CHAPTER 4

THE SMALFJORD TILLITE AT VARANGERFJORD

4.1 Introduction

The Smalfjord Tillite at Varangerfjord consists predominantly of current-deposited sandstone and conglomerate, with tillite a minor constituent.

Six important outcrops of the formation crop out along the inner part of Varangerfjord (fig. 17), while inland to the west, several small patches of tillite a few centimetres thick rest on an outlier of basement and are overlain by the basal part of the Nyborg Formation.

In the following sections, the six outcrops are described, approximately from south to north. Bjørlykke's (1967) subdivision of the Smalfjord Tillite of the area into a lower Kvalnes Conglomerate and an upper Karlbotn Quartzite is not adequate for the complexity of the formation. The units presented here are informal, and are based on a limited amount of field work.

4.2 Sedimentology

4.2.1. Kvalnes

On Kvalnes Peninsula, on the south side of Varangerfjord (fig. 17), the basal unit of the Older Sandstone Series, the Veinesbugten Formation, is overlain by the Smalfjord Tillite which forms a northward-dipping back slope.

The relationships of the facies can be studied best along the eastern part of the Peninsula (fig. 18). The formation is divided into five units: A and B, tillites; C, interstratified conglomerate and sandstone; D, well-bedded sandstones with conglomerate channels and horizons, and E, interstratified conglomerates and sandstones.

Units A and B, tillites

Description

The salient features of unit A are shown in figure 19.

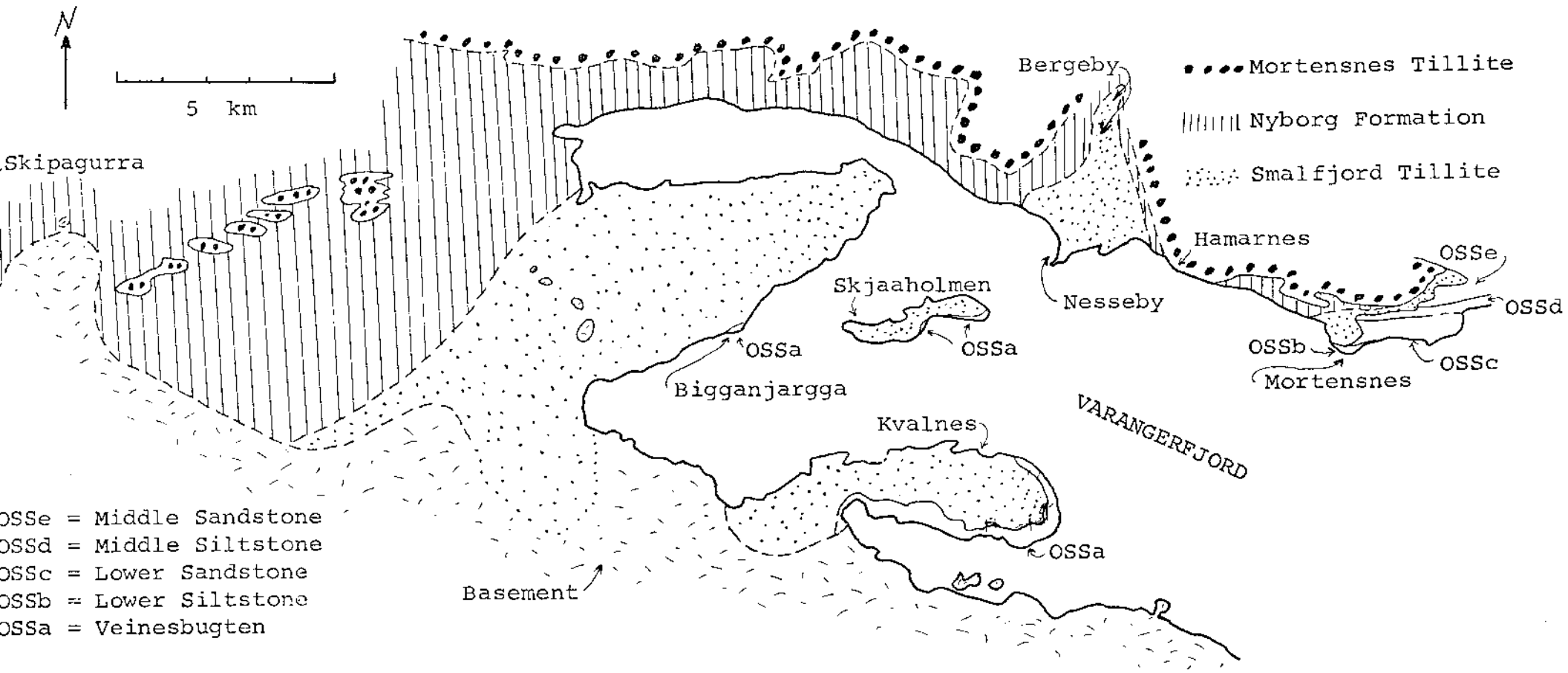


Figure 17. Geology of the area around the head of Varangerfjord.

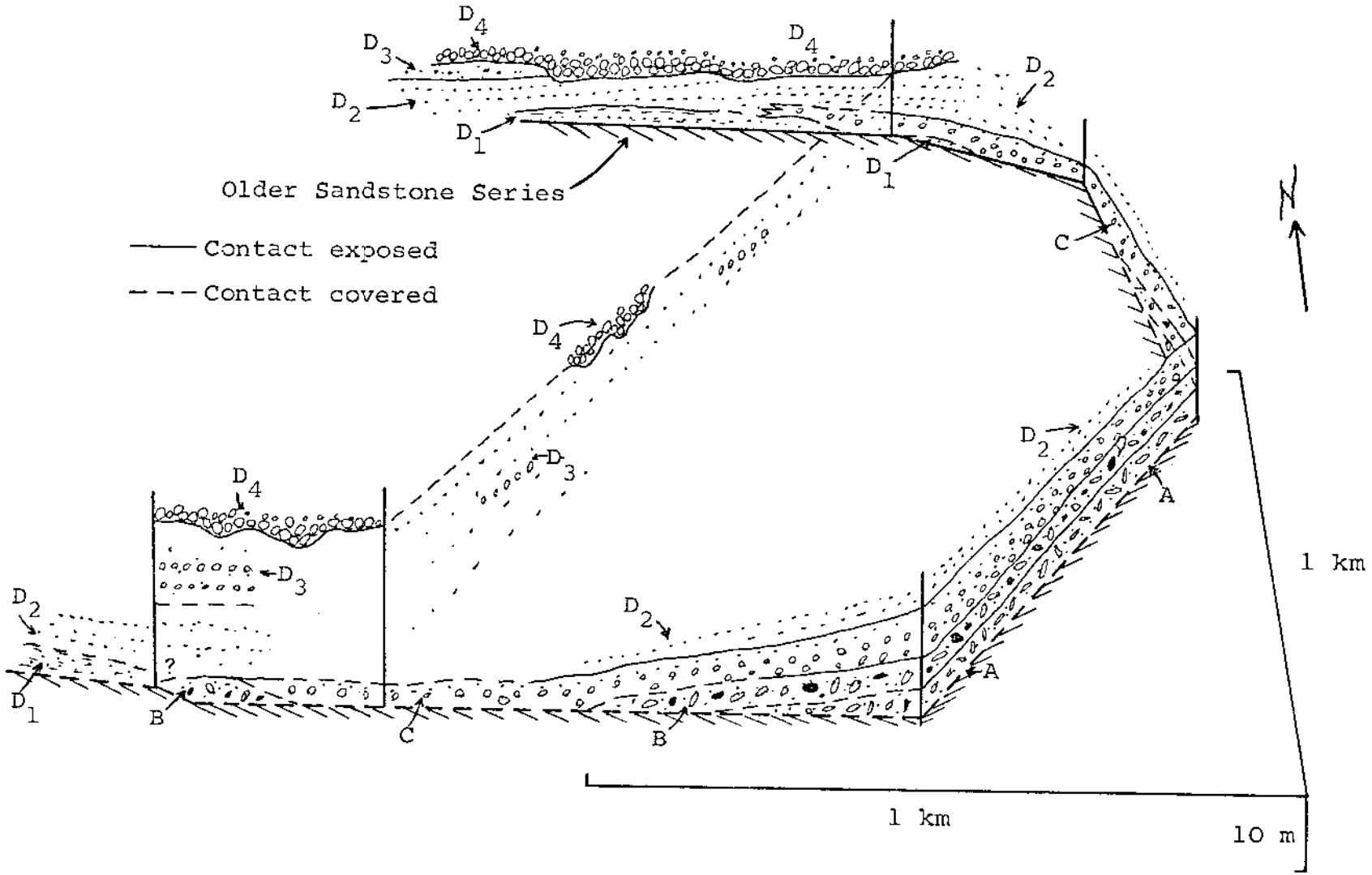
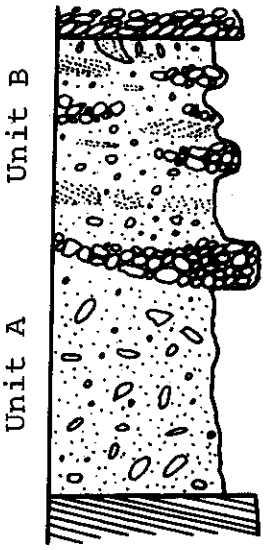


Figure 18. Geometry and relationships of the units around the eastern tip of Kvalnes.



	OBSERVATIONS	INTERPRETATION
Unit B	0-5 m, lenses and lenticular beds of conglomerate and sandstone, locally deformed, and surrounded by massive and winnowed grey tillite. Clasts of Older Sandstone Series, and crystallines including red and white granite, gneiss, and greenstones, but NO dolomite. Sand wedge at top is associated with nearly vertical stones.	Supraglacial moraine: combined processes of mass movements forming flow tills, aqueous currents forming conglomerate and sandstone, and locally winnowing till, and melting of buried ice forming deformation structures. Addition of crystalline clasts indicates increased transport distance. Sand wedge suggests freeze-and-thaw conditions in the periglacial zone.
Unit A	0-5 m, massive grey tillite, >99.9% sandstone and shale clasts derived from Veinesbugten Member of the Older Sandstone Series. Rare volcanic and white granite clasts near top. Occasional facetted and striated clasts. Sandy matrix.	Ground moraine: consists of locally derived materials only. Unsorted texture suggests deposition by lodgement or subglacial melting.
	Unconformity not exposed beneath unit A.	
	Older Sandstone Series: red and white sandstone, glauconitic sandstone, grey siltstone and shale.	

Figure 19. Description and interpretation of Units A and B, tillites at the base of the Smalfjord Tillite, eastern tip of Kvalnes Peninsula, Varangerfjord.

Its most important properties are that it contains only sandstone and shale derived from the Older Sandstone Series, and has a massive structure. The clast size is mostly 1-10 cm, but clasts up to 40 cm occur. The tillite rests on the Veinesbugten Formation, and is overlain by unit B. It apparently thins and dies out to the south, west, and north (fig. 18).

Unit B has both sandstone and crystalline clasts, and contains numerous stratified lenses up to 1 m thick and several metres long (fig. 19) (Pl. 2). It rests on unit A, and the Older Sandstone Series, and is overlain by unit C, and unit D_2.

At the top of unit B is a curved, downward tapering wedge of sandstone and gravel, which is associated with nearly vertical pebbles in the associated tillite (Pl. 3). The structure is overlain by unit C conglomerate.

Interpretation

The glacial origin of units A and B is suggested by the

presence of facetted and striated clasts, and the unsorted nature of part of the deposits. Alternatives, such as a fan breccia can be ruled out because the units die out to the south rather than thicken as would be expected, especially if one accepted the view that the crystalline-sediment contact is an ancient fault (however, Bjørlykke (1967) has argued effectively against the tectonic origin of this boundary, see Chapter 1). Unit B offers the key to the sequence in the intercalation of tillite and sorted deposits. These typically form in the proglacial zone of a glacier (see Chapter 3). A ground moraine origin is thus most likely for unit A as it is massive and locally derived (fig. 19).

The development of the sandstone wedge at the top of unit B, and the associated near-vertical pebbles may have been due to freeze-and-thaw conditions (fig. 20).

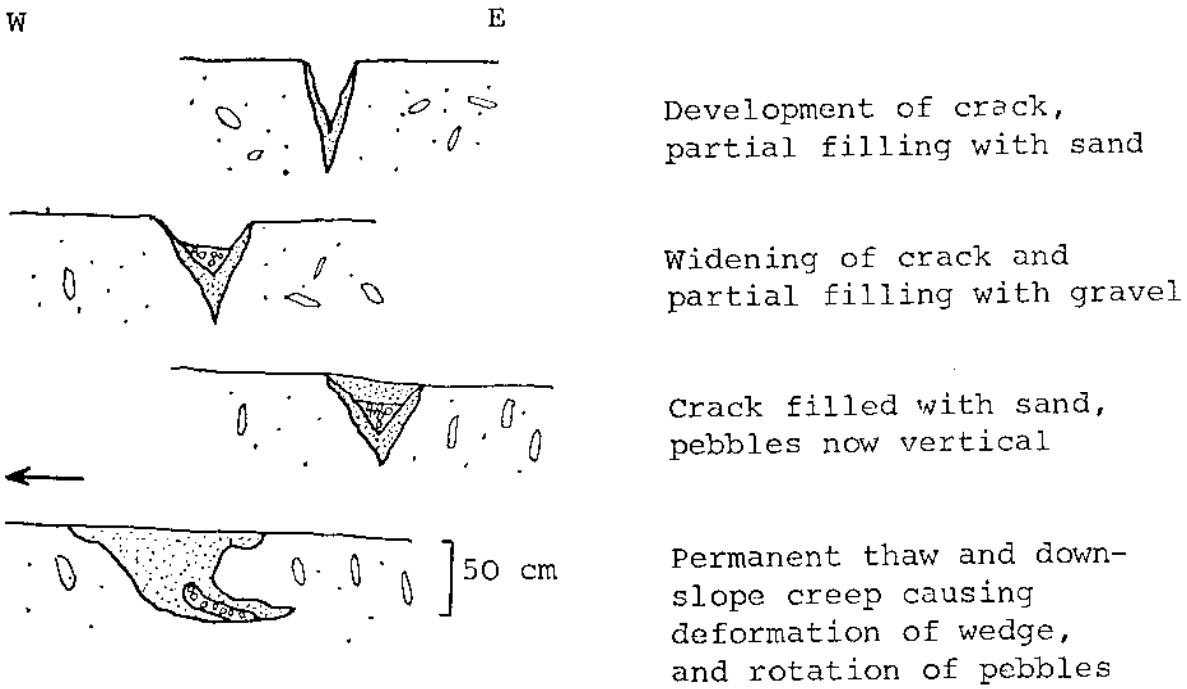


Figure 20. Interpretation of the development of the sand wedge at the top of unit B at Kvalnes

Spencer (1971) noted sandstone wedges in the late Precambrian Dalradian of Scotland which he also attributed to freeze-and-thaw conditions. Most of these show lamination aligned parallel to the walls (p.44), which Spencer does not explain. Sandstone wedges, also interpreted as periglacial in origin, have been described by Chumakov (1968).* The presence of subaerial conditions is further supported by the independent interpretation of the overlying unit C as a braided stream deposit.

The abundant red granite clasts in unit B indicate that there was a northward component in the direction of glacier flow, as red granite is a prominent lithology in the basement of the south. The orientation of the deformed periglacial features suggests a local slope to the northwest.

Unit C

Description

Unit C overlies units A, B, D_1 and the Veinesbugten Formation. It passes laterally into and is overlain by facies D_2 (fig. 18). The important features of the unit are shown in figure 21. Additional aspects are presented below.

The composition of the base of the unit near to where the tillites die out to the north is entirely sandstone. Where the contact between the unit and Veinesbugten Formation is seen, the surface is irregular; resistant sandstone beds project upwards, while erosion is pronounced along bedding planes and intercalated shale.

Westwards, along the north coast, the grain size decreases, and the unit gradually passes into unit D_2 sandstones.

Interpretation

The structures of unit C are typical of braided stream deposits (see Table 25, Chapter 8). Pebble imbrication indicates that currents flowed predominantly to the northwest. The irregular surface of the unconformity beneath unit C suggests that subaqueous erosion modified the original,

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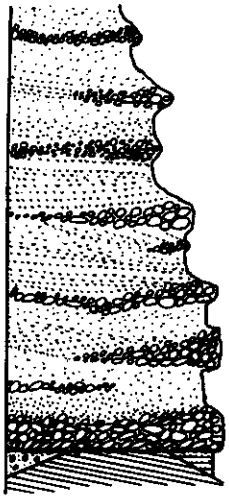
* These occur in the late Precambrian tillites of Spitsbergen.



OBSERVATIONS	INTERPRETATION
8 m, alternating conglomerates and sandstones broadly fining up. Pebbles up to 50 cm, mostly <5 cm, consist of sandstone (c. 40%), dolomite (c. 40%), and red and white granite, gneiss, greenstones, and vein quartz. Sandstone pebbles are tabular, others equant, and all show various degrees of rounding. Conglomerates tend to have sharp or erosive bases, and rest in shallow scours. They die out laterally into massive, parallel-laminated, or rarely cross-bedded sandstone. Occasional pebble imbrication. Sandstones are fine- to medium-grained, and in the lower part rarely have silty drapes.	Braided stream deposits formed by: 1) lateral migration and filling of shallow channels and scours, and 2) the migration of sandy and gravelly bars. Transport direction as indicated by pebble imbrication was to the northwest.
Unconformity with Older Sandstone Series, and erosive contact with units B and D_1.	Small-scale relief on the unconformity suggests subaqueous erosional modification.

Figure 21. Description and interpretation of unit C, stratified conglomerate and sandstone at the eastern tip of Kvalnes Peninsula.

probably smooth, glacial surface.

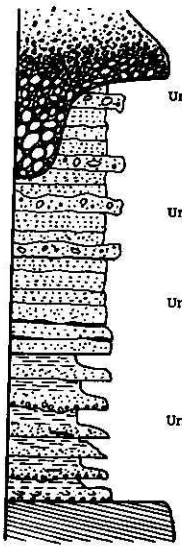
Unit D

Description

Unit D consists of four interrelated units which together comprise about 50-75 m between unit C and the Veinesbugten Formation below, and unit E above. The important features of the four units are shown in figure 22. The lower part, which consists of the sequence shown in figure 22, is succeeded by a further 20-40 m of units D_2, D_3 and D_4, before unit E is reached.

Unit D_1 (Pl. 4) occurs only at the base of unit D and rests on a smooth unconformity with the Veinesbugten Formation. It is overlain erosively by unit C and grades up into unit D_2. Bjørlykke (1967) observed a striated surface on the unconformity beneath this facies at the base of Kvalnes Peninsula.

Unit D_2 overlies both unit D_1 and unit C. It occasionally has small normal faults which dip to the northwest. Along the north coast, where the unit is beneath a D_4 channel (Pl. 5), it



	OBSERVATIONS	INTERPRETATION
Unit D_4	0-c.15 m, very poorly sorted conglomerate, pebbles commonly up to 20 cm, include crystallines, dolomite and sandstone. Commonly in steep-sided channels, eroding 2-3 m, up to 7-8 m. Often well graded, with occasional inverse grading at base. Channels may occur preferentially along an horizon, or may be isolated.	Submarine feeder and fan channels, cut and filled by strong, turbulent currents, associated with steep slopes to the west. Channels may migrate, or switch suddenly.
Unit D_3	0- 5-10 m, similar to D_2, but with lenticular medium beds of pebbly, muddy sandstone (diamictite). Deformation internally, and of bedding contacts. Base and top sharp.	Pebbly sandstones deposited rapidly by dense, turbulent currents. May largely be channel levee deposits.
Unit D_2	c. 10-15 m, parallel to lenticular medium-bedded sandstone, massive and parallel-laminated, rarely with ripple drift. Thickness of siltstone intercalations varies, may be absent. Sharp or erosive base, sharp top.	Sandy fluxoturbidites, proximal turbidites, or grain flow deposits on submarine fan.
Unit D_1	0-5 m, parallel to slightly lenticular thin- to medium-bedded sandstones with intercalated siltstones (c. 50/50). Pebbly, erosive base, with grooves and rare flutes. Internally massive, parallel- or ripple laminated (in Bouma sequence), well-graded with siltstone clasts and rare solitary crystalline boulders.	Turbidites, intermediate between proximal and distal. Deformation structures indicate slopes to the west and northwest. Grooves indicate north-south currents.
	Unconformity is smooth with local gravel lag.	Glacially formed suface is preserved
	Older Sandstone Series.	

Figure 22. Description and interpretation of unit D at Kvalnes Peninsula.

is strongly deformed into a large anticline overturned to the west (Pl. 6).

Unit D_3 occurs erosively below unit D_4, and occasionally above it. In the latter case beds can be traced into a channel fill of unit D_4 (fig. 23).

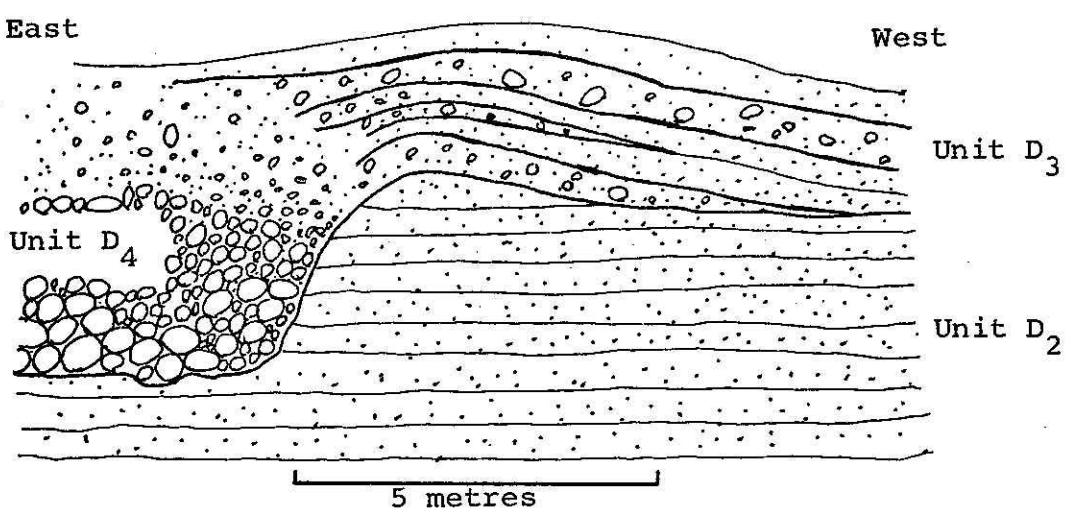


Figure 23. Lateral development of unit D_3 from a D_4 channel, having the appearance of levee deposits.

progradation of a submarine fan and fan channel association, with the coarse channel deposits cutting into and overlying the finer fan deposits.

The presence of unit D_1 below unit C suggests that a transgression occurred prior to the outbuilding of the braided stream. The deposits of the stream graded into marine sandstone as indicated by the lateral transition of unit C into unit D_2. Continued transgression flooded the fluvial environment but the rapid influx of sediment caused the deposition of turbidity currents and grain flow deposits to continue.

Unit E

Description

Unit E outcrops on much of the northwest coast of Kvalnes. It grades up from unit D and consists of interstratified sandstone and conglomerate. The thickness is probably greater than 30 m; an upper boundary is not observed.

At the base of the unit is several metres of trough cross-bedded sandstone with rippled tops. Cross-bed and cross-lamination dips are mainly to the northwest.

Alternations of conglomerate and sandstone form the rest of the unit. These are often trough cross-bedded in sets up to 3 m thick. The sorting of the conglomerate beds is very variable; most beds have an erosive base, and are lenticular. On a larger scale are groups of medium bedded, parallel-laminated sandstones which dip gently to the north and northwest, as low-angle cross-sets.

Interpretation

Unit E is interpreted as the deposits of braided streams. The presence of trough cross-bedding associated with conglomerate beds with erosive bases suggests deposition by migrating bars and the filling of channels (e.g. Doeglas, 1962).

Discussion

The sequence of environments in the Kvalnes area suggests

that the following events occurred:

1) Glacial erosion and formation of the unconformity,
2) Glacial retreat first depositing a ground moraine, unit A, and then a supraglacial moraine, unit B, followed by deposition of sand wedges in a periglacial environment.
3) Overall transgressive phase during which early marine deposits (D1) formed in the northwest at the beginning of the transgression. Later, fluvial deposits, (C) which passed laterally into coeval marine deposits (D1 and D2) to the northwest, prograded to the northwest, possibly associated with a minor drop in sea level. During continued transgression the river deposits were finally covered by the sea.
4) Continued rapid sedimentation led to progradation first of submarine slope and fan environments (unit D), and later of a braided river alluvial plain (unit E). Sedimentation was probably rapid enough to suppress the effects of shoreline processes, and the thickness of the shoreline deposits may have been reduced by fluvial erosion.

4.2.2 Bigganjargga

Bigganjargga is the site of the well known Reusch's Moraine (fig. 17). It has recently been described in detail by Bjørlykke (1967) who also reviewed the literature. The moraine is 3 m thick compared to the 100 m of Smalfjord Tillite at this locality.

Older Sandstone Series and Unconformity:

Description

Only several metres of the Older Sandstone Series is exposed below the Smalfjord tillite at Bigganjargga. This is pink and grey sandstone which is cross-bedded with current directions to the west. Føyn (1960), Harland (1964) and Crowell (1964) considered the sandstones around the moraine to belong entirely

to the Smalfjord Tillite. However, the similarity between this sandstone and the Older Sandstone Series of Varangerfjord is striking (Rosendahl, 1931). Moreover, an angular discordance separates the cross-bedded sandstone from the overlying moraine at the west end of the outcrop (Pl. 7). The discordance is a perfectly planar striated pavement (Pl. 8 and Frontispiece), which dips gently to the east. Most of the striations strike NW-SE, a few strike roughly E-W (Bjørlykke, 1967). The contact between the Smalfjord Tillite and the underlying sandstone can be traced about 20 m to the west of the end of the moraine where a conglomerate lag rests upon the planar surface which here lacks striations (Føyn, 1960). The striations become visible within 10 m of the moraine (Føyn, 1960).

Unit A Reusch's Moraine:

Description

Reusch's Moraine is the basal unit of the Smalfjord Tillite on the peninsula. It is up to about 5 m high and is 70 m long. The tillite contains pebbles of various types of sandstone, similar to those observed in the Veinesbugten Formation of the Older Sandstone Series and a variety of crystalline clasts including red granite. No sedimentary structures were seen in the tillite, but the matrix, predominantly grey, has irregular white patches from which the fines appear to have been winnowed.

In profile, the upper surface of the moraine shows a hump whose axis is aligned northeast-southwest. Along the sides of the moraine the overlapping sandstone beds (Pl. 9) are pebbly and contain several pieces of tillite, probably derived from the moraine.

Unconformity and Reusch's Moraine:

Interpretation

The planar surface of the unconformity suggests glacial erosion. Subaerial erosion tends to form irregular surfaces because the harder lithologies tend to protrude, and the rocks split and erode more easily along bedding planes. In contrast,

glacial erosion can form smooth surfaces regardless of the bedding or lithological inhomogeneities in the rock.

The presence of sandstone pebbles in the tillite indicates that the sandstone was indurated, at least to some extent, before its erosion. (A conclusion also reached by Rosendahl, 1931, p.499). It is well established that 1500 to 2000 m of the Older Sandstone Series was eroded from the area around Reusch's Moraine (fig. 5, Chapter 2).

The preservation of the striations 10 m away from the moraine, where the moraine was eroded away as shown by the lag conglomerate, and where sand was subsequently deposited, also indicates the indurated nature of the Older Sandstone Series at the time when Reusch's Moraine was formed.

It is thus unlikely that the striations formed by any kind of movement, glacial, slumping or otherwise over a frozen, or unconsolidated surface, as has been suggested by Crowell (1964, p.95). Considering the deep striae on an indurated, or partially indurated surface, it seems that slumping would not be sufficient to cause the striation, but that glacier overriding would.

However, a glacial origin for the pavement does not prove that the tillite did not slump into place. This problem can be resolved by indirect means: 1) the composition of Reusch's Moraine is identical to that of unit B at Kvalnes, and 2) both Reusch's Moraine and unit B at Kvalnes have a matrix which is both grey and white, the white areas being slightly winnowed. It is possible that Reusch's Moraine has the same supraglacial origin as unit B. The irregular distribution of grey and white tillite in Reusch's Moraine may be a disrupted equivalent of the horizontal stratified horizons in the unit B tillite.

The striation direction on the pavement is approximately normal to the long axis orientation of the pebbles (Bjørlykke, 1967). The pebble orientation is similar to the axis of the humped top of the moraine. Perhaps Reusch's Moraine is a remnant of an end moraine formed largely by supraglacial

processes. Thus, mass movement may have been involved in the formation of the moraine, but directly related to the downwasting of a glacier, or to the melting of stagnant glacier ice.

The remainder of the sequence above Reusch's Moraine has been studied only casually by the author. It bears a strong resemblance to the Smalfjord Tillite in other areas around Varangerfjord.

Unit B

Surrounding and overlapping onto the moraine are medium bedded, massive sandstones with thin siltstone intercalations, load structures, and rippled top surfaces. The beds thin and wedge out over the sloping sides of the moraine (Pl. 9). Above the moraine, over the next 7 m, the beds thin, the amount of siltstone increases, and soft sediment deformation occurs as overfolds, slumping and loading.

The sandstones and siltstones above the level of the moraine resemble closely the turbidite unit D_1 of Kvalnes. However, graded bedding did not seem to be common at Bigganjargga. The lower sandstones with rippled top surfaces have no equivalent at Kvalnes. These were likely formed in shallow water.

Unit C

This consists of 2 m of grey-green diamictite, with dolomite clasts. It appears massive internally, but resembles certain beds in unit D_3 of Kvalnes.

Unit D

Above the tillite bed are about 80 m of sandstones with conglomerate horizons towards the top. The 30 m of sandstone at the base appear massive internally, and are medium bedded. Intercalated siltstones were not observed, but occasional beds with scattered pebbles, similar to those in unit D_3 at Kvalnes occur. Dolomite grains are abundant.

Over the next 35 m are conglomeratic sandstones, both grain and matrix supported. Associated sandstones are

lenticular and massive. Glauconitic sandstone is a common lithology in the conglomerate.

The upper 15 m consist largely of massive and parallel-laminated medium bedded sandstone.

Unit E

At the base of unit E are sandstones with large-scale low-angle cross stratification in sets up to about 4 m thick (Pl. 10). Lenses of conglomerate occur in association with these sets. The horizon can be traced for a distance of about 3.5 km along the margin of the plateau of Bigganjargga (M. Carpenter, pers. comm.). It thins and dies out to the west, and thickens to the east.*

Above are conglomeratic sandstones and conglomerates with trough cross-bedding dipping to the west. These resemble closely the unit E braided stream deposits at Kvalnes.

Discussion

Based on the tentative correlations suggested in the previous section, the history of the Bigganjargga area is interpreted as follows:

1) Glacial advance, and erosion of the unconformity, formation of the striated pavement.
2) Glacial retreat, while the glacier margin was stationary supraglacial moraine (unit A) was deposited directly over the striated pavement.
3) Marine transgression covering the moraine with sandstone, and winnowing the till adjacent to the moraine, and possibly removing striations from those parts of the surface exposed for greater lengths of time. The overlying deposits (unit B) formed in progressively deeper water as the transgression continued.

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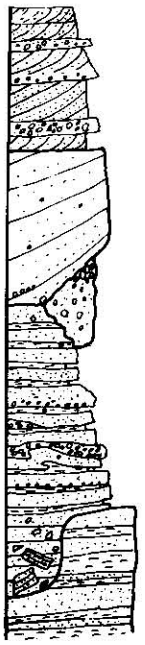
* These were discussed in the field with Dr. D.K. Hobday who suggested a beach origin. The low-angle cross stratification represents the swash zone, while the conglomerate near the base of the sets represents the break-point step where pebbles accumulated.

4) Regression began with the influx of turbidites and other sandstones (unit C) filling the basin, followed by progradation of a shoreline and alluvial plain.

4.2.3 Skjaaholmen

The exposure of the Smalfjord Tillite Formation on this narrow island in the centre of Varangerfjord is an important link between the exposures of Kvalnes, Bigganjargga and Mortensnes (fig. 17).

The tillite consists of four units: A) bedded sandstones with a local breccia at the base, B) tillite, C) large-scale cross-bedded sandstone, and D) stratified conglomerate and sandstone (fig. 24).



	OBSERVATIONS	INTERPRETATION
Unit D	c. 30 m, intercalated sandstone and conglomerate. Poorly-sorted conglomerate-filled channels up to 3 m high. Trough cross-bedded sandstones up to 1 m high, and parallel-laminated sandstones in gently inclined medium beds forming units up to 4 m high. Many sets have basal conglomerate, and occasional soft-sediment faulting.	Braided stream deposits formed by channel migration and filling, and by bar migration. Flow was to the west and northwest.
Unit C	c. 10 m, large-scale foreset, dips c. 5-10° to the west. Consists of parallel-laminated brown sandstone with scattered pebbles and conglomerate lenses. Pebbles of dolomite, crystallines and sandstone.	Delta foreset which prograded to the west.
Unit B	0-4 m, tillite: to west is sandy, dolomite clast tillite, to east contains crystallines (no red granite) and much sediment derived from unit A. Both tillites have local clast-rich zone at top up to 1 m thick.	Probable ground moraine indicated by erosion and incorporation of underlying sediment. Possible sub-aerial weathering, or current erosion or both at top.
Unit A	0-15 m, thin- to medium-bedded, parallel-laminated sandstone with intercalated siltstone. Sharp contacts, occasional grading, and erosive, pebbly base. Isolated gravel lenses, and pebbles scattered in sandstone and siltstone. Abundant soft-sediment folding with axes tipped to the west. Clasts of dolomite, sandstone and crystallines. Local basal breccia of large, angular blocks of Older Sandstone Series.	Sediment deposited rapidly on a slope by turbidity currents, mass flow, or grain flow, or combination of these. Basal breccia may be reworked glacial moraine, or a local product of marine erosion.
	Unconformity; local strong relief as near vertical walls up to 4m high, and striking N-S and NE-SW. Sharp breaks in slope.	Glacial surface may be modified by wave and current erosion. Steep slopes may be palaeo wave-cut cliffs.
	Older Sandstone Series.	

Figure 24. Description and interpretation of the units at Skjaaholmen.

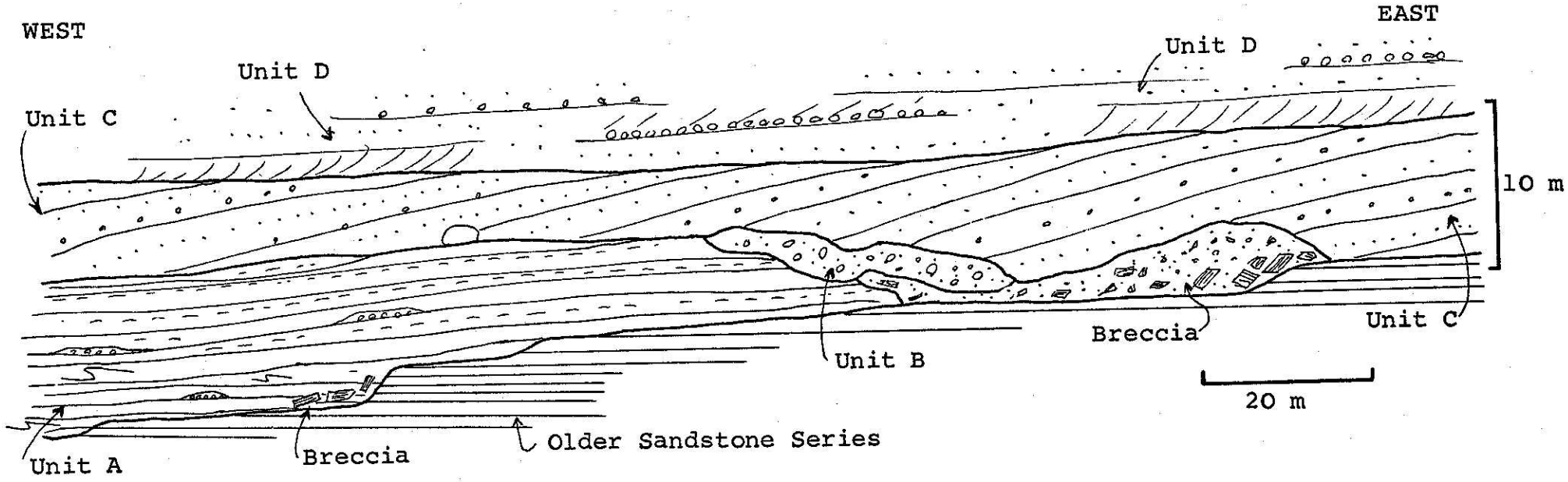


Figure 25. Relationships between the four units at Skjaaholmen along the south coast, western part of the east half of the island.

dip to the west where, according to the palaeocurrent evidence, a marine environment would be expected, and 3) the abundance of sandstone blocks in the lee of the cliffs formed by the undercutting of the soft parts of the cliff by waves and the collapse of the overhanging sandstone beds.

Unit B

Resting erosively on unit A are two distinct tillites, a sandy dolomitic tillite which occurs to the west (figs. 24 and 25), and a crystalline rich tillite which occurs to the east (fig. 24), (Pl. 12), containing clasts of white granite, greenstone, vein quartz, jasper, dolomite, chert and sandstone. The crystallines are up to 40 cm in diameter.

Neither of these tillites contain red granite and thus do not appear to correlate with the Bigganjargga tillite, or the Kvalnes tillites. Alternatively the tillites may be related to the braided stream deposit of unit C on Kvalnes. This is supported by the large amounts of dolomite both in unit C at Kvalnes and one of the tillites at Sjkaaholmen. The presence of two kinds of tillite along the same horizon is puzzling, and the relationship between them unclear. Both tillites have a high clast concentration in the uppermost metre, and the crystalline tillite locally has a distinct weathered appearance as well, both suggesting subaerial processes of winnowing and chemical alteration.

Unit C

Erosively above units A and B is an horizon consisting of one large-scale cross-set of pebbly sandstone which dips uniformly to the west (Pl. 13). The set can be traced continuously along the south coast of the eastern half of the island (fig. 25).

Although the top surface of the set is planar, the lower surface is irregular reflecting the topography of the underlying units.

The large-scale cross-bedding and poor sorting suggests a deltaic foreset origin for the set. The set is much more poorly sorted than the large-scale cross-bedded horizon in unit E at Bigganjargga. However, both are marginal deposits, and may have formed during one passage of the coastline over the area.

Unit D

This unit, which overlies unit C, can be observed along the north coast of Skjaaholmen (fig. 24). It is very similar to unit E at Kvalnes, and to the upper part of unit E at Bigganjargga, and it also appears to have formed in a braided stream environment.

Discussion

The Sjkaaholmen succession suggests the following sequence of events:

1) Glacial erosion and scouring of the unconformity.
2) Transgression, during which the unconformity was further modified by the formation of wave cut cliffs. Unit A sandstone was deposited by turbidity currents, grain flow, or mass movements.
3) Glacial readvance during which unit B was deposited, with attendant erosion of unit A. Subaerial conditions may have followed the glacial retreat.
4) Both a transgression and a rapid influx of sediment caused the formation of shallow water delta. Rapid influx continued as an alluvial plain with braided streams built out to the west and northwest.

4.2.4 Mortensnes

The outcrop of Smalfjord Tillite at Mortensnes is the most easterly, all exposures of tillite further east belonging to the Mortensnes Tillite. About 3 km east of Mortensnes it is cut out beneath the Mortensnes Tillite (fig. 17).

The unconformity between the Older Sandstone Series and the Smalfjord Tillite is dramatically exposed at Mortensnes. Over a north-south distance of about 800 m, it cuts through the 140 m of the Lower Sandstone; the average slope is about 10°. In detail the surface is very undulating, sometimes dipping about 45° south-southwest to the bedding in the Lower Sandstone (the Older Sandstone Series here has a regional dip of between $5\text{-}10^{\circ}$ to the north) (fig. 26). Where the contact between the Lower Sandstone and the Tillite is sharp, the beds are smoothly truncated against the unconformity. Occasionally the lower part of the Tillite is so sandy that the exact contact cannot be located, the distinction being based on both the colour, grey in the Lower Sandstone and brown in the Tillite, and the sedimentary structures, the Lower Sandstone being cross-bedded, and the Tillite massive or with irregular parting at the base.

Four exposures near the coast were studied, and the relationship between them determined (fig. 26).

Outcrop I

The eastern end of outcrop I (fig. 26) is described carefully for a distance of about 100 m (fig. 27). Five units are recognised.

Unit A

Directly overlying the Older Sandstone Series is up to 8 m of brown sandstone with a haphazard arrangement of parting planes. No material other than sandstone was observed, and it is suggested that the zone is essentially a breccia of locally derived material from the Older Sandstone Series,

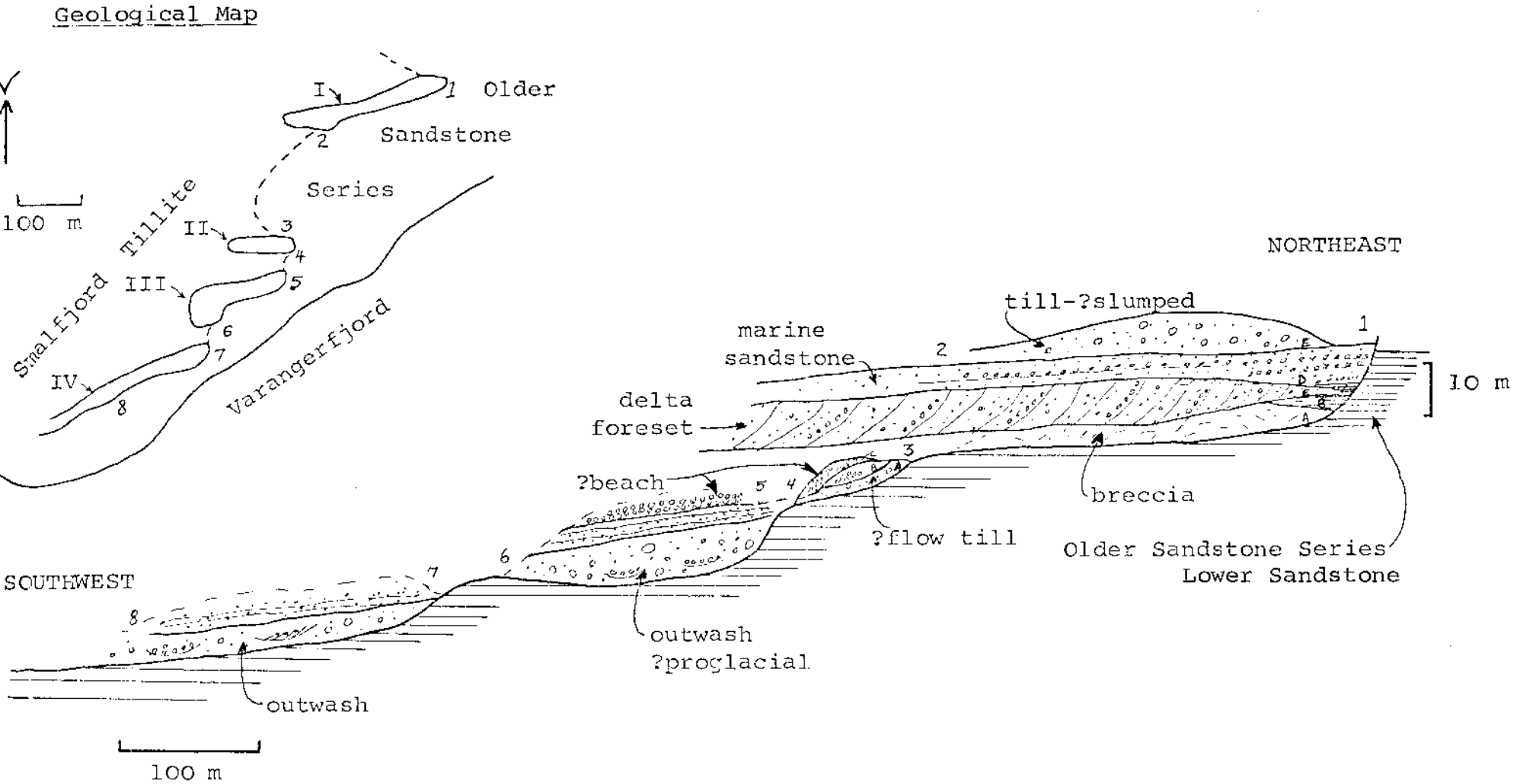
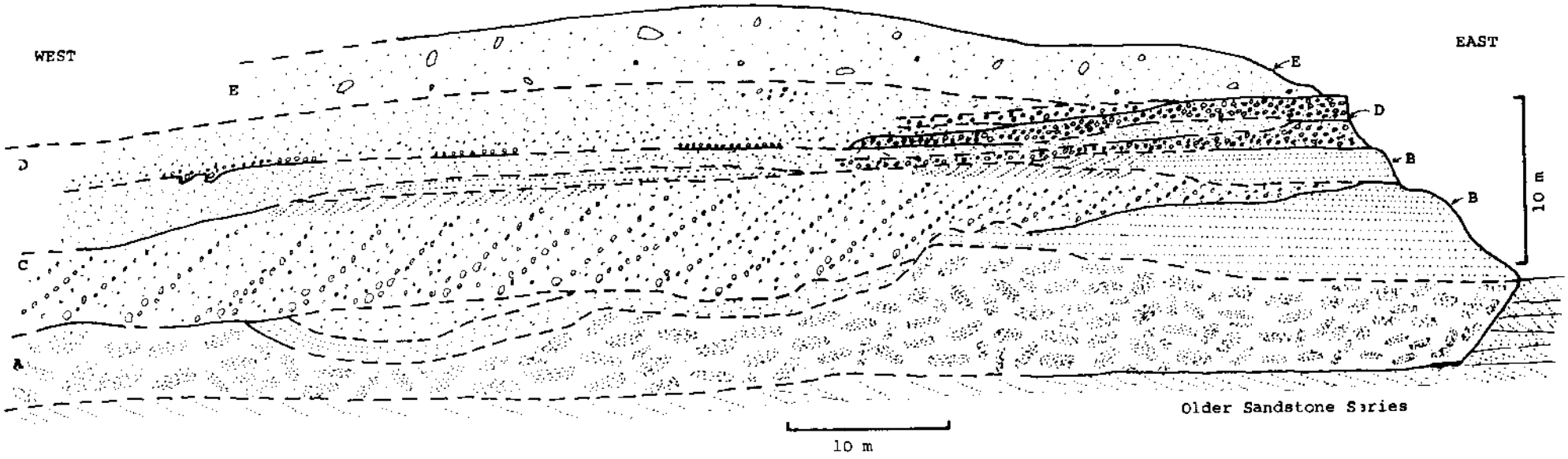


Figure 26. Relationships between the four outcrops at Mortensnes. View between stations 2 and 3 is foreshortened.



A) breccia of Older Sandstone Series, Lower Sandstone Member.
B) parallel-laminated brown sandstone, deformed to the west.
C) large-scale foreset unit, very poorly sorted conglomeratic sandstone. Dips c. 30°, fines upward, pebbles mainly dolomite; chert, granite, greenstone, and sandstone. Small-scale trough sets at the top.
D) poorly sorted lenticular conglomerate and sandstone. Graded, and inversely graded, prod casts, vertical sheet structures, some parallel-lamination.
E) sandy, buff-brown tillite, rare deformed lamination. Clasts mainly dolomite and sandstone, also vein quartz and crystallines.

Figure 27. Sketch of the units in the Smalfjord Tillite, Mortensnes, Varangerfjord.

formed by subglacial, and perhaps englacial comminution.

Unit B

This is brown parallel-laminated sandstone which is deformed at the western end of the exposure, but horizontal and undeformed in the eastern part. Primary current lineation cannot be observed because of the absence of parting planes along the bedding. The sandstone is interpreted as deposited as a plane bed in the lower part of the upper flow regime, probably under fluvial conditions.

Unit C

This is a large-scale foreset up to 7 m thick which dips to the west at about 20 - 30°. It fines upward from very poorly sorted conglomerate to granular sandstone. The composition is mainly dolomite, but includes other lithologies (fig. 27). The unit is interpreted as a delta foreset formed by strong, rapid currents, the fining up a result of avalanching of the coarse material. Immediately above the large foreset are small trough cross-sets of sandstone up to about 40 cm thick which also dip to the west. These may represent migrating linguoid dunes in a fluvial environment on top of the delta.

Unit D

Sharply overlying the large and small-scale foresets is up to 6 m of conglomerate and sandstone in discontinuous and lenticular beds (fig. 27). These are very poorly sorted, and show grading, inverse grading, prod casts, vertical sheet structures (Laird, 1970), and lateral changes in grain size.

These features suggest deposition by strong currents with high concentrations of sediment. They seem to have formed in a subaqueous environment, perhaps as dense underflows, comparable to the process that may deposit a "fluxoturbidite" (discussed in Walker, 1971). Current flow, as indicated by prod casts, and westerly lateral fining, was to the west.

The unit appears dissimilar to other lithologies observed in the Varangerfjord Smalfjord Tillite.

Unit E

This unit is up to 5 m of sandy buff-brown tillite with clasts predominantly of dolomite and sandstone (fig. 27). Deformed layering is seen in one small area.

The tillite truncates horizons in the underlying unit (fig. 27), which might suggest that it is an erosively based ground moraine. However, the similarity in composition to the underlying material, and the presence of local slopes up to 10° indicate that a flow till origin is possible.

Outcrop II

This outcrop has three units separated by erosional contacts (fig. 28). The basal unit A consists of poorly sorted sandstone with a few scattered clasts of dolomite, and rare deformed lamination.

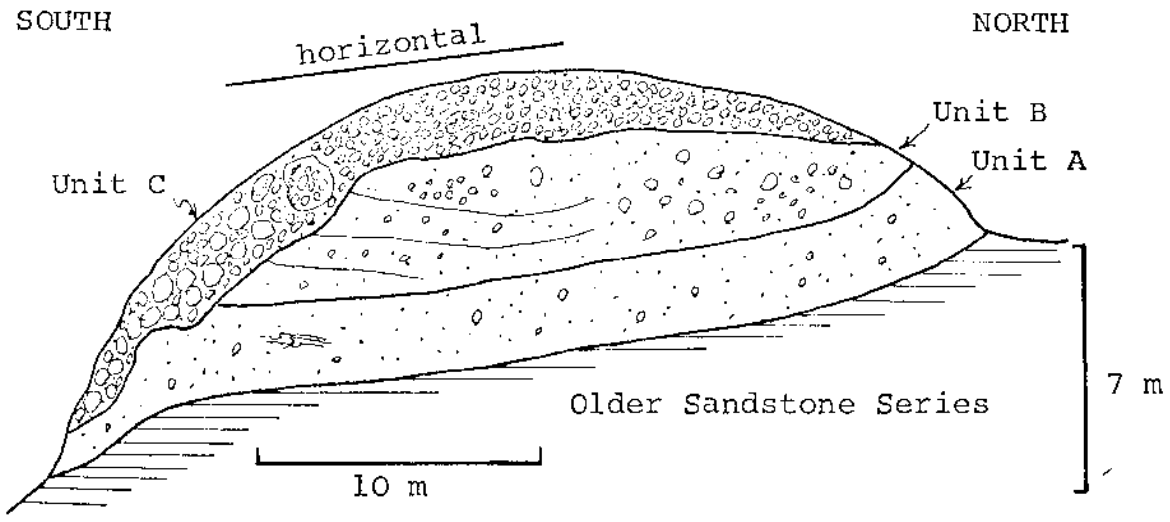


Figure 28. Form of the three units of outcrop II at Mortensnes. Unit A may be a flow till, while unit C may be a beach deposit.

Eroding into the sandstone is very poorly sorted conglomerate, unit B, with poor stratification appearing to the south. Unit C above, is a well-sorted conglomerate with very well-rounded pebbles of dolomite, blocks of outwash, and several blocks up to 130 cm of the "peculiar conglomerate", a marker horizon of reworked concretionary structures in the Middle Sandstone Member (Holtedahl, 1918).

Outcrop III

This contains very poorly sorted conglomerate, shallow gravel-filled channels, cross-bedded sandstone and conglomerate, and blocks of conglomeratic sandstone with deformed lamination (Pl. 14). A few metres from the base it grades into bedded sandstones which are overlain by a well sorted conglomerate that may be the same as unit C in the previous outcrop (fig. 26). At the east end of the outcrop the beds in the Lower Sandstone are sharply truncated by the unconformity.

Outcrop IV

This consists of stratified conglomerate with shallow scours, cross-bedding, ripple-drift cross-lamination and large boulders up to 80 cm across, followed by medium bedded massive and parallel-laminated sandstone.

Interpretation of Outcrops II, III and IV

The very poor sorting, the deformed blocks of glacial sediment, and the rapid changes in grain size suggest that these sediments were deposited in the proglacial zone of a glacier as braided stream outwash, and possibly as ice contact deposits.

The very well sorted conglomerate may be a beach deposit as no other conglomerates in the Smalfjord Tillite interpreted as fluvial are as well rounded, or sorted .

The form of the unconformity at outcrop III is that of a small linear depression trending WNW-ESE. The sharp

truncation of the beds in the Lower Sandstone indicate direct glacial erosion without subsequent modification.

Discussion

The relationship between the four outcrops is depicted in figure 26, and the following sequence of events is indicated:

1) Glacial erosion and scouring of the Older Sandstone Series, formation of the basal breccia (unit A, outcrop I).
2) Glacial retreat with the deposition of little ground moraine, but mainly proglacial outwash and ice-contact deposits (unit A and B, outcrop II; lower part of outcrop III and IV).
3) Transgression indicated by the beach deposits. (Unit C, outcrop II, top of outcrop III)
4) Local building out of delta foresets (unit C, outcrop I).
5) Continued transgression suggested by possible marine deposits of unit D (outcrop I).
6) Deposition of upper tillite, (unit E, outcrop I) either by glacial readvance or mass movements in a subaerial or submarine environment.

4.2.5 Nesseby

There is a discontinuous section through the Smalfjord Tillite exposed along the coast west of Nesseby, on the north coast of Varangerfjord (fig. 17). The Older Sandstone Series is not seen, but judging by the section at Mortensnes it is probably just a few metres below the base of the section at the southern most tip of the point. A gap of less than a metre separates the Smalfjord Tillite from the Nyborg Formation, exposed west of the small stream about 1 km west of Nesseby. The section was examined only briefly.

The Section

Starting at Nesseby point and working westwards, the Smalfjord Tillite consists of 1) 5 m of brown sandstone with

rare scattered pebbles of dolomite. Sedimentary structures were not observed, but the sandstone has irregular parting surfaces (it appears very similar to the basal unit A of outcrop I at Mortensnes). The sandstone is probably torn-up fragments of the Older Sandstone Series; a breccia.

2) Several metres of parallel-laminated brown sandstone, very similar in appearance to unit B of Mortensnes.

3) A large-scale cross-set about 10 m thick of sandy conglomerate which dips to the west. This resembles unit C of Skjaaholmen, but is somewhat coarser grained. It is similar to unit C, outcrop I of Mortensnes.

4) Discontinuously exposed for about 1 km are alternating stratified conglomerates and sandstones. Trough cross-bedding is common, and many beds fine up from conglomerate to sandstone. The probable thickness is about 30-50 m. It closely resembles unit D of Skjaaholmen, unit E of Kvalnes, and the upper part of unit E at Bigganjargga.

5) Sharply overlying the sandstone and conglomerate is a grey-green tillite unit about 1 m thick and consisting of mainly dolomite, with some crystalline clasts in a sandy matrix. Crude deformed parallel layering was observed. The basal red shales of the Nyborg Formation follow after a small gap.

Discussion

The Nesseby section combines elements of the sections to the south and west, with those to the north and east. Correlation between the large-scale foreset and similar units elsewhere is uncertain, but the stratified conglomerates and sandstones in the upper part of the section are likely equivalent to the similar units observed at the other sections. An upper tillite unit is also seen at the Mortensnes and Bergeby sections. Further observation at Bigganjargga may reveal an equivalent tillite there.

4.2.6 Bergeby

Outcrops along the Bergeby River, north of Nesseby (fig. 17), were examined briefly. In an exposure about 2 km north of Nesseby, a tillite, of which the base is not seen, passes up into brown sandstones. The 6 m thick tillite is grey and brown with a variety of crystalline clasts and dolomite and quartzite. Clasts are up to 50 cm across.

This grades upwards into about 6 m of coarsely laminated, and bedded tillite (Pl. 15). Upwards clasts die out rapidly.

Above is at least 30 m of medium to thick-bedded massive and parallel-laminated sandstone with occasional grading and soft sediment deformation. The top is not seen.

About a kilometre to the north the contact between the Smalfjord Tillite and the Nyborg Formation is exposed along the river. About 2-3 m of green-grey massive tillite with crystalline, dolomite and shale clasts is overlain sharply by purple shales of the Nyborg Formation. The upper 10 cm of the tillite are red.

Discussion

The two exposures cannot be correlated with each other, but it is likely that the tillite at the northern outcrop overlies the sandstones of the southern one. Correlation with the Nesseby exposure is not possible.

The bedded tillite has continuous stratification suggesting a subaqueous rather than subaerial origin. The overlying sandstones resemble proximal turbidites with the thick bedding, and upward sequences of massive to parallel-laminated sandstone in some beds. The direction of transport could not be determined.

4.3 Conclusions

The environmental relationships based on the correlation of units is shown in figure 29. It demonstrates the presence of rapid lateral facies changes, and the lenticular nature of most facies.

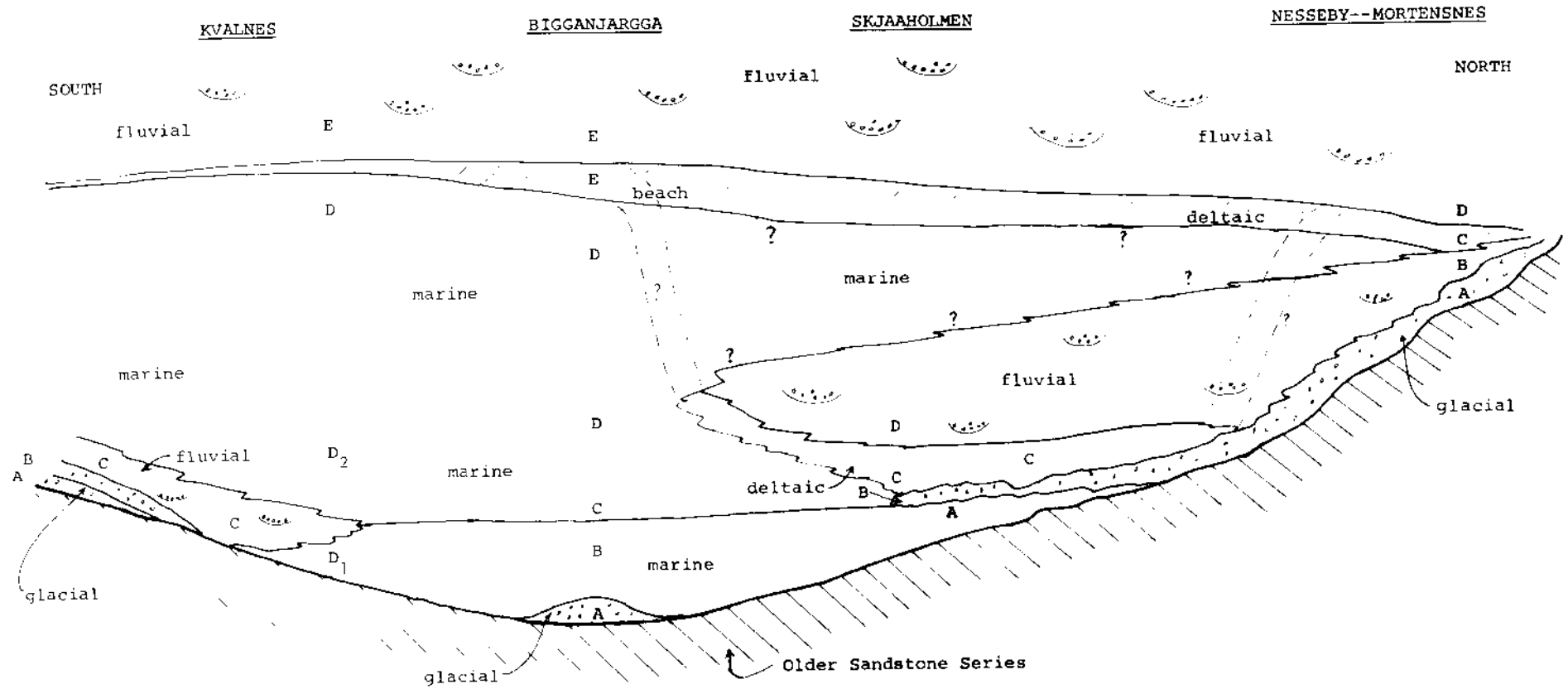


Figure 29. Correlation of the units in the Smalfjord Tillite at Varangerfjord, and their broad environments of deposition.

4.3.1 Sedimentation

Four major kinds of sedimentary environments are recognised in the Smalfjord Tillite at Varangerfjord:

1) Marine; characterised by rapid deposition of conglomerate and sandstone largely by gravity driven mechanisms such as turbidity currents, mass-flow, and grain-flow. Soft-sediment deformation is common and seems to indicate deposition on a slope. Beach deposits form a small part of the marine facies.

2) Deltaic; large-scale foresets up to 10 m thick are attributed to small deltas. These vary in foreset dip and in grain size from sandy to pebbly.

3) Fluvial; interstratified conglomerate and sandstone with abundant trough cross-stratification, in crude fining-upwards units without siltstone. These were deposited by braided streams.

4) Glacial; mainly tillites of which two kinds are present. Massive tillites with erosive bases are attributed to subglacial deposition, while tillite with lenticular gravel and sand horizons was probably deposited in a supraglacial environment. Periglacial effects are indicated by a sand wedge associated with nearly vertical pebbles.

According to Bjørlykke (1967) sedimentation has occurred in a linear trough aligned parallel to the contact between the crystalline shield to the south and the Older Sandstone Series to the north. No evidence for a fault separating the two provinces postulated by Holtedahl (1918) has been found in this study. The unconformity between the Smalfjord Tillite and the Older Sandstone Series is an unfaulted surface which dips gently to the south in the region of Varangerfjord. The contact between the basement and the Older Sandstone Series dips at least 5^{o} to the north and it is the intersection of this surface with the upper unconformity that causes the linear boundary between the sediments to the north and the basement to the south. Some tilting of the Older Sandstone Series has apparently occurred (see also Bjørlykke, 1967).

4.3.2 History

The history of the Smalfjord Tillite at Varangerfjord includes two glacial episodes associated with pronounced lateral movements of the shoreline:

1) first glacial; scouring of the unconformity, deposition of the Kvalnes tillites, and the Bigganjargga tillite during retreat.

2) first interglacial; transgression associated with the deposition of turbidities and related sediments at Kvalnes, Bigganjargga and Skjaaholmen.

3) second glacial; deposition of tillite at Skjaaholmen. Possibly contemporaneous with unit C fluvial deposits at Kvalnes, and proglacial deposits at Mortensnes and Nesseby.

4) second interglacial; marine conditions in the south and deltaic and fluvial in the north. Eventually the shoreline retreats to Mortensnes, possibly associated with continued glacial retreat.

5) regression; continued sedimentation with the filling in of the basin and the establishment of an alluvial plain over the area.

6) ?third glacial; is indicated by upper tillites Mortensnes and possibly at Nesseby. The relationship to Bergeby is uncertain.

The definite end of the glaciation is marked by the basal transgressive beds of the Nyborg Formation.

4.3.3 Direction of Transport

As remarked by Bjørlykke (1967), the palaeocurrent indicators (mainly small- and large-scale stratification) in the Smalfjord Tillite indicate flow persistently to the northwest, and west. The restriction of red granite pebbles to the southern outcrops indicates that glacier flow did not have a stronger northerly component than the axis of the trough of sedimentation.