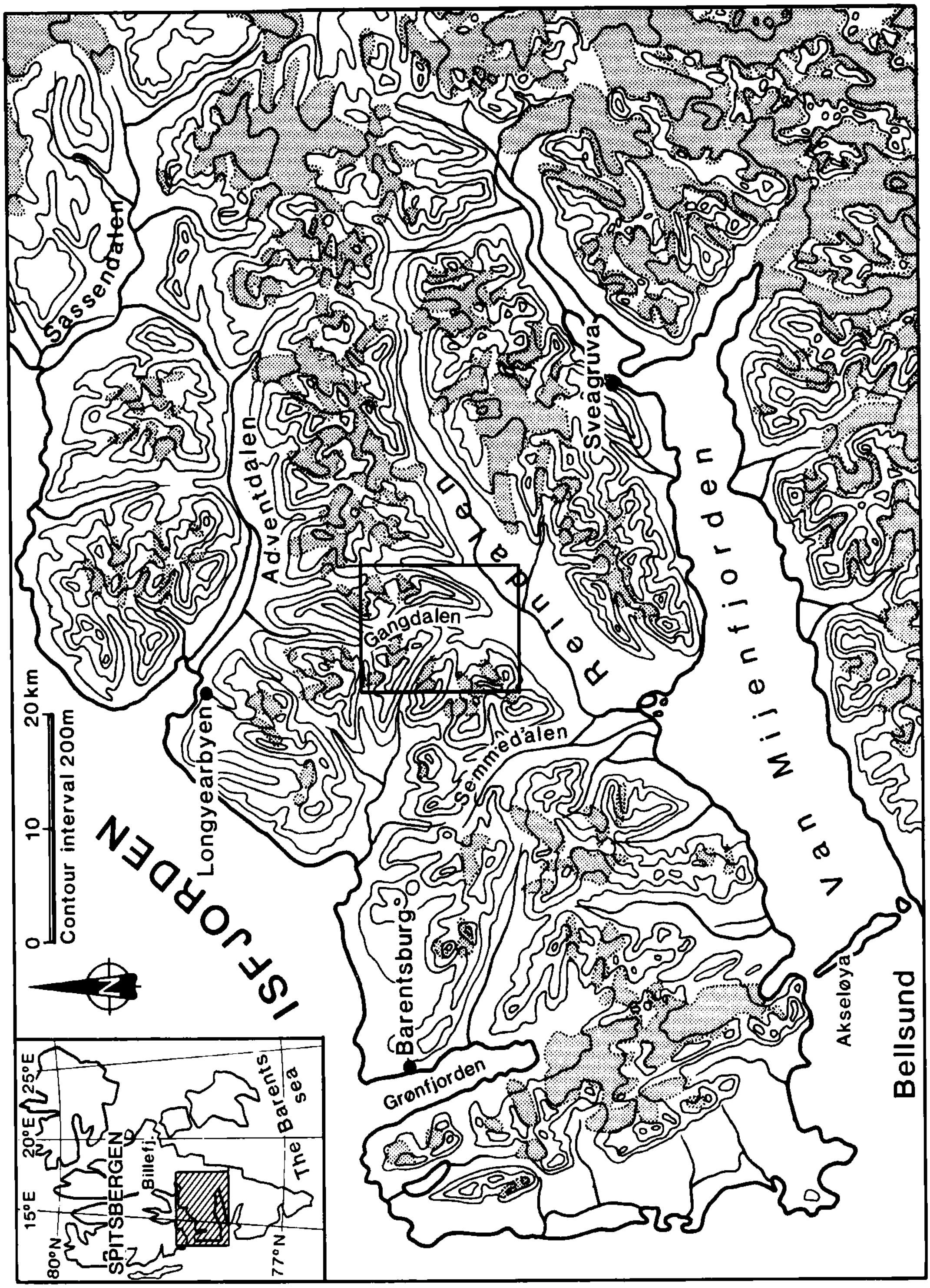

Fig. 1. Map of Nordenskiöld Land between Isfjorden and Van Mijenfjorden. Glaciers are shaded. Position of map in Fig. 2. inserted.

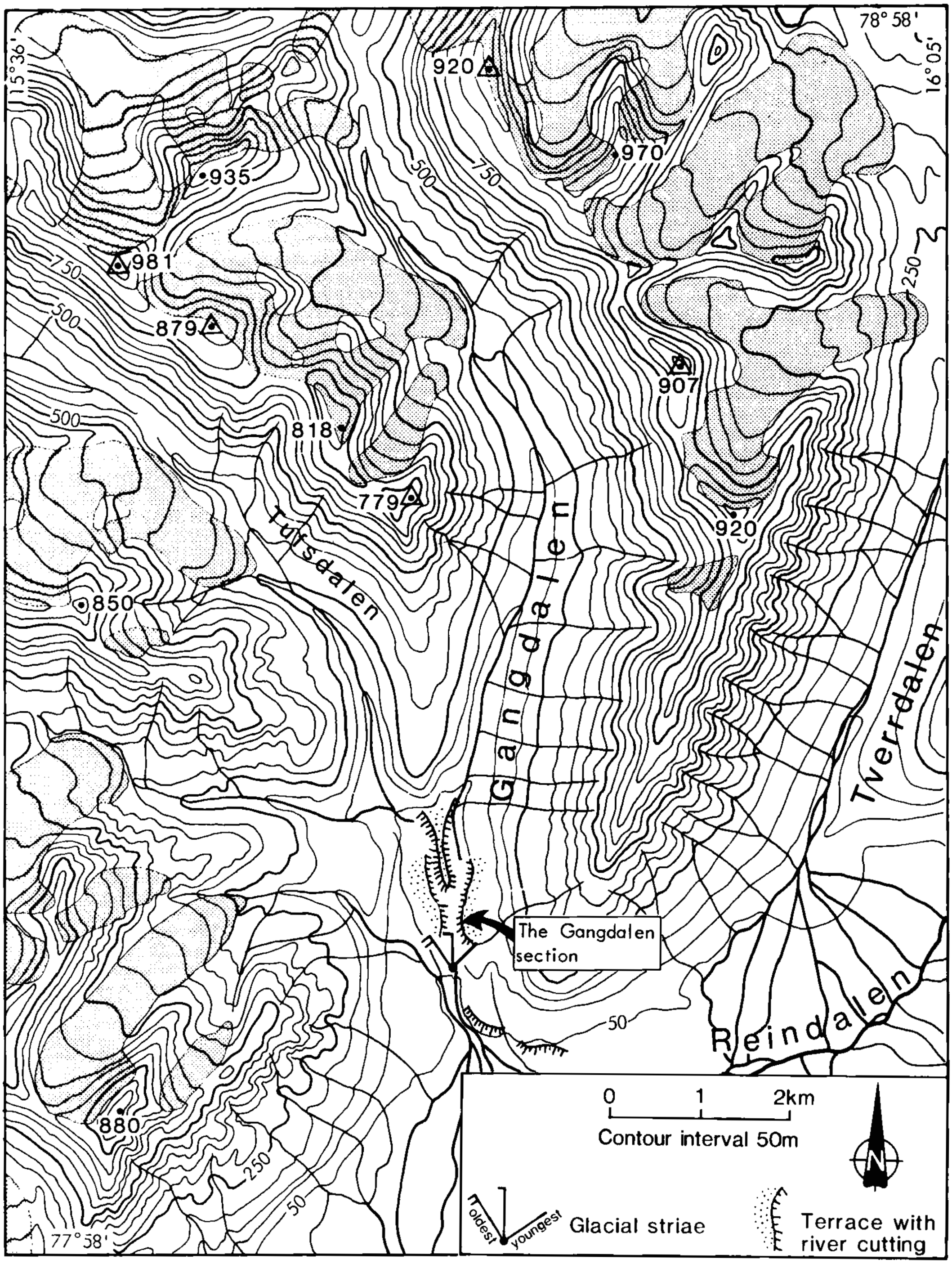

Fig. 2. Map covering the Gangdalen area. Glaciers are shaded. The described terraces, river cuttings and glacial striae are shown. For location, see Fig. 1.

The mean maximum particle size through the Gangdalen gravel was determined in the field by measuring the b-axis of the ten largest particles found within each bed.

For provenance studies pebble counts were carried out in the gravel fraction (Fig. 4). Three rock types from the Lower Palaeocene (Steel & Worsley 1984) are distinguished: a black siltstone from the local underlying Basilika Formation, a greenish to light grey sandstone from the Grumantbyen Formation, and a dark organic-rich silty sandstone from the Kalthoffberget Member (A. Dalland pers. comm. 1983). The Grumantbyen Formation has a wide outcrop all over the Central Tertiary Basin (Major & Nagy 1972), and this sandstone can therefore not be used to determine transport directions. The Kalthoffberget Member is developed along the southern margins of the basin (Steel et al. 1981) with significant outcrops both to the west and east of Gangdalen (Major & Nagy 1972). To the west the member outcrop along Grønfjorden (Steel et al. 1981), but a transport from there is highly unlikely and can be rejected. The presence of Kalthoffberget Member erratics (Fig. 4) thus indicates transport from the east.

Roundness analysis of the fraction 16–64 mm was performed in the laboratory using the method of Krumbein (1941).

Gangdalen

Gangdalen is a north-south tributary valley to Reindalen (Fig. 1), surrounded by mountains with maximum altitudes of 900–1000 m. Presently some mountain glaciers terminate in tributary valleys.

Only the southern part of Gangdalen north to the tributary valley Tufsdalen has been investigated (Fig. 2). This part of the valley is covered by relatively thick Quaternary deposits, and bedrock is found only near the river bed. Terraces of 25–30 m thick sediment units occur on both sides of the valley (Fig. 2). We assume that these terraces are erosional remnants and not ice marginal terraces as suggested by Semevskij & Shkatov (1965).

Due to solifluction processes the surface of both terraces is sloping 1°–2° towards the valley axis. The slope of the studied eastern terrace increases to 4° towards the river cutting (Fig. 3), suggesting some disturbance of the uppermost deposits.

The exposure in Gangdalen (Fig. 3) is due to active river erosion in the eastern terrace (Fig. 2). The general orientation of the section is 035° with a surface dip of 38° W, but several minor ravines cut into it. A 100 m long section between about 75 and 100 m above sea level has been investigated.

Lithostratigraphy

The following stratigraphy is found and the three most important units are given informal lithostratigraphical names (Figs. 3 and 4):

5. Solifluction deposit.
4. Gangdalen upper till.
3. Gangdalen gravel.
2. Gangdalen lower till.
1. Bedrock.

1. Bedrock and glacial striae

The Basilika Formation siltstone (Palaeocene) is eroded by the river at the base of the section (Fig. 3). The bedrock surface is in some places unweathered and nicely polished and striated. Crossing glacial striae with corresponding directions and age relationships were found at two sites, 23 m from each other. Striae towards 150° polish the surface and are cut by younger striae towards 165° (Fig. 5).

400 m to the southwest of the main section crossing glacial striae occur on bedrock underlying several metres of till (Fig. 2) corresponding in altitude to the Gangdalen lower till. The two directions mentioned above are also present here, but in addition they are cut by younger striae towards 210° (Fig. 2). Although not registered at the base of the Gangdalen section, we assume that the glacier movement towards 210° occurred also there.

The oldest striae suggest a valley glacier down Tufsdalen from the mountains in NW (Fig. 2), with a subsequent change into an ice movement topographically controlled by Gangdalen, and finally to a topographically independent ice movement towards SW. This shows that the glaciation started with glaciers in the local mountains growing into a larger ice-cap centred between Reindalen and Adventdalen (Fig. 1).

2. Gangdalen lower till

The bedrock is overlain by a c. 2 m thick diamicton interpreted as a basal till. The till surface

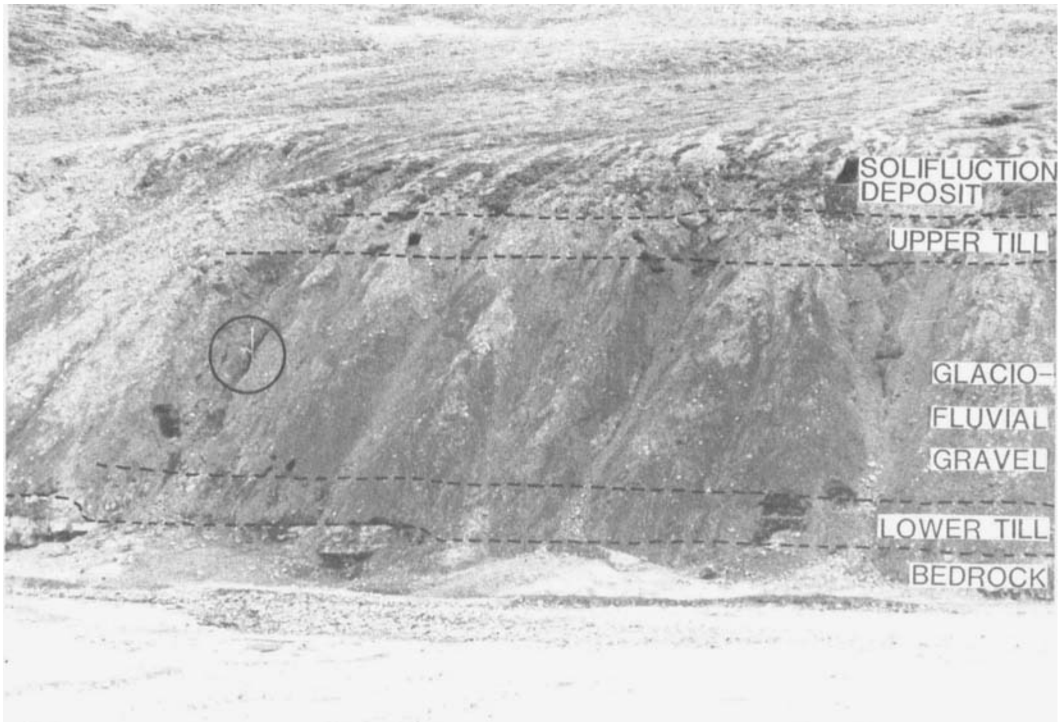

Fig. 3. The Gangdalen section towards the east. The levels of lithological boundaries are indicated. Vertical height of the river cutting is c. 25 m, note person as scale (circle).

is subparallel to the bedrock (Fig. 3), dipping 03° S. The bed is divided into three zones (Fig. 4) on the basis of colour and grain-size.

Zone A.—The lowermost c. 0.6 m is a loosely packed clast supported diamicton containing large stones in a porous grey silty sandy matrix. The cobbles are mainly subangular, and some of them seem to be frost cracked after deposition.

Zone B.—The stone content abruptly decreases, and there is a 0.5 m thick zone containing minor stones floating in a grey silty sandy matrix with some pores.

Zone C.—The uppermost 0.7 m shows an increase in the content of larger stones and a more greyish brown silty sandy matrix with some sorted pockets c. 10 cm in diameter. The roundness of the gravel fraction decreases (Fig. 4).

The gravel fraction through the whole till bed is dominated by sandstones while the underlying siltstone constitutes only 4–5% (Fig. 4). The presence of the silty sandstone (Kalthoffberget Member) indicates glacier movement from the east, which is also in agreement with the fabric analyses.

Fabric analyses were performed in zone B and zone C (Fig. 4) showing a rather high dispersion, but there is a concentration of 13–14% in the direction WNW-ESE. By means of maximum dip direction and supported by the erratic composition of the gravel fraction, we interpret the glacier movement to have been towards WNW. This movement was independent of the local topography and indicates a major ice sheet somewhere in the sector east to south of Gangdalen.

3. Gangdalen gravel

The Gangdalen gravel which is interpreted as a sandur deposit is resting on Gangdalen lower till (Fig. 3), with a discordant contact to the Gangdalen upper till. The thickness varies between 13 m and 15 m.

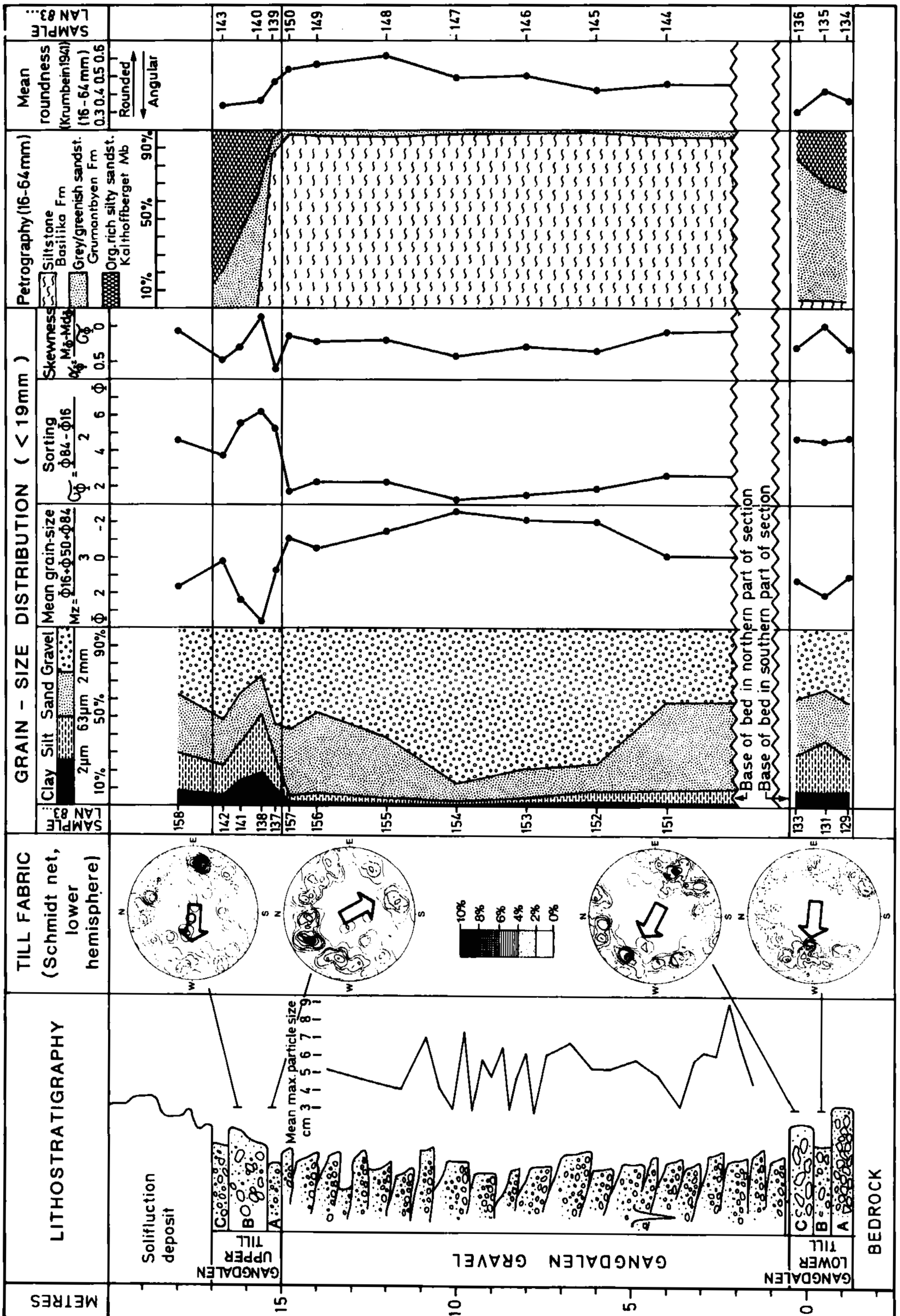

Fig. 4. Lithostratigraphy of the Gangdalen section showing observed and analyzed properties of the sediments. Open arrows indicate ice movements as inferred from till fabric and petrography.

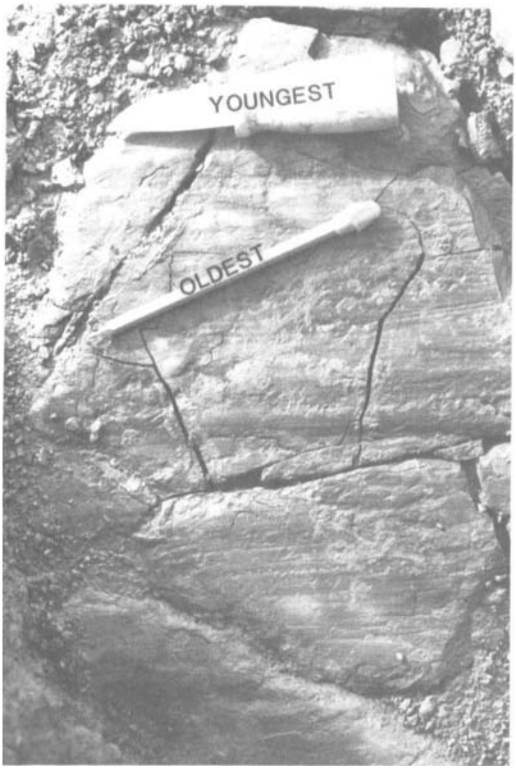

Fig. 5. Older (pencil) and younger (knife) crossing glacial striae on the siltstone bedrock newly exposed from the Gangdalen lower till. Ice movement from right.

Between the lower till and the gravel there is an about 10 cm thick zone of weakly laminated sandy clay which is lithostratigraphically included in the Gangdalen gravel. The clay is draping over stones in the top of the till and the overlying gravel particles are pressed into this sediment. As no soil occurs on the till, the clay is interpreted to have been deposited immediately after the deglaciation, and it indicates that there is no major hiatus between the till and the sandur.

The Gangdalen gravel consists of clast supported rounded gravel and stones derived from the underlying Basilika Formation siltstone (Fig. 4). The sediment shows an open structure with infilling of a sandy matrix, and c. 30 cm thick fining upward sequences dipping 14°–20° towards the sector south to west. In one place the uppermost 1.4 m of a wedge-shaped structure with vertically oriented longitudinal clasts was exposed. It cut the bedding and continued to an unknown depth in the permafrost (Figs. 4 and 6). It was overlain by primary deposited sediments and is interpreted to be an ice wedge cast formed during deposition of the Gangdalen gravel.

The many fining upward sequences reflecting waning flood pulses lead us to interpret the Gangdalen gravel to be of glaciofluvial origin. There are no signs of ice proximal features, and the cross bedding suggests that deposition occurred in longitudinal bars in a braided river some distance away from the glacier. The interpretation of bar development is also supported by the presence of the ice wedge cast which needs subaerial conditions to develop. Cross bed orientation shows current direction down the Gangdalen valley. The relatively stable level of flow competency suggested by the maximum particle size (Fig. 4) is in the upper part interrupted by frequent lowerings. At the same time there is an increase in pebble roundness (Fig. 4), probably resulting from more frequent resedimentation giving the particles a longer transport history. Both parameters indicate a reduction in glacier run-off and material input to the braided system. As the

Fig. 6. Upper part of the more than 1.4 m deep ice wedge cast in the Gangdalen gravel. Note the vertical orientation of elongated stones and the upper cutting by primary deposits. Length of scale is 0.5 m.

change from till to sandur deposition is interpreted as a deglaciation sequence, the change in these parameters is probably a result of continued glacier retreat. We therefore interpret the Gangdalen gravel to have been deposited in the initial part of an ice-free period.

We also conclude that the relative sea-level was higher than today. Studies of maximum particle size versus surface slope on recent sandurs (Boothroyd & Ashley 1975; Haraldsson 1981), indicate a surface gradient for the reconstructed sandur between 2 m/km and 8 m/km. If the sandur extended southward to the mid axis of Reindalen, these gradients indicate a sea level 40–80 m higher than present. The present river cutting of the deposits also suggests a higher base level than today during deposition of the sandur.

There are no signs that major river erosion occurred during the ice free period before deposition of the Gangdalen upper till, suggesting a high sea-level stand during the entire period. This can be explained by either an interstadial of short duration without full glacio-isostatic rebound, or the presence of larger ice masses in adjacent areas. Shoreline displacement curves from Spitsbergen show a very rapid initial uplift after the last deglaciation (Salvigsen 1984; Salvgisen & Österholm 1982), and the suggested high sea-level is most likely explained by glacio-isostatic depression of the land during an inter-stadial.

4. *Gangdalen upper till*

Above the subhorizontal unconformity to the sorted gravel (Fig. 3) is a c. 2.0 m thick diamicton which includes three zones different in lithology and colour (Fig. 4), all interpreted to belong to the same till bed.

Zone A.—Resting directly on the Gangdalen gravel is a c. 0.4 m thick zone with rounded local siltstone (Basilika Formation) pebbles supported by a greyish sandy matrix (Fig. 4). The petrographical composition, clast size and degree of roundness indicate high redeposition of sediments from the underlying sandur.

Zone B.—Upwards there is an abrubt change into a c. 1.3 m thick zone with a brown grey sandy silty matrix supporting the clasts. More than 30% of the clasts are larger than 2 cm and increase from pebbles to small boulders through the zone. The gravel fraction consists of sandstones from the Grumantbyen Formation and the Kalthoffberget Member only (Fig. 4), and some of the minor clasts reveal glacial striae.

Zone C.—Above a 10 cm thick stone lag there is a c. 0.4 m thick clast supported zone with 50–60% of the clasts larger than 2 cm, infilled with a blueish grey silty sandy matrix. As in zone B only sandstones are present (Fig. 4). The clast supported character makes this bed unsuitable for fabric analyses.

Fabric analyses were performed in the two lower zones (Fig. 4). Zone A shows a concentration of particles dipping towards NNW. The symmetry and degree of dip indicate a parallel fabric (Lindsay 1970), and thus a glacier movement towards SSE can be inferred. This is also supported by the local character of the gravel petrography and particularly the lack of the Kalthoffberget Member sandstones (Fig. 4).

The fabric in zone B is characterized by some scattered, very high dipping particles, but also a very strong maximum dip towards ESE (Fig. 4). This is a very clear change in orientation from the underlying zone, and coincides with the disappearance of the local siltstone and the marked entry of the Kalthoffberget Member sandstone (Fig. 4). Glacier movement towards WNW is thus inferred.

These conclusions lead us to interpret the Gangdalen upper till first to have been deposited by glaciers coming down the tributary valley Tufsdalen (Fig. 2). Ice movements subsequently turned into more regional topographically independent glacier movements originating from an ice centre ESE of Gangdalen. The change in till fabric and petrography seems to coincide with the sharp change in matrix colour, indicating an erosional or non-depositional hiatus between zone A and zone B. The possibility that intermediate sediments have been removed can therefore not be excluded.

5. *Solifluction deposit*

Above the upper till there is a change in lithology and a decrease in surface slope from 38° to 24° along the whole section (Figs. 3 and 4). A ditch revealed c. 3 m of a clast supported diamicton containing subangular stones (50%) and boulders (30%). Some of the larger boulders are striated and are obviously redeposited erratics. The matrix is a blueish grey silty sand showing a porous structure. Upwards there are some brown oxidation zones which are stretched out by the solifluction processes.

The solifluction deposit exposed is dependent upon the presence of the river cutting. Even if redeposition from a stratigraphically higher bed can not be excluded, the outer edge of the terrace represents a zone of accumulation and a downslope movement of only topographically higher situated sediments seems most probable.

Discussion

Geological history

The geological events interpreted from the Gangdalen section are as follows:

1. Deposition of Gangdalen lower till starting with glacier ice down Tufsdalen, and subsequently development of a local ice centre on Nordenskiöld Land coalescing with a major ice-cap to the east.
2. Deglaciation and deposition of Gangdalen gravel during a period of high relative sea level.
3. Deposition of Gangdalen upper till starting with local glaciers turning into a larger ice sheet.

Development of glaciation

The similarities of the two glaciations lead us to suggest a repeated three phases glaciation development:

Phase 1: Growth of local mountain glaciers protruding into the valleys.
Phase 2: Growth of local ice domes several places on Spitsbergen.
Phase 3: Coalescence of local ice domes with a major ice sheet over eastern parts of Svalbard.

A section showing alternating tills and marine deposits is found on Kapp Ekholm in Billefjorden NNW of the present study area (key map, Fig. 1) (Lavrushin 1969; Boulton 1979a; Troitsky et al. 1979). Boulton (1979a) recognized three tills each with petrographical composition showing local derived elements in the lower part corresponding to our phase 1, and more far transported elements in the upper part corresponding to phase 2. The age of the upper till is disputed (Mangerud & Salvigsen 1984), but we will only consider the lithostratigraphical observations.

We find it likely that at least one of the three tills at Kapp Ekholm are contemporaneous with one of the Gangdalen tills. As the topographically independent phase 3 movement is not registered at Kapp Ekholm, only a local ice dome may have existed on northeastern Spitsbergen when Gangdalen during earlier glaciations was overrun by phase 3 glaciers from the east. Local ice domes older than the Late Weichselian are also reported from northeastern Spitsbergen (Salvigsen & Österholm 1982) supporting the conclusion that Spitsbergen was influenced by several ice domes during the glaciations.

Timing and correlations

At present no glaciation of the entire Van Mijenfjorden area is dated. Westerly glacial striae at Akseløya (Mangerud et al. 1984a) demonstrate a regional glaciation that is a possible candidate for correlation to the Gangdalen upper till. Based on an apparent drop in the marine limit from the outside to the inside of Akseløya, Mangerud et al. (1984b) concluded that the last ice-front position at Akseløya could be dated to 11,000 years B.P. However, during field work in the summer of 1984, J. Y. Landvik and J. Mangerud (pers. comm.) found that the 11,000 year old shoreline possibly continued inside Akseløya. At present we therefore consider it unknown whether Akseløya and Van Mijenfjorden were covered by ice or not during the Late Weichselian.

Concerning the dating of the Gangdalen gravel, high relative sea-levels of pre-Late Weichselian age have been inferred from both raised beaches and sections on western and northern Spitsbergen (see Salvigsen & Nydal 1981; Salvigsen & Österholm 1982; Miller 1982). Radiocarbon datings on shells from these events have given finite ages between 22,000 and 44,000 years B.P., but the amino-stratigraphy suggests that these are minimum ages, and also that several older episodes of higher sea-levels exist (Salvigsen & Nydal 1981; Miller 1982). A firm correlation based on a high relative sea-level is thus impossible.

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