Sedimentology of the Upper Proterozoic glacial record, Vestertana Group, Finnmark, North Norway

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Upper Proterozoic sediments in Finnmark show direct and indirect evidence for glaciation in four stratigraphic units at the base of the Vestertana Group: 1) the Smalfjord Formation, the first glacial episode, 2) the Nyborg Formation which is interglacial, 3) the Mortensnes Tillite, the final glacial, and 4) the Lillevatn Member of the Stappogiedde Formation, which is postglacial.

Each glacial formation rests on a glacially scoured, regional angular unconformity, and consists primarily of lodgement tillite with subordinate laminated mudstones, often with dropstones. The repeated vertical sequence of erosively-based lodgement tillite overlain by laminated mudstone is interpreted as a submarine glacial retreat sequence. At least five such sequences are preserved in the Smalfjord Formation, and two in the Mortensnes Tillite. In addition, the lower part of the Smalfjord Formation fills two elongate paleovalleys that contain predominantly water-deposited facies, especially deposits of subaqueous sediment gravity flows and braided streams. Examination of deformation structures resulting from glacial shear indicates that ice sheets advanced not only from the south, but from the north as well.

The interglacial and postglacial units both show evidence for local isostatic uplift and eustatic rise. Regressive basin fill sequences progress from relatively deep, quiet water, to shallow, agitated conditions. However, the style of the fills contrast in that the basinal facies of the interglacial Nyborg Formation is dominated by turbidite sandstones, while that of the postglacial Lillevatn Member is dominated by mudstones. Similarly, the shallow water deposits of the Nyborg Formation formed in a tide- and wave-dominated delta front, whereas those of the Lillevatn Member formed in coarse-grained alluvial channels. The sediment source for both units appears to have been primarily south of the basin.

The structural and depositional center of this small epicontinental basin was situated southwest of Tanafjord. Enhanced glacial erosion of sediments adjacent to the Fennoscandian shield resulted in an asymmetric basin having a steep southern margin and a gentle northern margin.

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CONTENTS

Foreword

The tillites in Finnmark, North Norway (Fig. 1) have been known for almost a century, since Reusch described in 1891 the famous 'Bigganjargga tillite' which rests on a striated pavement. The tillites and adjacent deposits were subsequently the subject of several important publications, namely Holtedahl's (1918, 1931) pioneering accounts of numerous tillite localities, Føyn's (1937) determination of the correct stratigraphic sequence and age of the tillites, and Reading and Walker's (1966) innovative and influential discussion of the depositional environment of the tillites and related sediments. In addition numerous other papers have appeared; however many of these were based on relatively brief field observations, chiefly because of the very isolated location of the tillites, and thus did not contribute extensively to a general understanding of the glacial deposits.

Realizing the need for additional extensive studies of the tillites and related deposits, Harold G. Reading proposed this topic for a Ph.D. thesis. During this project, I spent ten months in the field, about half devoted to the tillites and half to the adjacent non-glacial deposits. This paper is to a large extent an updated, abbreviated form of the thesis (Edwards 1972). Copies are stored in the libraries of the Norwegian Geological Survey, Trondheim, and Oxford University.

Introduction

GEOLOGICAL SETTING

The glacial sequence occurs in the lower part of the Vestertana Group (Fig. 2), which occurs within a predominantly terrigenous clastic succession of Upper Proterozoic (Upper 'Riphean'; Vidal 1981) to Tremadoc age that reaches a thickness of about 5 km and crops out over an area of approximately 230 by 50 km (Banks et al.

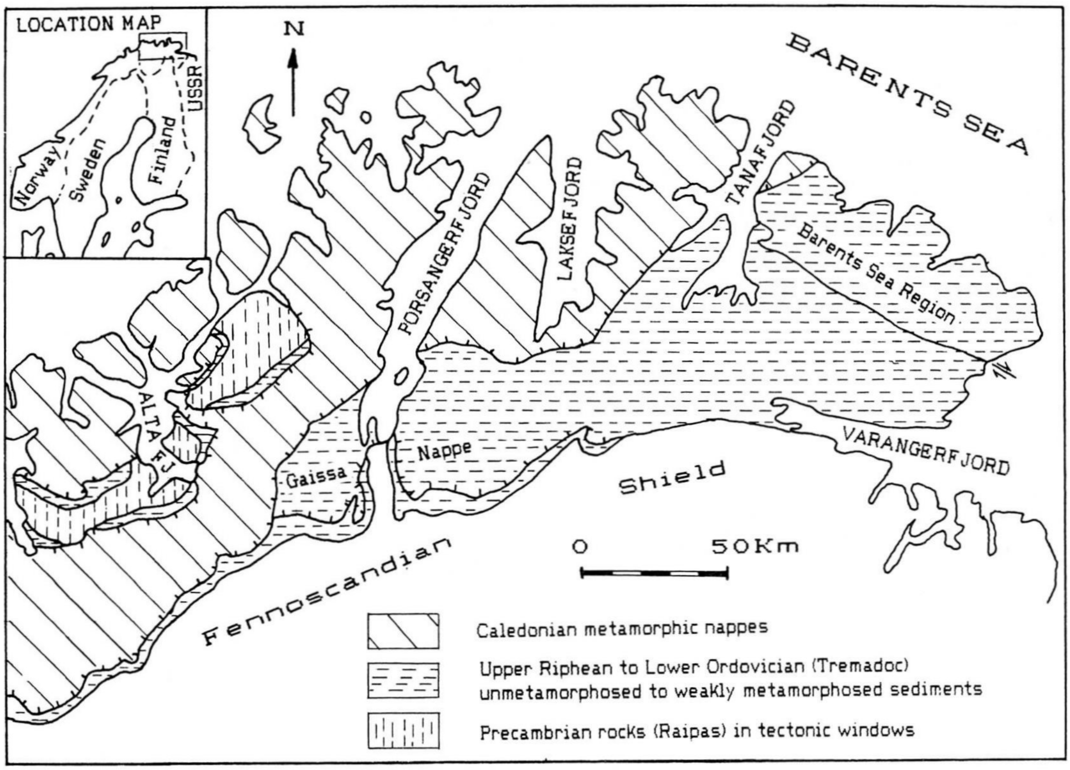


Fig. 1. Generalized geological map of East Finnmark (modified from Føyn, in press). The main study area is around the inner parts of Varangerfjord and Tanafjord, end extends to Laksefjordvidda south of Laksefjord. To the west, the sequence becomes allochthonous in the Porsangerfjord area (Gaissa Nappe).

1971). Virtually all of these deposits consist of paralic facies, ranging from alluvial coastal plain to shallow water shelf. The few turbidite-bearing formations that occur appear to have formed in water depths of less than a few hundred meters. Units in the Vestertana Group which illustrate glacial influence include the Smalfjord Formation (first glacial episode), the Nyborg Formation (interglacial), the Mortensnes Tillite (final glacial), and the Lillevatn Member (postglacial) of the Stappogiedde Formation (Fig. 2; Edwards & Føyn 1981).

Along the southern shore of the inner part of Varangerfjord, and to the west of the fjord the sedimentary succession rests unconformably upon basement of the Fennoscandian shield. In this area the sediments are little deformed. However, further to the west the sediments become parautochthonous and have moved some tens of kilometers to the south, as part of the Gaissa Nappe (Føyn 1967). In the northwest, the sediments are overthrust by a succession of increasingly metamorphosed Caledonian nappes (Gayer 1973). As would be expected, the autochthonous sediments show increasing degrees of folding and thusting toward the north. To the northeast is a major strike-slip fault which separates rocks of the Barents Sea Region, a 14 km-thick upper Proterozoic succession, from the autochthonous sediments (Johnson et al. 1978).

Revised, unpublished geological maps of the Polmak and Vestertana sheets, based on both published and unpublished data, have been prepared by S. Føyn for the Norwegian Geological Survey.

AIMS AND METHODS

This paper presents the results of a field-oriented study of the depositional environments and systems, basin configuration, and controls on sedimentation which characterized the lower part of the Vestertana Group. In addition, studies of particular parts of the succession, which will be treated in some detail, provide insight into depositional models for certain glacial, deltaic and marine environments.

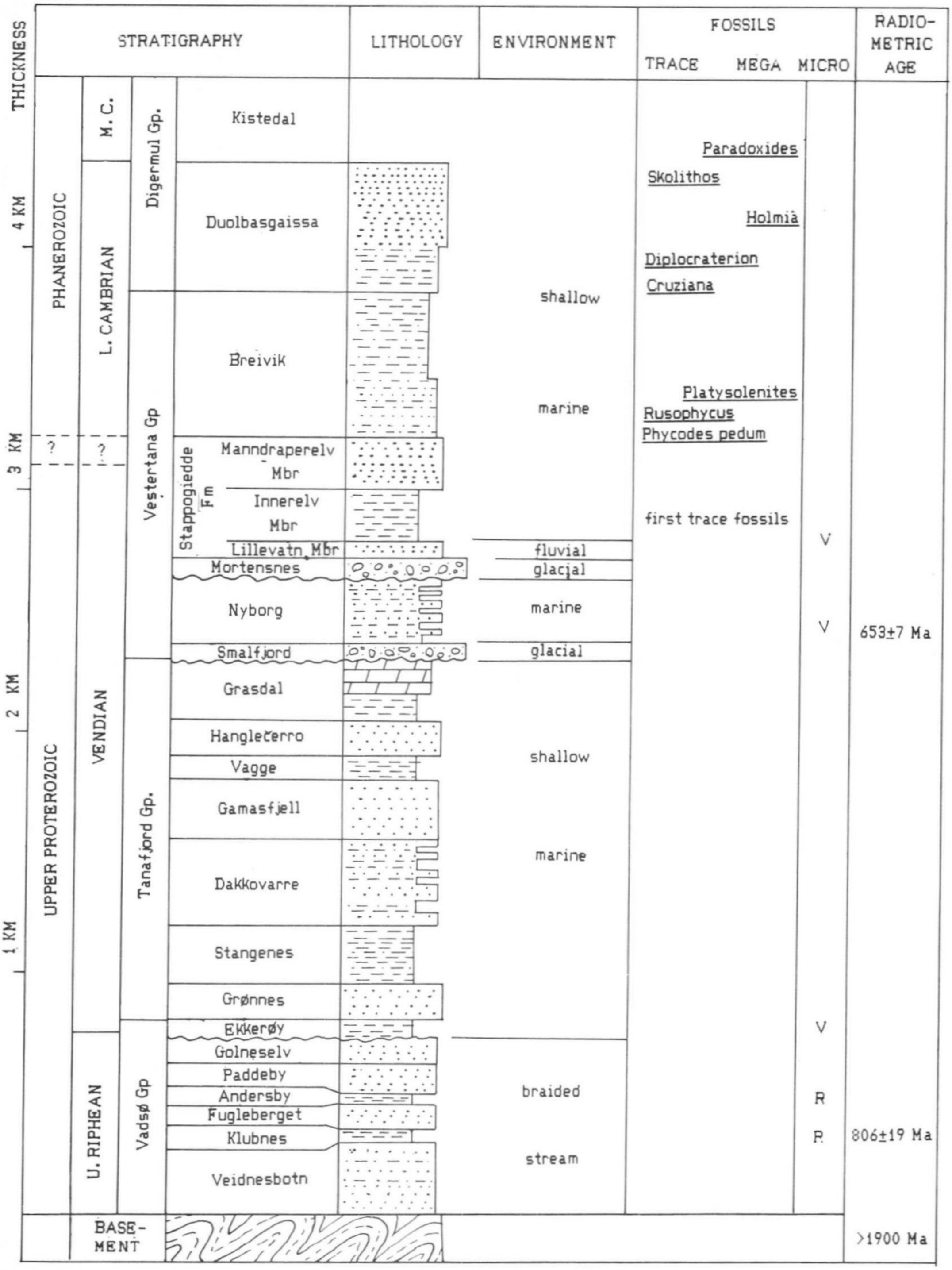


Fig. 2. Upper Proterozoic to Cambrian stratigraphy of East Finnmark, with highly generalized lithology and environment of deposition. Compiled from Johnson et al., 1978; Føyn & Glaessner, 1979; Vidal, 1981, and Siedlecki, 1980.

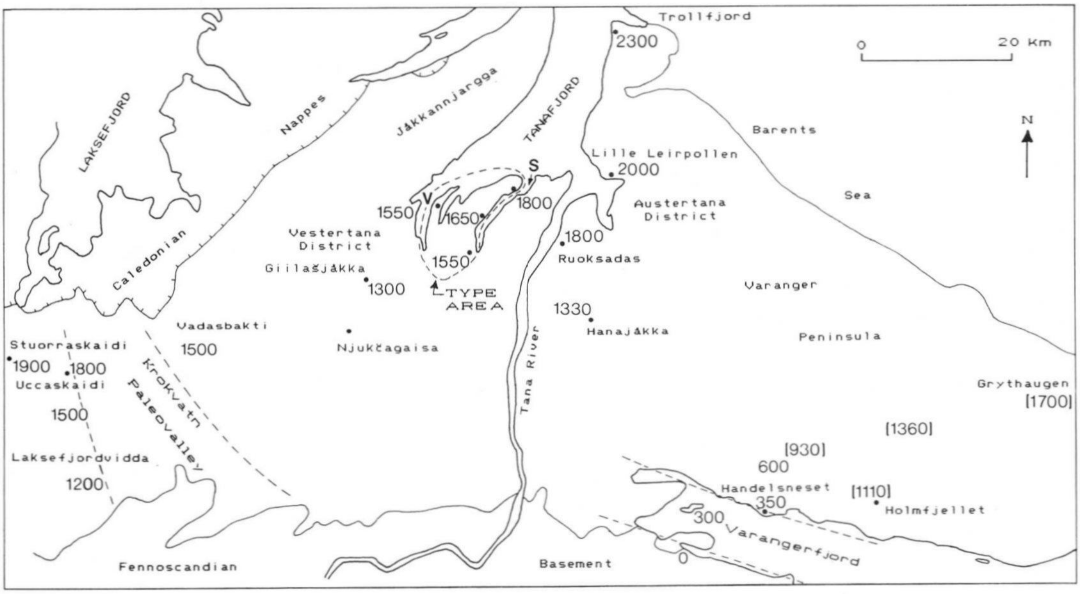


Fig. 3. Location of the Krokvatn Paleovalley on Laksefjordvidda, and the Varangerfjord Paleovalley, Varangerfjord, which were filled primarily with conglomerates and sandstones during the first phase of the Smalfjord Formation. During phase two, tillite with minor mudstone was deposited outside of these areas, and locally within the paleovalleys. The type area of phase two is shown between Vestertanafjord (V) and Smalfjord (S). Numbers indicate the estimated thickness in meters of the Vadsø and Tanafjord Groups preserved below the sub-Smalfjord Formation unconformity. In the east the Smalfjord Formation was removed below the Mortensnes Tillite; here, the figures in parentheses indicate the thickness of strata underlying the Mortensnes Tillite. Thicknesses of stratigraphic units are given in Johnson et al. (1978), supplemented by Røe, 1971, Føyn & Siedlecki, 1980, and Siedlecki, 1980.

The methods employed were detailed section-measuring, observation of sedimentary structures, contacts and paleoflow indicators, lateral tracing of important stratigraphic horizons, petrographic study of thin sections, and geological mapping where necessary. The technique of facies analysis in environmental reconstruction has recently been summarized by Reading (1978).

GEOGRAPHIC NOTE: REVISED PLACE NAMES

Recently, the Norwegian Geographical Survey has issued new high quality topographic maps of the study area, scale 1:50,000. The new maps reflect an increasing awareness of the ethnic identity of the native Lapps, by incorporating their usage for place names. A major disadvantage of the renaming of many geographical features in the study area is that in many instances names present on the previous maps, which were used for decades, are absent or substantially changed, and place names in formal and informal stratigraphic terms can no longer be located on a map. A striking example of this is the replacement of 'Bigganjargga' by Oaibaččannjarga, which, incidentally, has been moved to the actual tillite locality.

At the suggestion of S. Føyn, I have chosen, in this paper, to use the new names to identify geographic locations. Old names are retained for previously defined, formal stratigraphic units. For the first usage of a new name, the corresponding old name follows in parentheses, and a listing of all renamed localities used in this paper is provided in the appendix.

The Smalfjord Formation – First Glaciation

The Smalfjord Formation (Bjørlykke et al. 1967; 'lower tillite' of Føyn, 1937) consists of two distinct groups of facies: 1) sandstones with minor conglomerates, and 2) tillites with minor mudstones. In this paper, the term tillite refers to diamictite (Flint et al. 1960 a & b) deposited directly from glacial ice (Boulton & Deynoux) 1981). The term diamictite refers to lithified, poorly sorted sediments containing large particles (clasts) dispersed in a fine-grained matrix. The first group occurs in two low-relief paleovalleys, the Varangerfjord paleovalley which coincides closely with inner Varangerfjord (Bjørlykke 1967), and the Krokvatn paleovalley which oc-

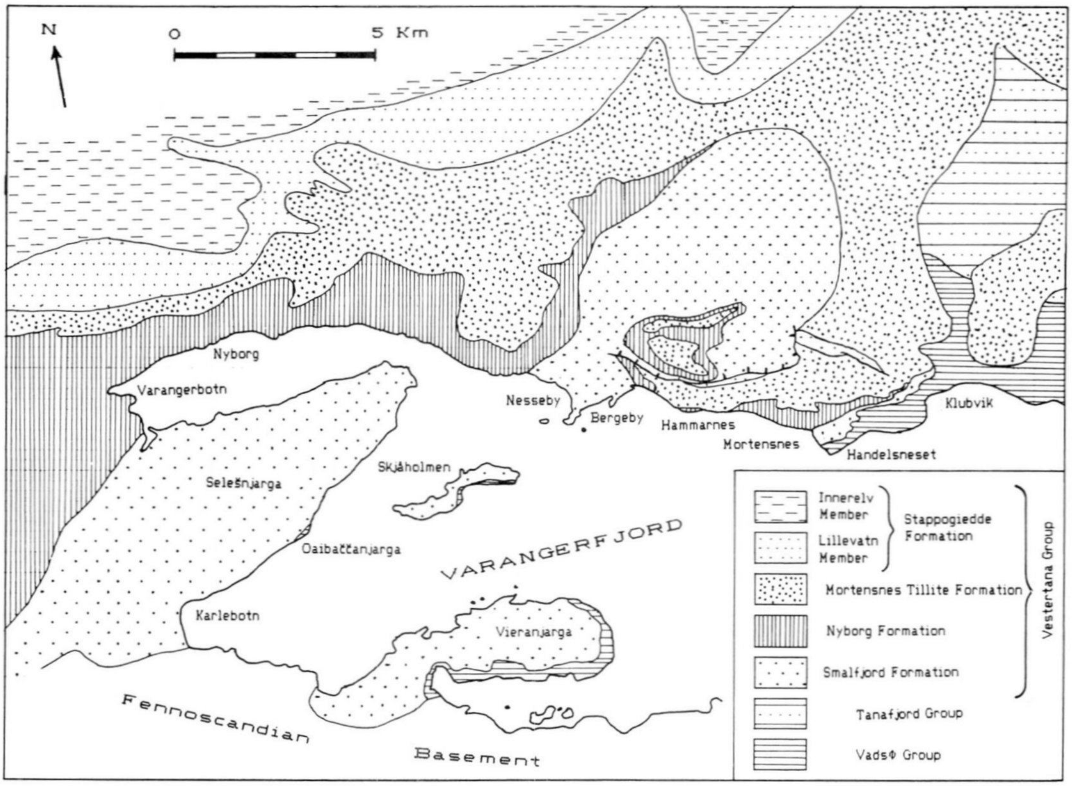


Fig. 4. Geological map of the inner Varangerfjord area, modified from Banks et al., 1974. The area between Bergeby and Klubvik is based on my mapping for the Norwegian Geological Survey. The large area of Smalfjord Formation inland from Hammarnes is hypothetical, as this area contains only a few poor exposures of sandstone.

curs on Laksefjordvidda, inland from the head of Laksefjord (Fig. 3; Føyn & Siedlecki 1980). The second, younger, group of lithofacies occurs both above the sediments filling the paleovalleys, and on older sediments in the intervening areas, for example around Tanafjord, and west to Stuorraskaidi on Laksefjordvidda.

THE SUB-SMALFJORD FORMATION UNCONFORMITY

Throughout East Finnmark the Smalfjord Formation rests unconformably upon the Vadsø and Tanafjord Groups (Figs. 2 & 3). Correlation of the blanket-like formations in these groups across widely scattered outcrops, enables estimation of the relative amounts of erosion beneath the unconformity. The maximum thickness of preglacial sediment is preserved at Trollfjord: a composite section from the base of the Vadsø Group at Varangerfjord to the top of the Tanafjord Group at Trollfjord is 2300 m thick (Johnson et al. 1978). This is the minimum amount of erosion below the unconformity. Considering the greater thickness of dolomite in the Porsanger Dolomite at Porsangerfjord (Fig. 1; minimum of 234 m, White 1969) than the equivalent upper dolomitic part of the Grasdalen Formation at Trollfjord (about 100 m. Siedlecka & Siedlecki 1971), and the abundance of dolomite clasts in the tillites, it is likely that considerably greater thicknesses of dolomite than those observed today were present prior to glacial erosion.

Throughout most of the area, the unconformity slopes gently to the south, dipping at about one degree around Tanafjord and increasing to about three degrees further to the south. Due to the gentle slope, truncation of the underlying beds cannot usually be detected in individual outcrops. However, unusually steep dips are observed along the margins of paleovalleys.

VARANGERFJORD PALEOVALLEY

The coincidence of a Precambrian glacial valley with the present-day Varangerfjord was pointed out by Bjørlykke (1967). Excellent exposures of glacial sandstones and conglomerates scouring

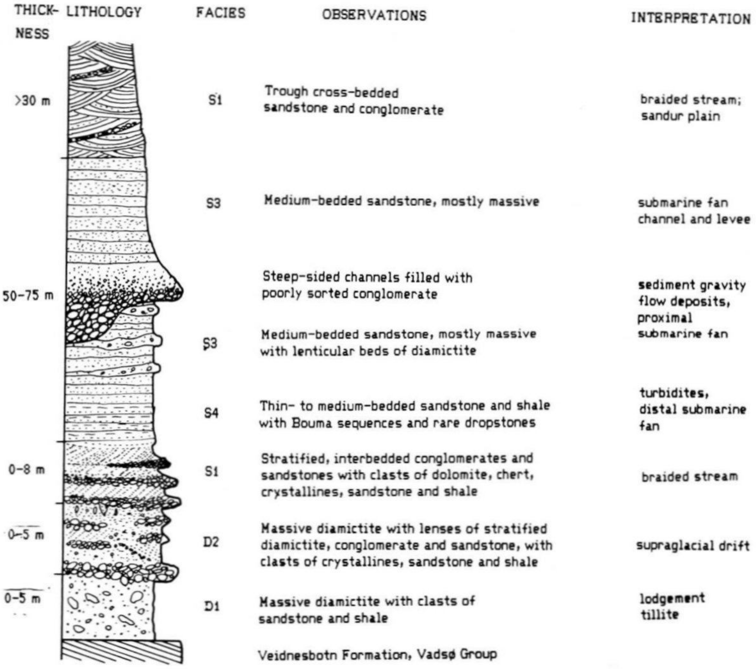


Fig. 5. Composite vertical sequence through the Smalfjord Formation preserved along the eastern and northern parts of Vieranjarga.

into sandstones and shales of the Vadsø Group are preserved at Vieranjarga (Kvalnes), Oaibaččanjarga (Bigganjargga), Skjåholmen (Skjaaholmen), and Handelsneset, near Mortensnes (Fig. 4). Other important outcrops occur at Nesseby and along Bergebyelva. In this area the Smalfjord Formation ranges in thickness from 0–100 m, and diamictite is only a minor component. Inland, about 10 km west of the fjord, small, thin patches of diamictite are plastered onto outlying hillocks of basement (e.g. Ruossoaivvi) that represent original topography (Holtedahl 1918, Bjørlykke 1967).

Facies

The deposits filling the valley comprise two types of facies, of which the first is predominant by far: 1) sandstones and conglomerates deposited by water, which include four volumetrically important facies, S1 to S4, and 2) two diamictite facies, D1 and D2.

The sandstone and conglomerate facies are:

S1 well-stratified pebble conglomerate and sandstone. Conglomerates are erosively-based lenticular beds, relatively well-sorted, with clasts occasionally imbricated. Sandstones show cross-bedding and parallel-lamination, and fining-upward trends are often seen between these lithologies. Discontinuous mud drapes are uncommon. This facies is interpreted as braided stream deposits, analogous to present-day sandur plain deposits (Edwards 1975b).

S2 large-scale foresets, usually 5–10 m thick, laterally continuous from several hundred meters to several kilometers. They range from steeply dipping, poorly sorted pebble conglomerates which probably formed as delta foresets, to well sorted gently dipping parallel-laminated sandstones which probably formed as beach foreshore deposits. Thus this facies represents shoreline progradation.

S3 sandstones, chiefly medium-bedded, parallel-sided to slightly lenticular, and internally usually massive, but occasionally parallel-laminated, rarely ripple-laminated. Sandstones do not appear graded, and mudstone partings are thin or absent. Deformational structures such as convolution, recumbant folds, and faulting are sporadically observed. Occasionally developed are lenticular interbeds of poorly sorted and ungraded sandy diamictite. This facies is distinct for the sparseness of internal stratification and may represent fluidized or liquified sediment flow deposits as discussed by Middleton & Hampton (1973) and Lowe (1976, 1982). Also present are isolated steep-sided channels filled with coarse, poorly-sorted conglomerate. The available data do not indicate the salinity of

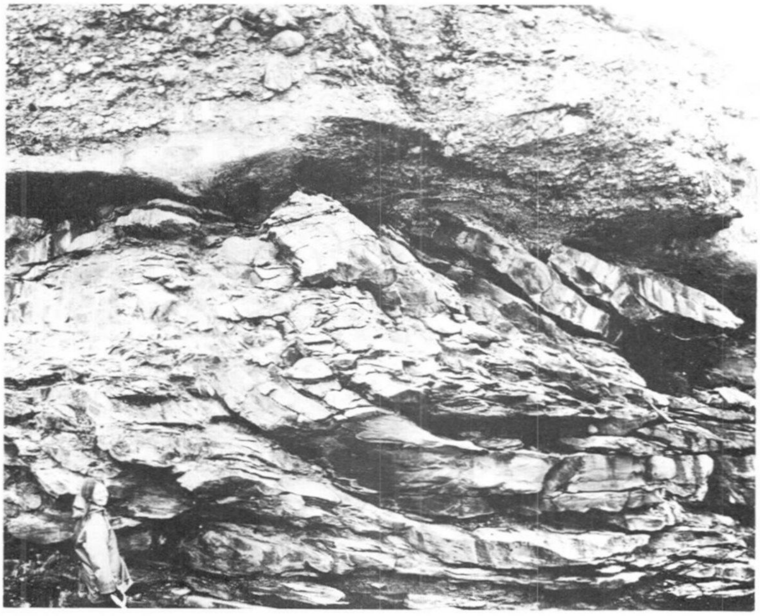


Fig. 6. Medium-bedded sandstones overlain by coarse conglomerates of facies S3, Smalfjord Formation, north coast of Vieranjarga. The sandstones show soft-sediment folds and thrusts indicating a paleoslope toward the west (right).

the water body in which these beds were deposited.

S4 interbedded sandstones and mudstones. Sandstones occur in thin to medium beds, laterally continuous, and display grading, parts of Bouma sequences, sole marks, convolute bedding and slump structures. These beds are interpreted to be turbidites.

The two diamictite facies are massive diamictite (D1) which is interpreted as lodgement tillite, and stratified diamictite (D2) which formed as supraglacial/proglacial flow diamict, melt-out till and winnowed till and conglomerate (Edwards 1975b, 1978). The principle occurrences of these facies are illustrated below.

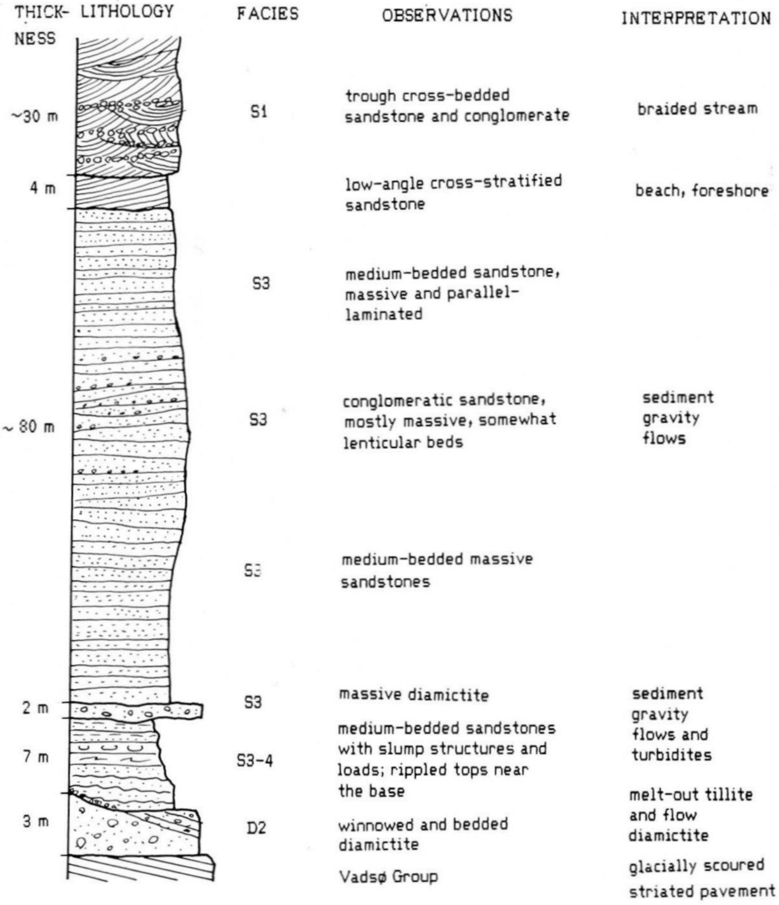
Description

Vieranjarga – The eastern part of this peninsula on the southern shore of Varangerfjord (Fig. 4) has excellent exposures of both lodgement tillite (facies D1) and supraglacial (facies D2) diamictites at the base of the Smalfjord Formation (Fig. 5; Edwards 1975b). These facies wedge out towards the northwest and are overlain by a thin braided stream deposit (facies S1). This in turn is overlain by a 50–75 m thick succession of possible sediment flow sandstones (facies S3), periodically cut by poorly sorted coarse conglomerates resting in steep-sided channels (Fig. 6). This unit is abruptly overlain by approximately 30 m of trough cross-bedded sandstones with occasional lenticular conglomerate beds (facies S1), an inferred braided stream deposit.

Selešnjarga – The southern slope of this peninsula has fine outcrops through the Smalfjord Formation, which exceeds 100 m in thickness (Fig. 7). Most attention has be focused on the unique striated pavement and overlying 'Reusch's moraine' only a few meters thick, which occurs at the base of the formation, at sea level. Many explanations have been offered for the origin of both the pavement and the tillite. Recently, Edwards (1975b) argued that the pavement was glacially scoured, and the tillite formed as a combined melt-out till and flow diamict unit, left by a retreating glacier. The overlying section is dominated by 80 m of primarily massive, medium-bedded sandstones, and interpreted as liquified sediment flow deposits, similar to those at Vieranjarga. Above is a 4 m thick low-angle cross-set interpreted as a prograding foreshore deposit. It can be traced along strike for 3.5 km (M. Carpenter, pers. comm.). At the top of the section are trough cross-bedded conglomeratic sandstones and conglomerates, which resemble the braided stream deposits at Vieranjarga.

Skjåholmen – This narrow island in the center of Varangerfjord (Fig. 4), has excellent exposures of the Smalfjord Formation, here at least 60 m thick (Fig. 8), particularly on the eastern half of the

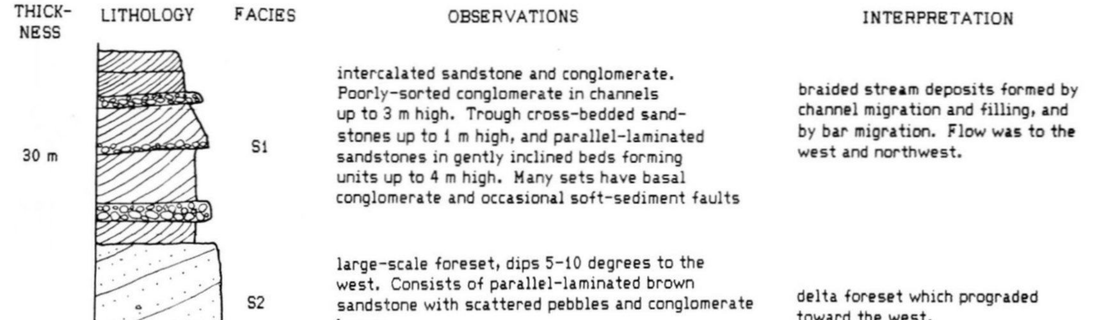
Fig. 7. Simplified vertical sequence through the Smalfjord Formation at Oaibaččannjarga.



island. The basal unconformity is unusual in that the surface, which generally is subparallel to bedding in the Vadsø Group, locally cuts down vertically as much as 4 m (Figs. 9 & 10). Coarse breccias composed of blocks of the underlying sandstones and shales are preserved against the paleoscarps. The smooth truncation of the beds suggests glacial erosion, and the irregular relief of the unconformity may reflect bedding control on that erosion. The overlying glacial sequence is complex (Figs. 8, 9, & 10), and could only be examined during a brief visit. As at Vieranjarga and Oiabaččanjarga turbidite-like sandstones and mudstones (facies S4) rest directly on the unconformity. These deposits are erosively overlain by two contrasting lenses of massive tillite (facies D1), both which have a higher clast concentration, and change in the color of the matrix at the top, suggestive of subaerial winnowing and weathering (Fig. 11). These units are eroded into an approximately 10 m thick cross-set of conglomeratic sandstone (facies S2; Fig. 12).

Nesseby – Along the coast is a discontinuous section through the Smalfjord Formation; the basal unconformity is not exposed. Near the base is a 10 m thick cross-set of sandy conglomerate (?facies S2). Above, to the west of Nesseby point is about 30–50 m of stratified conglomerates and sandstones, frequently trough cross-bedded (facies S1). At the top is a grey-green diamictite, about 1 m thick, followed after a gap of 1 m by the basal red shales of the Nyborg Formation.

Bergebyelva – Important outcrops along this river north of Bergeby (Fig. 4) were examined briefly. At 2 km inland is a large outcrop showing 6 m of massive grey and brown tillite (facies T1), containing crystalline, dolomite and sandstone clasts, passing up into 6 m of bedded and laminated diamictite, which is in turn overlain by 30 m of medium to thick-bedded, massive and parallel-laminated sandstones (similar to facies S4). Another kilometer north several meters of



THICKNESS	LITHOLOGY	FACIES	OBSERVATIONS	INTERPRETATION
30 m		S1	intercalated sandstone and conglomerate. Poorly-sorted conglomerate in channels up to 3 m high. Trough cross-bedded sandstones up to 1 m high, and parallel-laminated sandstones in gently inclined beds forming units up to 4 m high. Many sets have basal conglomerate and occasional soft-sediment faults	braided stream deposits formed by channel migration and filling, and by bar migration. Flow was to the west and northwest.
10 m		S2	large-scale foreset, dips 5-10 degrees 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 toward the west.
0-4 m		D1	mostly massive tillite, to the west is sandy with dolomite clasts, and to the east with crystallines and much sediment derived from underlying unit. Both tillites have local clast-rich zone at the top, up to 1 m thick.	probable lodgement tillite suggested by erosion and incorporation of underlying sediment. Possible subaerial weathering and winnowing at the top.
0-15 m		S4	thin- to medium-bedded, parallel-laminated sandstone with intercalated mudstone. Sharp contacts, occasional grading, and erosive, pebbly bases. Isolated gravel lenses, and pebbles scattered in sandstone and mudstone. Abundant soft-sediment folding with axial planes tipped to the west. Clasts of dolomite, sandstone and crystallines. Local basal breccia of large, angular blocks of Veidnesbotn Formation	sediment deposited rapidly on a slope by turbidity currents or sediment gravity flows. Basal breccia may be reworked glacial drift.
			Unconformity: local strong relief as near vertical walls up to 4 m high, and striking N-S and NE-SW. Sharp breaks in slope.	glacially scoured surface may have been locally modified by wave and current erosion. Steep slopes may be paleo wave-cut cliffs.
			Veidnesbotn Formation, Vadsø Group.	

Fig. 8. Generalized, composite vertical succession through the Smalfjord Formation at Skjåholmen.

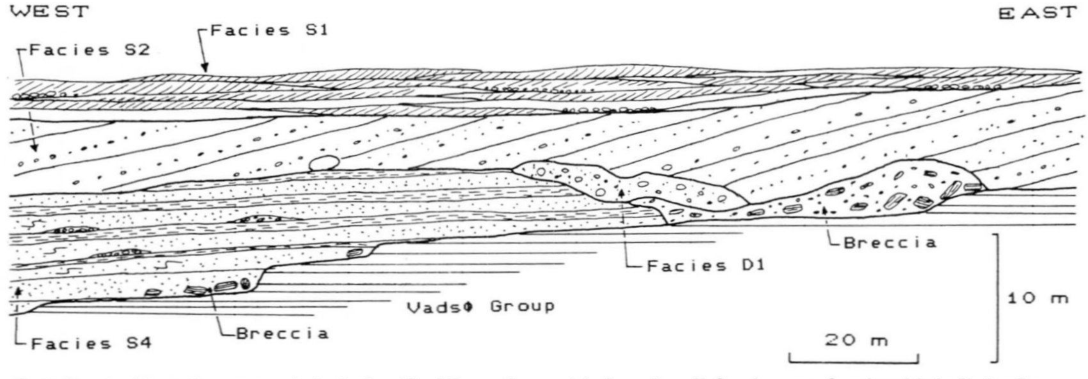


Fig. 9. Sketch of the sedimentary units in the Smalfjord Formation, and the irregular relief on the unconformity with the Vadsø Group, eastern part of Skjåholmen.

green-grey massive tillite are sharply overlain by the red shales of the Nyborg Formation.

Handelsneset – These excellent exposures occur near the eastern limit of the Smalfjord Formation (Fig. 4), where both it and the overlying Nyborg Formation are cut out beneath the Mortensnes Tillite 3 km to the east. Four adjacent outcrops

Fig. 10. Four-meter high vertical paleoscarp on Skjåholmen. Behind the geologist are interbedded sandstones and shales of the Veidnesbotn Formation, Vadsø Group. He is examining facies S4 sandstones of the Smalfjord Formation. About 1 m in front of him is a large block eroded from the Vadsø Group.

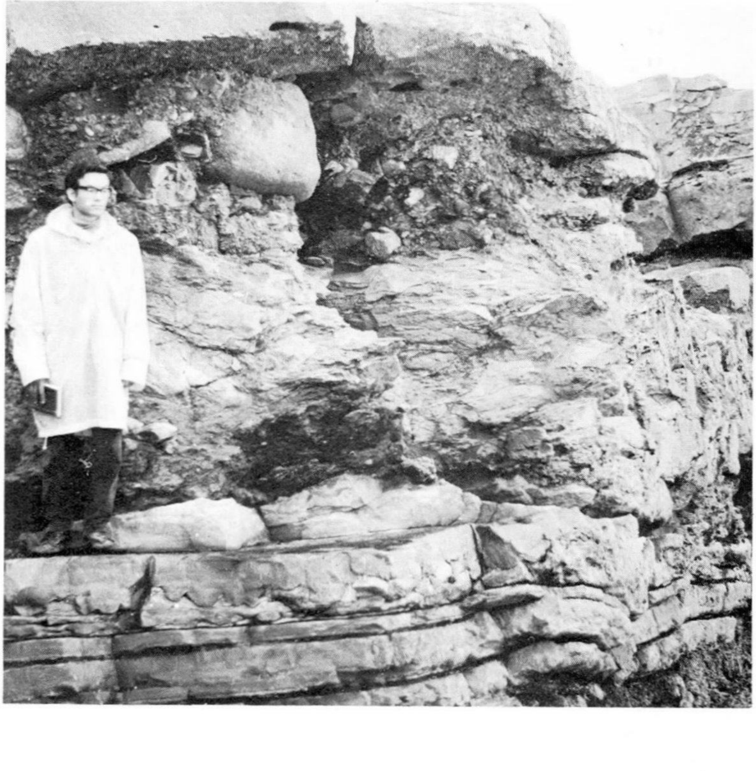


Fig. 11. Massive tillite, facies D1, in the Smalfjord Formation, at the eastern end of Skjåholmen. The tillite rests erosively on evenly-bedded sandstones, facies S4, and is overlain by the large foreset, facies S2. In the upper meter of the tillite, the color appears darker, and the clasts are more concentrated, suggesting subaerial winnowing and weathering.

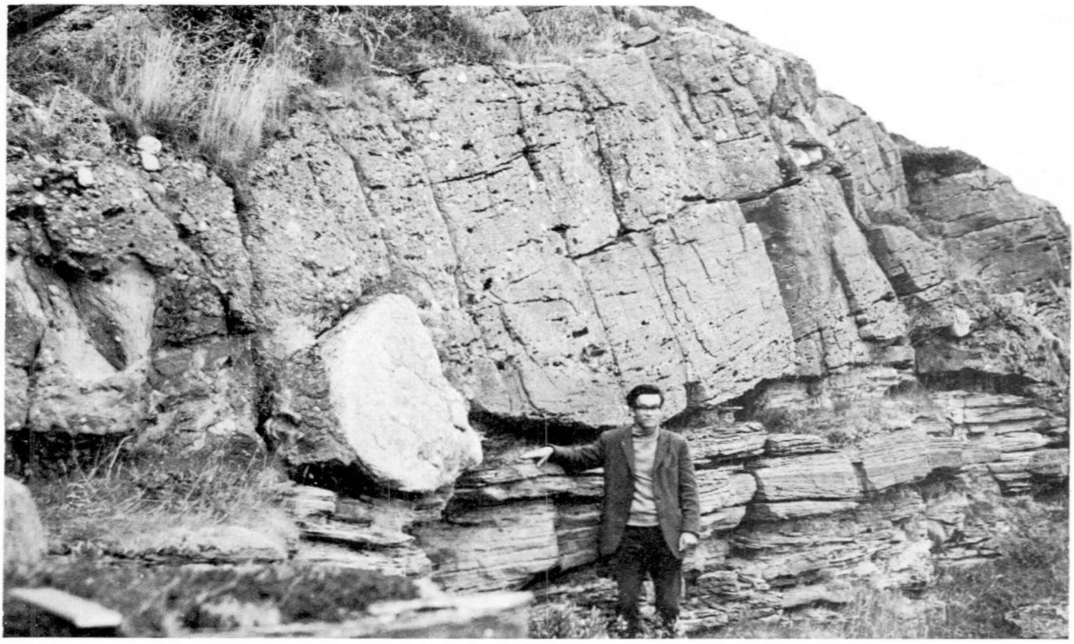


Fig. 12. Interbedded sandstones and shales of facies S4 are erosively overlain by the large-scale foreset, facies S2. Along the contact is a very large granite clast, possibly a remnant of a once more continuous tillite. The location along the south shore of Skjåholmen is indicated (Fig. 9) at the site of the large clast.

display a wide assortment of conglomerates and sandstones, and the unconformity at the base of the Formation erodes southwards through about 140 m of the Vadsø Group over a distance of about 800 m (Fig. 13). This is an overall slope of 10 degrees, but in detail the surface is smooth but undulating. The smooth but sharp truncation of the underlying beds suggests glacial erosion. The deposits overlying the unconformity show great variability, and differ somewhat from those described in the west. They include poorly sorted conglomerates and conglomeratic sandstones that resemble ice-contact glacial outwash (Banks et al. 1971), well sorted conglomerates with well rounded pebbles that resemble beach deposits, layers of diamictite that may represent debris flows, large-scale foresets formed by delta progradation, and sandstones deposited by turbidity currents or sediment gravity flows.

Depositional History

As described by Bjørlykke (1967) paleocurrents in the Varangerfjord area are generally to the northwest and west. This applies to trough cross bedding (facies S1), large-scale foresets (facies S2), and numerous examples of soft sediment folding and faulting in facies S3 and S4.

The morphology of the unconformity at the base of the Smalfjord Formation indicates that prior to glacial deposition, a large broad paleovalley was scoured into the Vadsø Group sandstones and shales, with the basement forming the southern side of the valley. Transport directions indicate that the ice moved toward the northwest, and the ice front retreated toward the southeast. The bulk of the valley fill consists primarily of meltwater deposits, especially cross bedded sandstones and conglomerates, which require considerable volumes of glacial meltwater, and suggest a temperate or warm glacial regime. In contrast, glacial deposits were preserved along the valley floor and rim, for example the supraglacial deposits at Vieranjarga (Edwards 1975b), suggesting that the ice margin was periodically cold and froze sediment and water to its base.

The reconstructed depositional sequence suggests the following sequence of events.

1) Glacial scouring of the paleovalley,
2) Irregular retreat of the glacier, leaving behind ice-cored moraine such as the 'Reusch's moraine', and the tillites at Vieranjarga,
3) Gradual rise in water level, turning much of the valley into a lake or fjord,
4) Continued deglaciation, with much release of

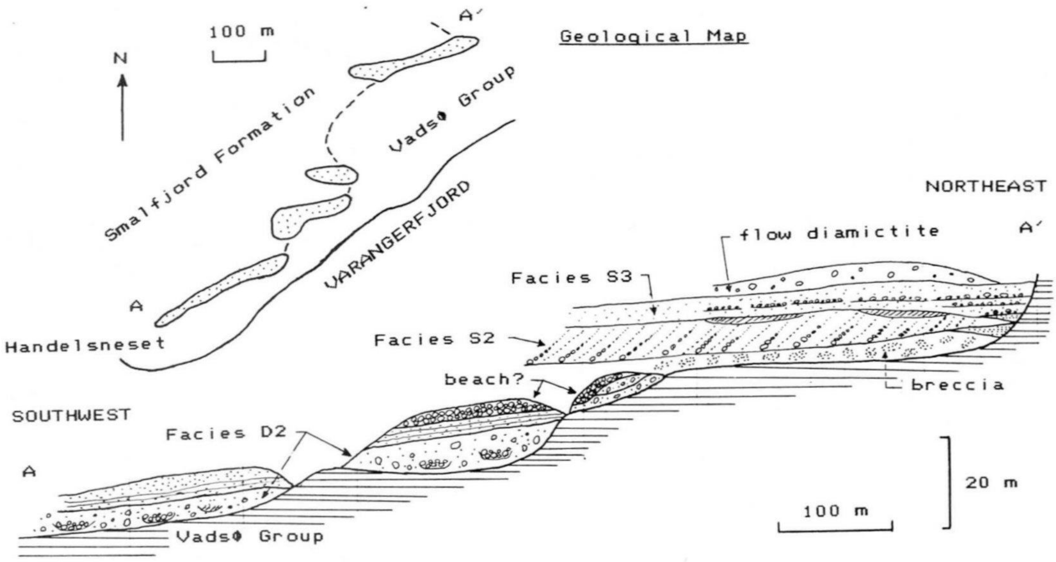


Fig. 13. Map of outcrops of the Smalfjord Formation at Handelsneset, and foreshortened cross-section of sedimentary units preserved. Dramatic erosion of the Vadsø Group is evident.

meltwater and rapid progradation of deltas and associated coastlines, and deposition of sandur plain deposits above sea level and sediment gravity flows below sea level, filling the shallow trough,

5) Additional diamictites high in the sequence may suggest subsequent glacial episodes, or slumping of sediment down the valley sides.

KROKVATN PALEOVALLEY

The Krokvatn paleovalley was defined by Føyn & Siedlecki (1980) based on extensive field studies on Laksefjordvidda (Fig. 3). Using additional previous work by Føyn (1967) and Edwards et al. (1973) they mapped the Krokvatn Sandstones whose distribution delineates a NW–SE-trending valley about 15 km wide, over a length of 30 km. The valley cuts down several hundred meters into the underlying Tanafjord Group and is filled primarily with sandstone and subordinate diamictite having a total thickness of about 300 m.

This sequence was subdivided into five informal members. The lower and middle diamictites are each 15 to 25 m thick, mostly grey, in part red, with a sandy matrix and clasts of sandstone, granite and gneiss. Clasts of red granite in the middle diamictite are similar to outcrops in the nearby basement, suggesting a northwest direction of transport. The resemblance and probable correlation of the lower diamictite to the grey lower tillites at Oiabaččanjarga and Vieranjarga was mentioned. The upper diamictite is a complex unit, up to 100 m thick, containing a buff tillite with dolomite clasts and matrix, a grey tillite with sparse crystalline clasts, and laminated mudstones with purple and blue-grey color. The upper diamictite member closely resembles parts of the Smalfjord Formation at Tanafjord, and detailed correlation between these areas, essential to establishing the regional extent of glacial units and the ice sheets that deposited them, is treated under 'Tanafjord Region', below.

The lower and the upper Krokvatn sandstone members, about 70 m and 200 m thick respectively, were characterized by Føyn and Siedlecki by their general lack of bedding and internal structures. They suggested that some of the finer sandstones and coarse siltstones might have been deposited as windblown silt and sand. However, they favored rapid deposition of sand from suspension in a quiet environment, with fresh water enabling clays to remain in suspension and be further transported away from the paleovalley. These authors pointed out the overall similarity of the valley morphology and the resulting fill to the Varangerfjord paleovalley, described above. Much of the sandstone in the Smalfjord Formation at Varangerfjord has a massive appearance, as described above, and in inland exposures even bedding is often difficult to detect. Perhaps the greater tectonism of Laksefjordvidda further subdues sedimentary features. Thus, it is possible that the Krokvatn sandstones were deposited by a similar mechanism to the structureless sandstones (facies S3) at Varangerfjord. The precise mechanism is uncertain, but was probably dominated by sedimentary gravity flow mech- anisms including liquified sediment flows to turbidity currents.

Depositional History

Føyn & Siedlecki (1980) inferred periodic advances and retreats of glaciers, on the basis of the alternation of tillites and non-glacial intervening deposits. They referred to this periodicity as stadial and interstadial, with reference to the Nyborg Formation as interglacial, and the Smalfjord and Mortensnes Formations representing glacial periods. This terminology is followed in this paper, more in reference to scale, rather then as a precise comparison with the periodicity of Quaternary climatic events.

The prominent feature of the Smalfjord Formation on Laksefjordvidda, as with Varangerfjord, is glacial erosion of a broad, gentle valley, followed by filling for the most part with sandstone. Derivation of granite clasts from the local basement indicate that the glacier from the southeast. The abundance of sandstone is again taken to indicates proportionally high volumes of glacial meltwater in reworking and transporting debris into the valley. The upper diamictite horizon signals a major change in the glacial climate and landscape.Tillite units at this level have much greater continuity than those below, and the interstadial deposits are primarily mudstones and siltstones rather than sandstones. This development is typical of the Tanafjord area.

TANAFJORD REGION

In the Tanafjord area the Smalfjord Formation displays a characteristic alternation of tillite and mudstone. A type area was designated between Smalfjord and Vestertanafjord (Fig. 3). Important outlying outcrops occur along Giilašjåkka northwest of Njukčagaisa,the Ruoksadas (Raudberget) cliffs, Arasuolo (Areholmen), the Austertana district in the east, and at Trollfjord in the north. Many of these localities were described by Føyn (1937) and Reading & Walker (1966). The eastern extremity of the outcrop of the lower part of the Vestertana Group around Austertana was mapped and described by Beynon et al. (1966). I was unable to reach the important outcrops at Skalnjuovča in the Hana valley south of Austertana due to diving buzzards.

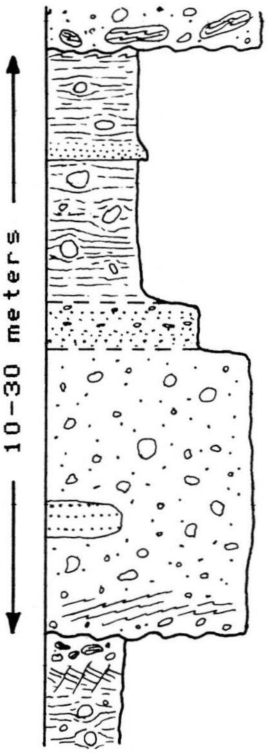
The combined factors of Caledonian folding and faulting, and Quaternary glaciation of a high-relief area have produced fine outcrops of the Smalfjord Formation in the Tanafjord region. Upstanding ridges of tillite can be followed in many cases for kilometers and detailed changes in facies can be mapped. These observation led to the recognition of a repetitive vertical sequence: 1) erosion surface, 2) lodgement tillite, and 3) laminated mudstone, occasionally with an intervening sandstone unit (Fig. 14). Further, individual tillite units could be mapped over areas of 10's to 100's of square kilometers, and the significant changes in lithology between successive tillites suggested that each sequence reflected 1) glacial erosion (erosion of underlying deposits), 2) glacial deposition (primarily of lodgement till) and 3) glacial retreat (proglacial deposits such as laminated mudstones). With this framework, each genetic sequence has been designated as an informal member, from 'A' (lowest) to 'E' (highest) and each contains at least two components; tillite and mudstone (Fig. 15).

Facies

The technique of facies analysis has been applied to glacial sequences by several workers; in this paper I follow Edwards (in press.) who classified glacial facies according to sediment texture and internal structure as related to depositional environment.

Massive lodgement tillite – Deposited in the subglacial zone, lodgement till generally appears structureless. It is the dominant facies in the Tanafjord area. The thickness varies from several to several tens of meters. The base is erosive, which is demonstrated by removal of underlying beds as seen regionally by mapping, or on outcrop scale by cutting out of beds, and by incorporation of the underlying material, especially if poorly consolidated at the time of erosion, into the tillite above. The exertion of glacial stresses against the substrate locally led to deformation structures. In particular 'step faults' (Biju-Duval et al. 1974) and folds (Berthelsen 1979) can be used to determine the direction of glacier flow. Massive tillite units contain rare, isolated bodies of stratified sandstone or conglomerate, deposited *in-situ* by subglacial meltwater (Edwards 1975a).

Banded tillite – Occasionally, locally-eroded material was mixed with far-travelled debris in the lower part of the glacier; the partial mixing of these materials by glacial shearing produces a marble-cake appearance which Edwards referred to as banded lodgement till. Similar structures in



LITHOLOGY	INTERPRETATION
Rhythmically laminated mudstone, with occasional dropstones and rare beds of graded sandstone.	Deposition from suspension by fresh-water overflow plumes in glacial marine setting; also rafting from floating ice, and rare density underflows depositing turbidites.
Crudely, horizontally laminated and bedded, poorly sorted sandstone with pebbles and silt.	Deposition at ice margin by tractional underflows and sediment gravity flows.
Massive tillite with rare in-situ bodies of stratified sediment.	Lodgement tillite with rare subglacial stream deposits.
Banded tillite.	Banded lodgement tillite
Erosion surface.	Subglacial erosion and incorporation of substrate into the glacier base.
Deformed substrate.	Subglacial deformation of substrate: deformation tillite.

Fig. 14. Summary of the tillite-to-mudstone sequence typical of the Smalfjord Formation in the Tanafjord area. Intervening sandstones are seldom observed. Only one example of proglacial outwash along a terrestrial ice margin was observed.

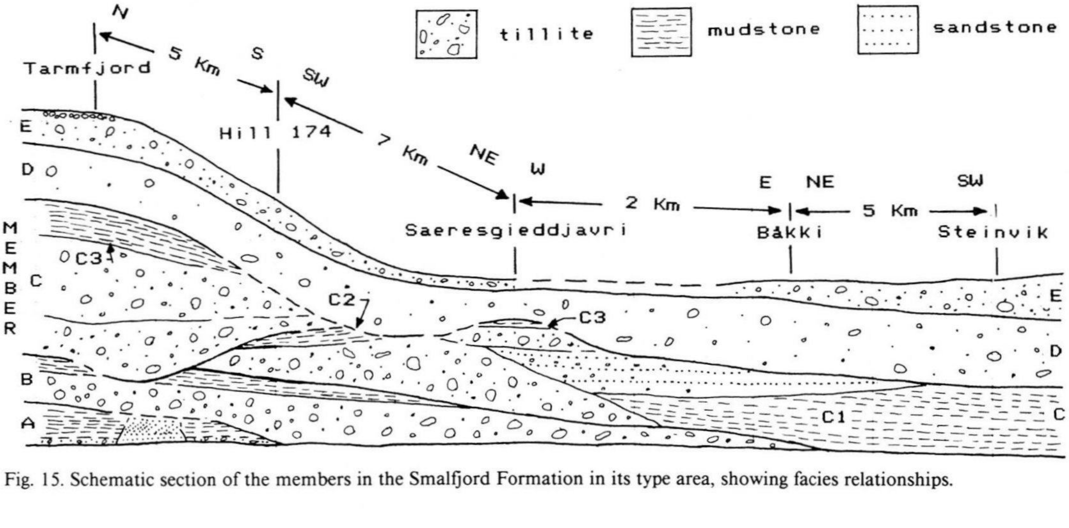


Fig. 15. Schematic section of the members in the Smalfjord Formation in its type area, showing facies relationships.

Quaternary tills have been called 'bands' (Berthelsen 1979) and 'smudges' (Krüger 1979). Banded tillite is often associated with the lower contact of the tillite sheets in this region.

Stratified sandstone and conglomerate – This facies accumulates where meltwater is concentrated at the ice margin. However, it is quite rare in this area, in the contrast to the paleovalleys described above. Examples resemble facies S1 and 3 in the Varangerfjord area.

Laminated mudstone – A wide range of mudstones occurs in this area, varying in color, pro-

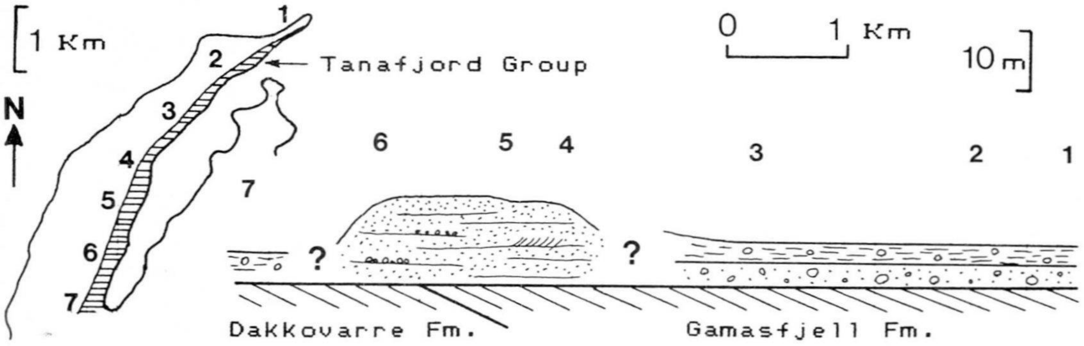


Fig. 16. Map and cross section of member A along the west side of Tarmfjord.

Table 1. Properties of the tillite units in the five members of the Smalfjord Formation, type area south of Tanafjord. * = most prominant clast type.

MEMBER	AREAL EXTENT	MAXIMUM THICKNESS	COLOR	CLASTS			MATRIX	SEDIMENT SOURCE	TRANSPORTED FROM
				CONCENTR.	SIZE	COMPOSITION			
E	7 x 20 Km	15 m	buff-yellow	5-10%	average 5 cm	*dolomite & crystalline	sand in carbonate groundmass	Tanafjord Group, Grasdal Fm ?older till	???
D	15 x 30 Km	30 m	grey-green	1-2%	average <5 cm max. 60 cm (cryst.)	*sandstone, dolomite & crystalline	sandy, silty mudstone	Tanafjord Group especially Vagge Fm	north
C	10 x 70 Km	40 m	brown & purple	10-20%	average 2-10 cm max. 70 cm (cryst.)	*dolomite & crystalline	sand in carbonate groundmass	Grasdal Fm, basement	north
B	10 x 70 Km	15 m	buff-yellow	25-60%	average 5-20 cm max. tens of meters	dolomite	dolomite with few sand grains	Grasdal Fm	northeast
A	3 Km	2m exposed	purple & green	5-10%	average 5 cm	sandstone	sandy siltstone with ferruginous cement	Tanafjord Group, Dakkovarre Fm	south?

minence of lamination, whether lamination is random or rhythmic, and abundance and composition of dropstones. In addition, some units contain beds of sandstone or diamictite. Most units are less than 10 m thick, but can be traced for at least several kilometers.

Member A

Member A is exposed along the west side of Tarmfjord (Fig. 16), where it contains tillite (Table 1), mudstone (Table 2) and sandstone (Table 3). The tillite is unusual in that it consists of clasts of fine sandstone set in a matrix of similarly textured sandstone, having a ferruginous cement. It is interpreted as a lodgement till, locally derived primarily from the ferruginous sandstone member of the Dakkovarre Formation, which subcrops beneath the unconformity with the Smalfjord Formation in this area.

The mudstone unit has a striking purple color, and distinct stratification (Føyn 1937, plate 4). Parallel-laminated mud is interrupted by very thin to thick laminae of siltstone (Edwards, in press) which display diatactic grading (Sauramo 1923). The poor sorting may indicate deposition from sediment-laden, freshwater overflow plumes (Edwards, in press). Some laminae contain rows of current ripples indicating bottom flow to the south to southwest. Rare dropstones formed plomp-and-drape structure. At the top, the mud-

Table 2. Properties of the mudstone units in the Smalfjord Formation, type ara.

MEMBER	*MAXIMUM THICKNESS	COLOR	STRUCTURE	CLASTS			
				COMPOSITION	DISTRIBUTION	AMOUNT	SIZE
E	30 cm	yellow-brown	random	dolomite, crystalline	dispersed	moderate	<1 cm
D	6 m	green	random	dolomite, crystalline	dispersed and in rows	moderate	mostly <5 cm, up to 30 cm
C3	5 m	green	rhythmic	—	—	none	—
C2	7 m	purple & green	rhythmic & random	mainly dolomite	in rows, increasing upward	few-> mod.	mostly < 5 cm, up to 20 cm
C1	10 m	green	random	—	—	none	—
B	3 m	purple	rhythmic	mainly dolomite	dispersed	few	mostly < 5 cm, up to 20 cm
A	2 m	purple	rhythmic & random	mainly dolomite	dispersed and in rows	rare	mostly < 2 cm, up to 8 cm

Table 3. Properties of the sandstones in the Smalfjord Formation, type area. The wind blown siltstone (loessite) is included for comparison.

Member and Locality	Texture	Structure	Associated Lithologies	Interpretation
Trollfjord	Moderately well sorted siltstone with fine pebbles in rows, homogeneous in thin section	crudely parallel-lam., medium parallel beds	lodgement tillite below, subaqueous mudstone above	loess
C, below C2 mudstone Type Area	poorly-sorted sandstone with few pebbles	massive, faintly parallel-lam.	as above	glacial marine
C, pebbly sandstone above C1 mudstone Type Area	very poorly sorted sandstone and pebbly sandstone	massive, parallel-lam., crudely horiz. bedded, rare grading, soft-sed. faulting	as above	as above
B, unit 2 at Auskarnes	moderately sorted sandstone and pebbly sandstone	steep- and gentle-sided asymmetrical scours filled with parallel-lam. sandstone	interfingers with supraglacial stratified diamictite	proglacial braided stream
A, Tarmfjord and south of Laksefjord	moderately sorted sandstone, locally conglomeratic	massive, parallel-lam. cross-bedded, broadly fines up at Laksefjord	passes laterally into purple mudstone, rests on regional unconformity	ice-contact outwash

stone is severely deformed along the contact with the overlying massive tillite of member B.

The sandstone unit is up to 15 m thick. It is brown-yellow, weathering dark brown to purplish brown, poorly sorted, medium-grained, and medium-bedded. Structures include parallel lamination and cross bedding. There are a few dispersed sedimentary clasts, and rare crystalline

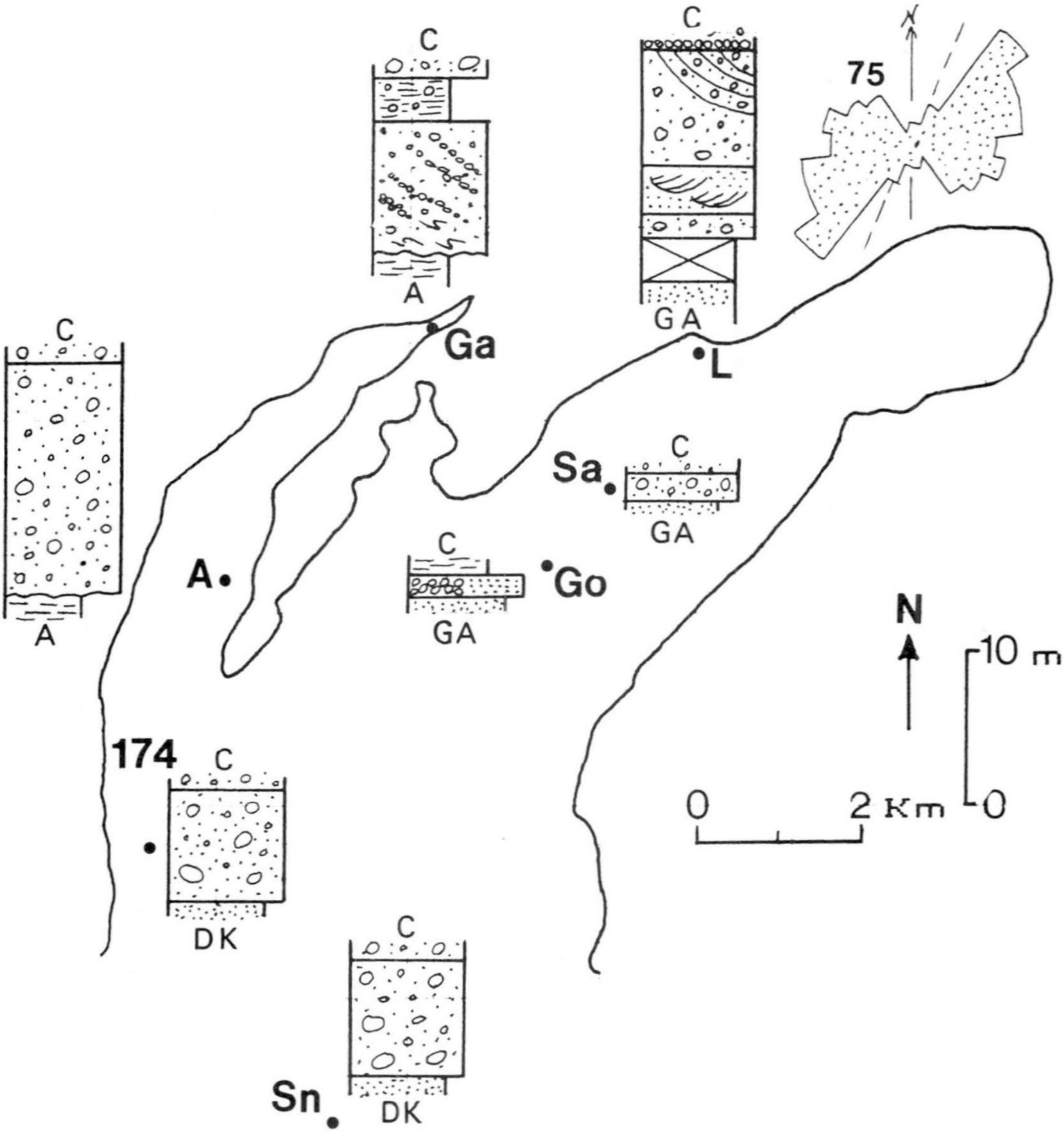


Fig. 17. Facies distribution in member B in the type area. Symbols: A through E = member of Smalfjord Formation, Dk = Dakkovarre Formation, Ga = Gamasfjell Formation, Va = Vagge Formation. Locality abbreviations: A, Addjagiidčåkka; B, Bakki; C, Cagannjarga; Ga, Gaessenjarga; Gi, Giilašjåkka; Go, Goakkebavtjavri; L, Luovtat; Sa, Saeresgieddjavri; Sn, Snuollajavri; St, Steinvik. Orientation of clast long axes in plane parellel to bedding, dashed line is cleavage.

clasts. The origin of the sandstone is uncertain due to the limited exposure, but the limited lateral extent suggests an ice-contact feature such as an esker or kame.

Member B

Member B occurs throughout the type area (Fig. 17), and extends to Rouksadas, Arasuolo, Giilašjåkka and Laksefjordvidda, and possibly north to Trollfjord (fig. 3). The member comprises tillite (Table 1), mudstone (Table 2) and pebbly sandstone (Table 3). It rests on various formations of the Tanafjord Group, and on member A of the Smalfjord Formation, and in most areas is overlain by member C.

The tillite is mostly massive, but a dramatic occurence of banded tillite occurs in the west side of Tarmfjord, at Gaessenjarga. The massive tillite is distinguished by its bright buff color, and high concentration of dolomite and chert clasts,

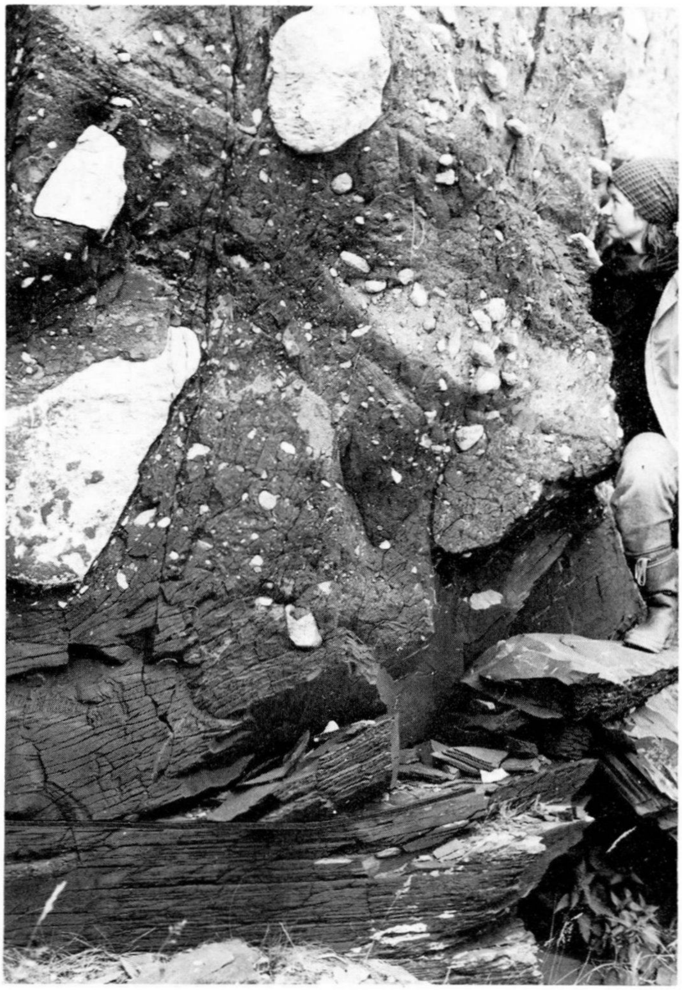


Fig. 18. Well laminated mudstone of member A, lowermost, is sharply overlain by cleaved massive mudstone occurring at the base of member B tillite unit. Above, the bands in the banded tillite dip toward the northeast (right), implying glacial flow toward the southwest. Gaessenjarga, Tarmfjord.

and dolomitic matrix (Table 1). There are rare *in-situ* stratified bodies of sandstone, which formed in subglacial tunnels.

Banded tillite in the lower part of member B is developed where the tillite rests on purple mudstone of member A. The zone of banding is about 10–15 m thick, and is overlain by massive tillite. The bands are formed by the intermixing in the base of the glacier of exotic buff-colored glacial debris with locally derived purple mud. Mixing was initiated when frozen, unlithified sediments along the sole of the glacier were carried up into the body of the ice by thrusting. The slabs of debris-bearing ice were emplaced sequentially in a direction opposed to that of glacier flow. The excellent preservation of deformation structures may reflect final deposition by subglacial melt-out. Where mixing proceeded far, a homogeneous brownish purple tillite was formed. At the base of the zone, the underlying purple mudstone has been homogenized (Fig. 18), and below a decollement surface, the mudstone retains its lamination, but displays step faults. The northeasterly dip of the step faults indicates that the stress from the overriding ice was directed toward the southwest. The dominant structure in the banded tillite is isoclinal folding which is developed on all scales (Fig. 19). Towards the top of the unit, the banding becomes more even in appearance, and looks very similar to sedimentary lamination (Fig. 20). In general the bands dip toward the northeast, suggesting glacial flow from that direction.

Northeast of Auskarnes at Luovtat is a unique occurrence of stratified sandstone, conglomerates and tillites. The pebbly sandstones show scour-and-fill structures and trough cross bedding (Reading & Walker 1966, Fig. 3). The tillites

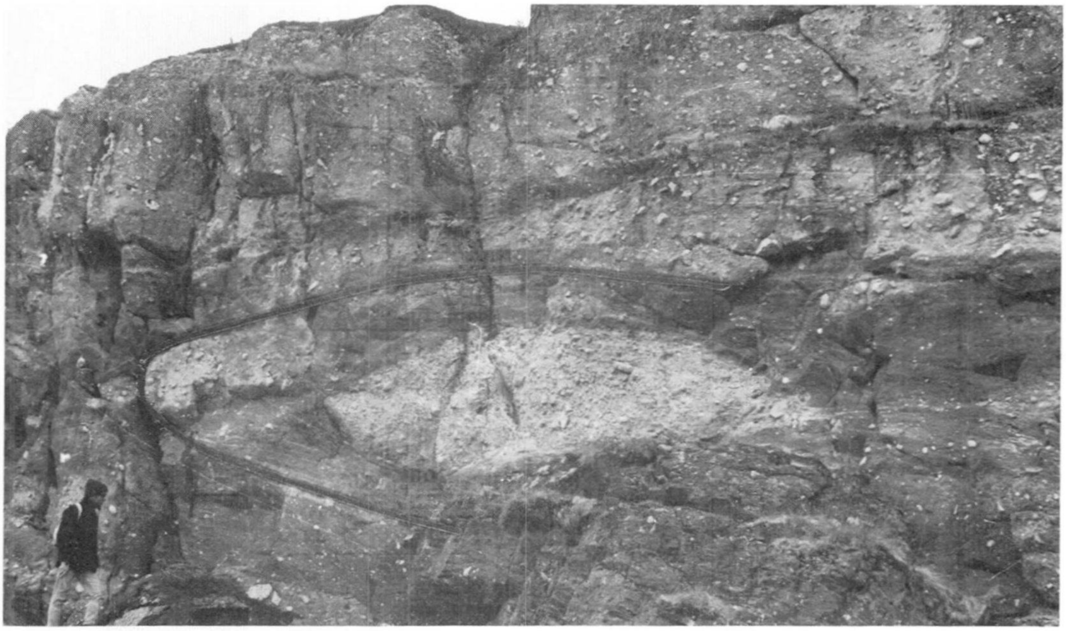


Fig. 19. Large-scale banding and overfolding in banded tillite of member B; Gaessenjarga, west of Tarmfjord. Bands dip toward the northeast (right).

Fig. 20. Banding in member B tillite, Gaessenjarga, Tarmfjord, with a very even appearance mimicking depositional lamination.

are unusual in showing local variations in texture as brought out by clast concentration, while at the top and base of the member, the tillite shows bedding. This is horizontal at the base, but at the top is bowed into a trough (Fig. 21). Truncating the bedded tillite is a layer of boulders, up to head size, whose composition indicates association with the overlying member C tillite. These stratified deposits in member B were interpreted by Reading & Walker (1966) as having formed beneath a wet-based ice shelf. The interpretation proposed here is that the pebbly sandstones are proglacial braided stream deposits, and the stratified and bedded tillites represent slightly winnowed flow diamicts and melt-out tills in an ice-cored, end moraine complex.

Locally preserved at the top of the member is a purple, rhythmically laminated mudstone with few scattered dropstones (Table 2). The rhythms have a three-fold construction, with a basal fine sandstone, grading up into silty mudstone, sharply overlain by mudstone with faint lamination.

Member C

In comparison with the other members, member C is unusually complex (Figs. 14 and 22), contain-

Fig. 21. Bedded diamictite at the top of Member B at Luovtat. The beds are deformed into a trough-shape, and are erosively overlain by tillite of member C. The tillite beds probably formed as proglacial flow tills, later deformed by melting of buried ice.

ing two tillite units (Table 1), three mudstones (Table 2) and a pebbly sandstone (Table 3). The member extends from Ruoksadas to Giilašjåkka (Fig. 3), and it may continue to Laksefjordvidda. It rests on member B in the west, and on the Tanafjord Group in the east, cutting down from the Vagge Formation in the north to the Dakkovarre Formation in the south. It is overlain by member D.

The presence of at least two tillite units in this member is demonstrated by their occurrence in the same exposure, separated by mudstone. However, they are similar in appearance, suggesting that they cannot be correlated on the basis of appearance alone. Although most of the tillite is brown, purple tillite occurs in the lower part of the member, where it rests on the purple mudstone of member B. Banded tillite is developed along the color boundary. Near Luovtat (Fig. 22) member C tillite rests on member B tillite and contains several large blocks of the light buff tillite of member B (Fig. 23), whose inclined orientation suggest they were thrust up along shear planes in the glacier base. The northward dip indicates glacier flow from that direction. On the northern part of the peninsula between Tarmfjord and Smalfjord, material derived from the Vagge Formation is abundant in the basal parts of the tillite. The occurrence of this debris south of where the Vagge Formation was removed by glacial erosion suggests a component of glacial flow from the north. Tillite of similar overall composition occurs in the upper Krokvatn diamictite unit on Laksefjordvidda (Føyn & Siedlecki 1980).

The mudstones in member C have contrasting features (Table 2). The oldest, C1, has random lamination and no dropstones. This unit is volumetrically dominant and extends to Ruoksadas, where it is about 12 m thick. The next, C2, has primarily random lamination with a few graded laminae, and there are a few dropstones which increase in abundance upwards. The youngest, C3, has rhythmic lamination, with laminae up to 1 cm thick, but has no dropstones.

The pebbly sandstone unit is prominent in the eastern and central parts of the area, and a similar lithology occurs at Ruoksadas. It is medium to coarse grained, poorly sorted, and very feldspathic, with a clayey, carbonate matrix. It tends to occur above the C1 mudstone where the latter is present. The sandstone lacks channeling or cross-bedding, and may represent subaqueous outwash deposited in front of a glacier margin

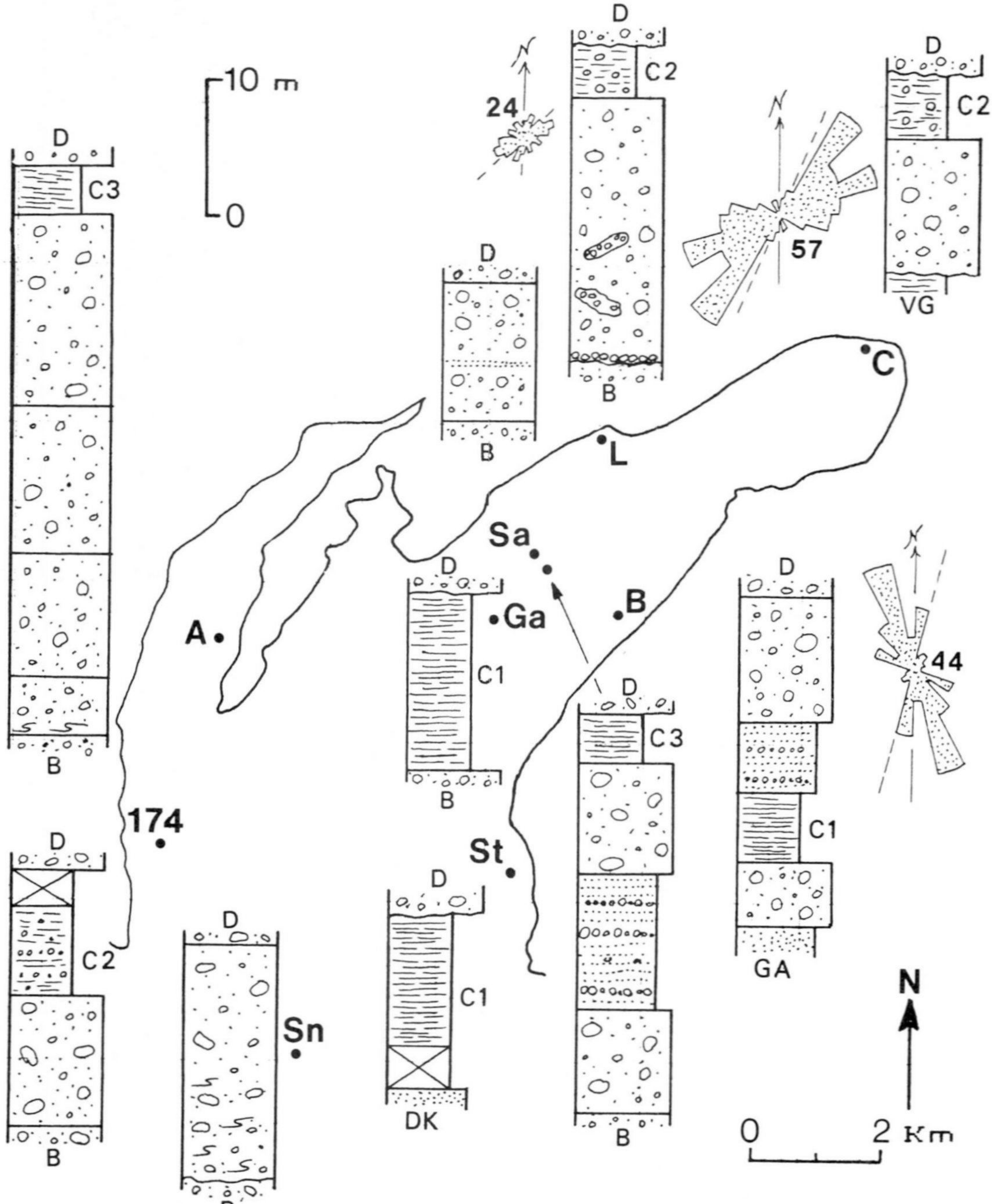


Fig. 22. Facies distribution in member C in the type area. Abbreviations as in figure 17.

which terminated in standing water, possibly by currents such as turbidity flows or sediment gravity flows.

Member D

This member consists of only a tillite unit and a mudstone unit, but it is laterally continuous in the type area (Fig. 24), and can be traced to

Fig. 23. Raft of member B tillite in the lower part of Member C tillite. The raft dips toward the north, suggesting it was upthrust in the base of a southward flowing glacier; Luovtat.

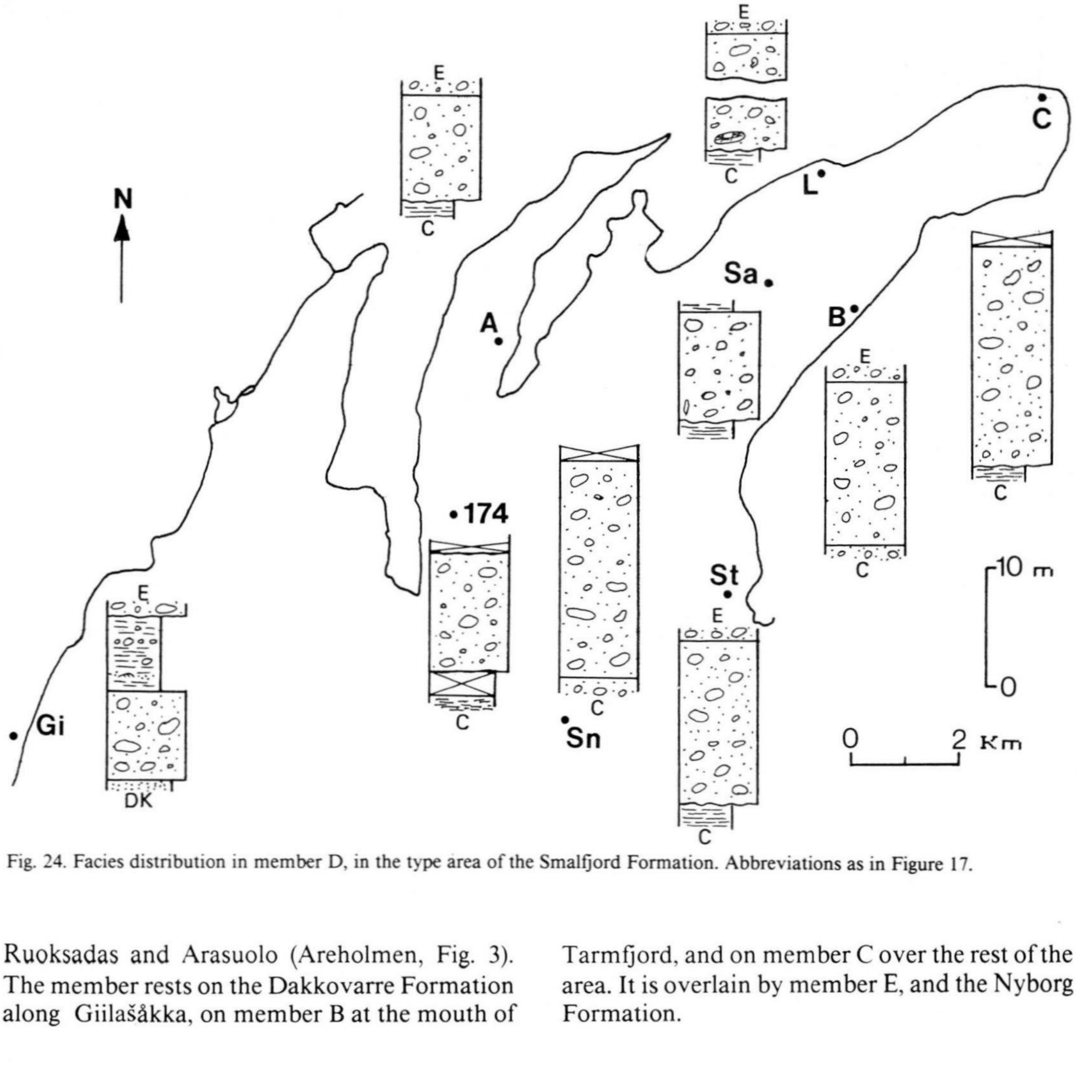


Fig. 24. Facies distribution in member D, in the type area of the Smalfjord Formation. Abbreviations as in Figure 17.

Ruoksadas and Arasuolo (Areholmen, Fig. 3). The member rests on the Dakkovarre Formation along Giilašåkka, on member B at the mouth of Tarmfjord, and on member C over the rest of the area. It is overlain by member E, and the Nyborg Formation.

Fig. 25. Step faults at the base of member D, Addjagiidåkka, Tarmfjord. The faults dip toward the northeast (right), suggesting glacier flow from that direction.

Fig. 26. Mudstone unit in member D showing dropstones and a sandstone turbidite bed with a waning flow sequence of sedimentary structures: parallel-laminated sandstone overlain by ripple-laminated sandstone. Cross-lamination indicates flow to the south.

In typical inland exposures, the tillite (Table 1) appears massive, but in the coastal exposures near Luovtat, faint banding, in part isoclinally folded, was observed. Here, the lower part of the tillite unit contains large blocks, 1 – 2 m high and at least 5 m long, of the underlying mudstone unit, C2. The blocks are deformed into step faults, folds and thrusts. These structures indicate

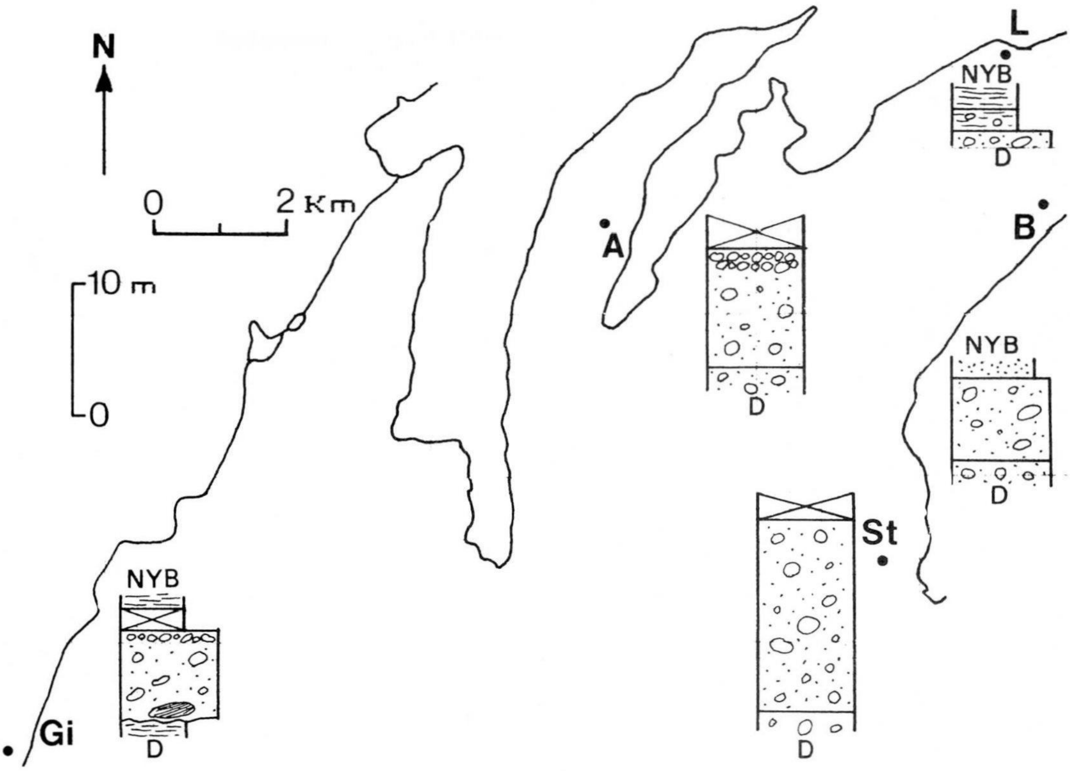


Fig. 27. Facies distribution in member E, type area. Abbreviations as in Figure 17; Nyb = Nyborg Formation.

glacial flow toward the south. At the mouth of Tarmfjord, the tillite rests on member B mudstone, and here step faults also indicate southward flow (Fig. 25). North of Njukčagaisa, the tillite rests on sandstones of the Dakkovarre Formation, and the lower part of the tillite is enriched in sand, which decreases upwards. An interesting feature of this unit is the lateral variability in clast content. This averages 1–2 percent of most of the Smalfjord area, but increases to about 10 percent west of Njukčagaissa. The low clast content is probably due to dilution of exotic glacial debris with locally derived, poorly consolidated mudstone from the Vagge Formation.

The mudstone unit in member D (Table 2) has fine horizontal lamination with numerous dropstones. A couple of thin sandstone beds displayed a waning-flow sequence of sedimentary structures, with ripple cross lamination indicating flow toward the south (Fig. 26).

Member E

The youngest member in this area consists mostly of tillite, with minor mudstone and conglomerate in the upper part. The member rests erosively on member D, and is overlain by the Nyborg Formation (Figs. 15 and 27).

The tillite (Table 1) generally appears massive, apart from local banded zones at the base, where it rests on member D mudstone or tillite. At Tarmfjord and at Giilašjåkka the tillite is overlain by a bed, up to 2 m thick, of rounded dolomite pebbles and cobbles. This appears to be a lag conglomerate, formed by winnowing of the underlying tillite. No data on glacier flow direction could be obtained.

Additional Observations

Several localities which could not be tied into the member stratigraphy of the type area are described briefly below.

Austertana District – East of Store Leirpollen (Fig. 3) the lower part of the Vestertana Group is very condensed (Beynon et al. 1966). The Smalfjord Formation is only about 8 m thick, and rests on quartzites of the Hanglečerro Formation. The tillite is massive, dark grey green, with small dolomite clasts in a muddy matrix with scattered sand grains.

Divgoaivi – About 1 km southeast of this hill,

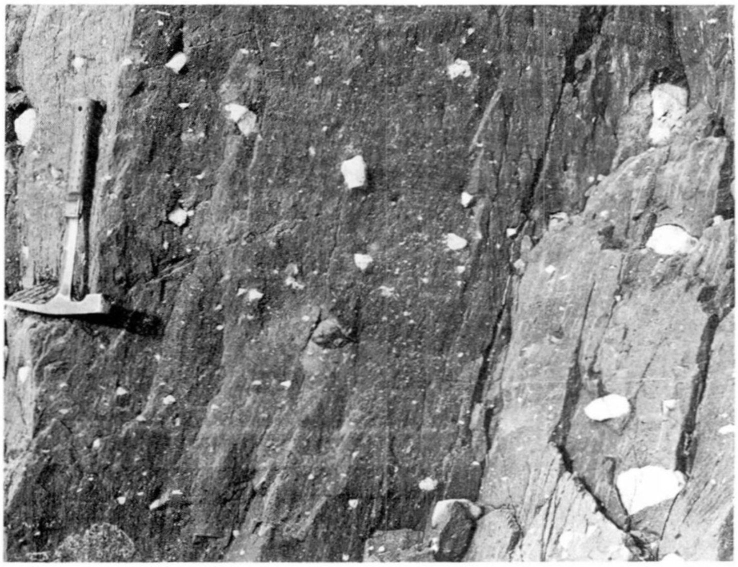


Fig. 28. Faintly banded, cleaved tillite in the Smalfjord Formation, south of Trollfjord. In the photograph the banding is horizontal and the cleavage close to vertical.

elevation 489 (479), located 6 km west of Njukčagaisa is a small anticline which brings up the Smalfjord Formation. A dolomite-rich tillite, similar to member A tillite is overlain by a tillite with a variety of clasts, similar to member C tillite. Also present is a mudstone with very well developed rhythmic lamination, which has been disturbed by high angle normal faulting. At the top of the formation is a 2 m deep channel filled with pebbly sandstone.

Trollfjord – North of Fadnuvaggi (Grasdalen), along Tanafjord (Fig. 3), are the northernmost preserved outcrops of the Vestertana Group. The Smalfjord Formation here contains three units (Edwards, 1979). At the base is 6 m of banded grey tillite with predominantly dolomite and mudstone clasts (Fig. 28). Between the tillite and the underlying black shales of the Grasdalen Formation is a thin layer of highly sheared shale. Reading & Walker (1966) interpreted the tillite is a glaciomarine deposit conformably overlying the shales of the Tanafjord Group. However, Siedlecka & Siedlecki (1971) reinterpreted the contact as unconformable. The observations of subglacial erosion and deformation leading to a basal breccia and banded tillite support the latter view. Sharply above is 3–6 m of bedded siltstone with thin layers of granules and small pebbles. The siltstone has been interpreted as a indurated loess deposit – loessite (Edwards 1979). Sharply above is 50 cm of randomly laminated mudstone with wave-formed ripple lenses and scattered dropstones.

GLACIAL HISTORY OF THE SMALFJORD FORMATION

The regional unconformity below the Smalfjord Formation and the great thicknesses of rock removed attest to a lengthy period of erosion prior to the onset of glacial deposition. The presence of a glacially striated pavement at Oaibaččannjarga and the frequent signs of erosion below massive tillites indicate that at least the final erosion was glacial.

Glacial deposition occurred in an early valley glaciation and later ice sheet glaciation. The first phase includes the lower and middle diamictites and the lower and upper sandstones of the Krokvatn paleovalley (Føyn & Siedlecki 1980), and almost all of the Smalfjord Formation in the Varangerfjord paleovalley, with the possible exception of massive diamictites poorly exposed along the northern margin of the valley. In this phase, the Varangerfjord and Krokvatn paleovalleys were filled primarily with sandstones, although the presence of intercalated tillite horizons indicates at least two glacial advances and retreats. The sandstones were deposited primarily as sediment gravity flows in water of unknown salinity, and as braided stream deposits. The abundance of sorted and stratified deposits indicates the importance of meltwater near the glacier margin which suggests a temperate glacial regime during deglaciation. The paleovalleys collected meltwaters, thereby concentrating the stratified sediments in these areas.

The ensuing phase of ice sheet glaciation was

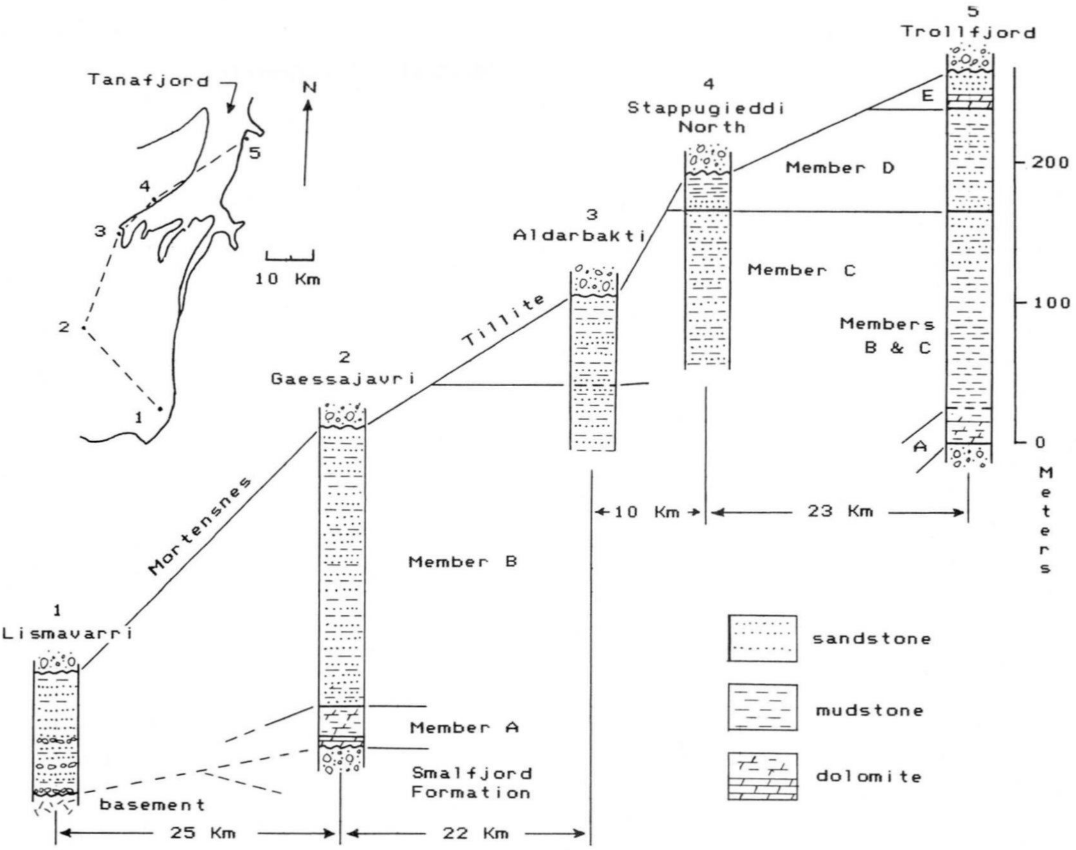


Fig. 29. Stratigraphy of the Nyborg Formation, based on correlation of the members between principle sections.

marked by accumulation of members A through E and lateral equivalents such as the upper Krokvatn diamictite, which consist of lodgement tillites with proglacial, probably marine, mudstones and rare sandy meltwater deposits. The configuration of the unconformity below these members suggests a low-relief surface, consistent with the lateral continuity of the tillite units. The mudstone deposits, characterized by rhythmic to random lamination, and rare to abundant dropstones, are not similar in detail to varves, and probably accumulated in shallow proglacial seas. The virtual absence of submarine outwash is attributed to rapid submarine retreat of the glacier, probably due to ice thinning and/or sea-level rise (Edwards, in press).

As with the first phase, the second phase was characterized by advances and retreats of the ice; at least five in the Tanafjord area. Each advance-retreat cycle deposited a lodgement tillite overlain by a laminated mudstone, rarely with an intervening sandstone (Fig. 14). The major changes in texture and composition between successive tillite sheets suggests major deglaciation and reorganization of the ice centers, analogous to Pleistocene glacial deposits of North America (e.g. Flint 1971).

The Nyborg Formation – Interglacial

The Nyborg Formation (Holtedahl 1960, 'red and brown sandstone and red and green shale' of Føyn, 1937) rests with a slight unconformity on the Smalfjord Formation, and is unconformably overlain by the Mortensnes Tillite (Fig. 29). Due to tectonic deformation, the thickness is difficult to measure in the Vestertana area (Fig. 30) where it is best developed, but is estimated to approximately 300 m.

The Nyborg Formation includes five informal members, from the base (Fig. 29):

A) buff dolomite and purple shale, usually 5–50 m thick,

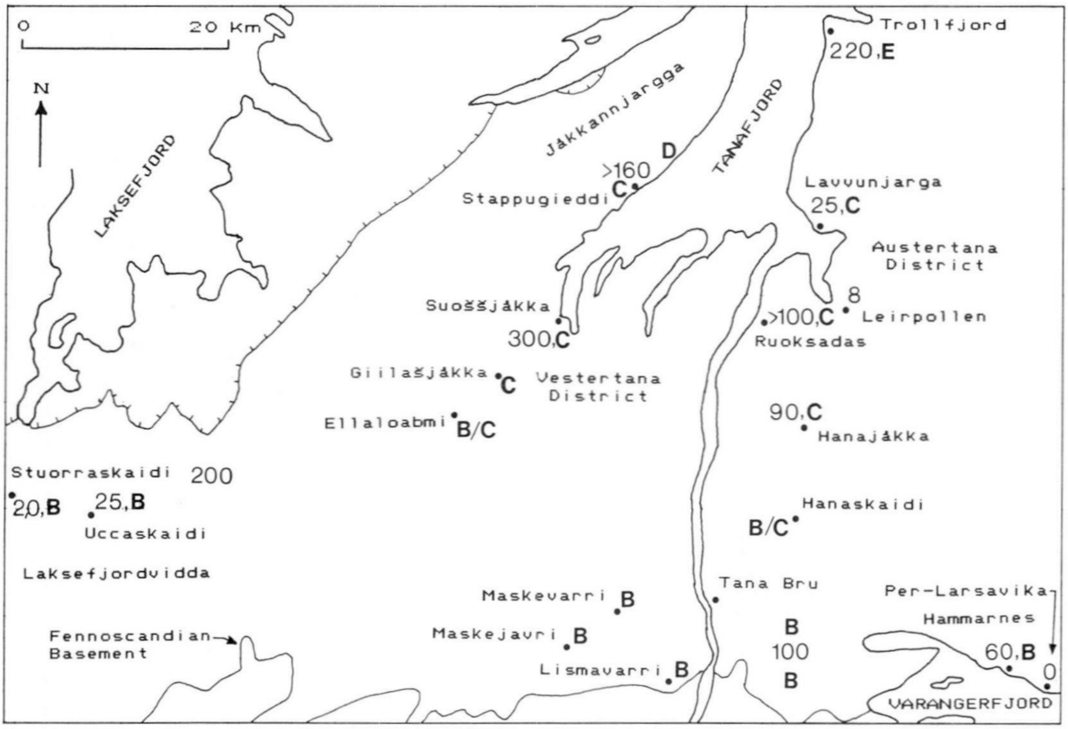


Fig. 30. Thickness of the Nyborg Formation, and member of the Nyborg Formation subcropping against the sub-Mortensnes Tillite unconformity. The rapid thinning of the Nyborg Formation towards the west on Laksefjordvidda and towards the northeast along Varangerfjord appear to reflect deposition over the margins of the Smalfjord Formation paleovalleys (see Fig. 3; Føyn & Siedlecki, 1980). The rapid thinning in the Austertana District may reflect deposition in an area of low subsidence rates.

B) interbedded red-brown sandstone and purple shale, up to about 200 m thick,
C) interbedded grey-green sandstone and shale, thickness unknown, but probably about 150–200 m,
D) purple sandstone and grey-green shale and sandstone, about 70 m thick, and
E) white-grey sandstone with interbedded dolomite, at least 25 m thick.

The younger members are present only in the north, where they are preserved below the sub-Mortensnes Tillite unconformity which cuts down toward the south (Fig. 30). Outside of the Vestertana area, the thickness of the Nyborg Formation decreases markedly; at Stuorraskaidi on Laksefjordvidda to about 20 m, east of Store Leirpollen to about 8 m, and at Per-Larsavika it is totally removed below the overlying unconformity.

In order to emphasize the genesis of the strata, the Formation is divided into four well-defined stages:

1) post-glacial transgression, member A,
2) quiet-water basin fill, member B and most of member C,
3) regressive transition to shallow water, top of member C, and
4) shallow marine and concluding transgression, members D and E.

STAGE 1: POST-GLACIAL TRANSGRESSION: MEMBER A

Facies

Overall, member A represents a transition from dolomite at the base to shale at the top. The member is very variable in thickness and lithology (Fig. 31). It consists of five facies.

1) Buff-yellow dolomite, 0 to 10 m thick. The lower part of this resistant bed shows coarse horizontal lamination, made up of alternating laminae of micrite, up to 5 mm thick, and spar, up to 2 mm thick, with occasional lenses of coarse spar with silica-infilled cavities. Polished specimens show the micrite to be flat, angular fragments separated by spar, with the coarse spar and silica filling voids between the fragments. It thus

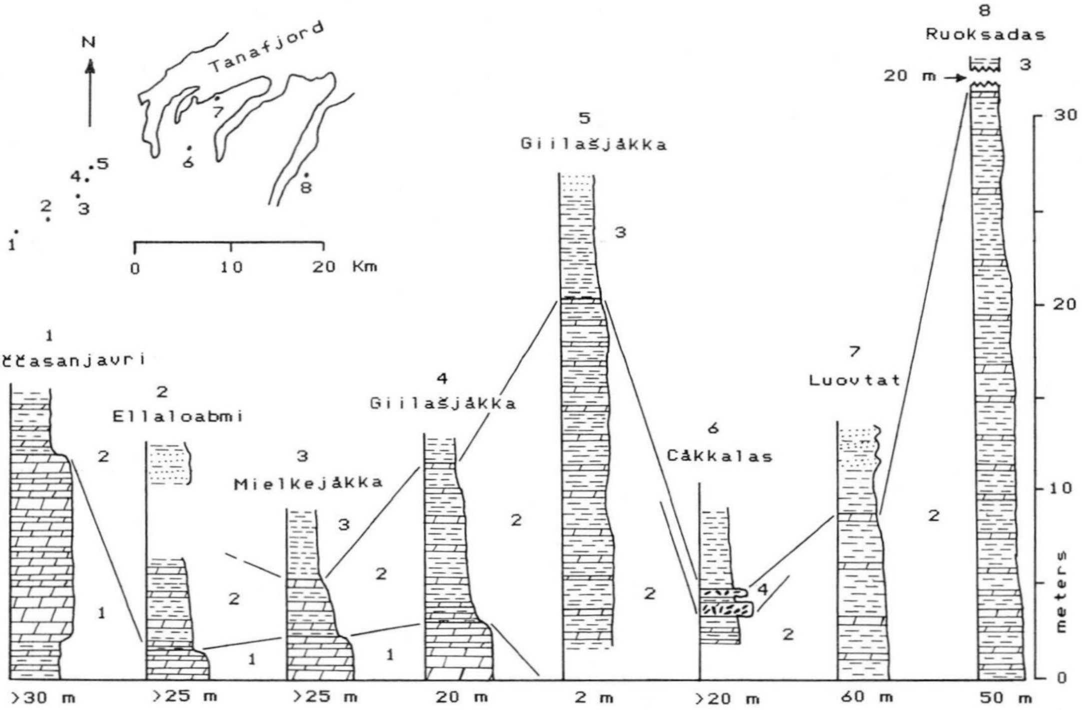


Fig. 31. Lithofacies 1 through 4 in member A of the Nyborg Formation, southwest and south of Tanafjord. The numbers along the bottom represent the thickness of the underlying Smalfjord Formation.

has the appearance of intraformational breccia. Towards the top, the dolomite is more evenly and finely laminated, due to variations in amount of fine sand grains of quartz and dolomite.

The even lamination and micritic texture of most of this facies suggest an primary or very early diagenetic origin, with deposition in quiet water, and restricted input of terrigenous sediment. The breakage of the micrite into plate-like slabs, and the subsequent infilling of the voids with spar suggest subaerial shrinkage and cracking of the micrite, with early cementation by spar, probably in a peritidal environment (Matter 1967). Rare, gentle, mound-like structures may represent some type of algal structure, but no definitive evidence was observed.

2) Alternating parallel laminae of purple mudstone and buff-yellow dolomite, up to about 25 m thick, rests on either facies 1, or the Smalfjord Formation. The proportion of dolomite decreases gradually upwards. This facies illustrates the gradual onset of terrigenous clastic sedimentation in the basin, which increases upwards. The even lamination and fine grain size attest to quiet water conditions.

3) Purple mudstone or shale up to 25 m thick occurs in most sections between facies 2 and member B. It is finely parallel-laminated and clay-rich. This facies represents the domination of clastic deposition, at the expense of carbonates.

4) Dolomite 'edgewise' conglomerate occurs in lenticular beds up to 60 cm thick, intercalated with facies 2 or 3. The beds are sharply or erosively based and may grade up into sandstone. The clasts are plate-shaped, faintly-laminated dolomicrite, in a matrix of purple mudstone or grey sandstone (Fig. 32). These conglomerates clearly represent retransport of 'low-energy' materials such as micrite, mud and sand by periodic high-energy currents.

5) Fine grained, apparently structureless sandstone up to several meters thick is rarely observed. Due to sarse observations, the origin of these sandstones is uncertain.

Facies 1 through 4 are widely observed in East Finnmark, from southwestern Varanger Peninsula to Laksefjordvidda. The first three normally occur in vertical sequence from the base of member A, while facies 4 occurs as interbeds in facies 2 and 3, and facies 5 is very rare, occurring in the lower part of member A. Excellent exposures of facies 4 near Mortensnes (Fig. 4), have previously

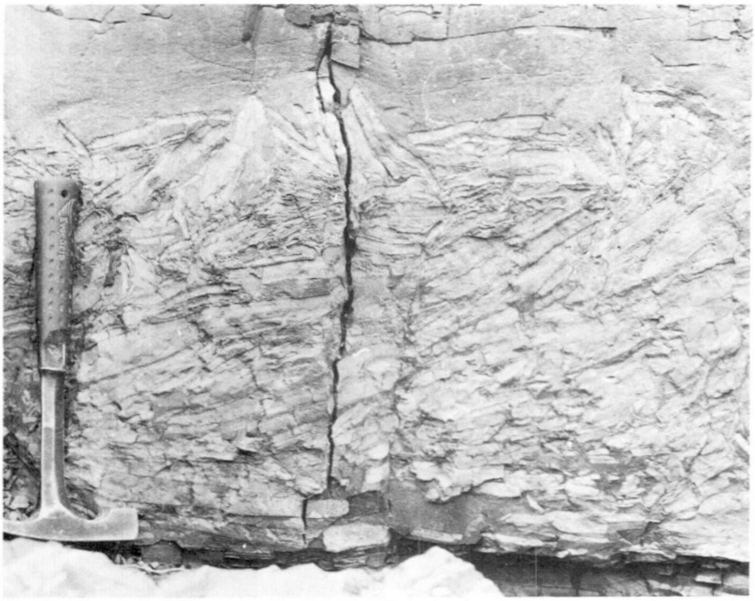


Fig. 32. Dolomite 'edgewise' conglomerate, facies (4) overlain by parallel-laminated fine sandstone. Pebble imbrication suggests flow to the north (right). Bergeby River, 3 km from the coast.

been described (e.g. Holtedahl 1918, Bjørlykke 1967). Ripple-laminated sandstones indicate current flow to the west, north and east. Along Bergebyelva, in gorges about 3 km inland from Bergeby, the deposits of facies 2 have been extensively deformed by small-scale penedontemporaneous faulting and slumping. The orientation of the features indicates a paleoslope dipping toward the north.

Depositional Model

The presence of carbonate sharply overlying the Smalfjord Formation suggests deposition during a rapid, overall transgression (Reading & Walker 1966, Banks et al. 1971). The lateral facies changes in member A observed in connection with thickness changes in the underlying tillite west of Njukčagaisa suggest that topography may have been an important control on facies deposition (see also Føyn & Siedlecki 1980). During the sea-level rise, dolomite was preferentially deposited around islands or highs in shallow water, while mud accumulated in the troughs (Fig. 33). This is consistent with the distribution of the conglomerates of facies 4 which represent dolomite, originally deposited in shallow water as facies 1, retransported into deeper water where mud was accumulating. The agent for this process was probably storm-generated currents.

STAGE 2, QUIET-WATER BASIN FILL: MEMBER B AND MOST OF MEMBER C

These deposits compose most of the Nyborg Formation and underlie vast areas. Because the Nyborg Formation is the lowest structurally incompetant unit resting on competant strata it is

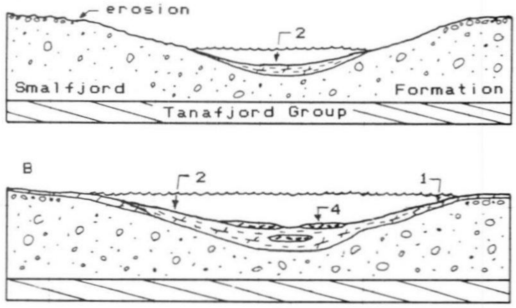


Fig. 33. Depositional model for Stage 1, post-glacial transgression (member A), Nyborg Formation. A) Facies (2) is deposited during gradually rising sea level. B) with higher sea level, facies (1) is deposited in the highs, but also retransported during storms into the troughs as facies (4) where facies (2) is normally deposited. C) Facies (3) is deposited over all areas as the entire area is submerged during further sea level rise.

Fig. 34. Massive and crudely horizontally-stratified sandstones and conglomerates in strongly erosive scours, facies (1) of member B, Nyborg Formation. Platy dolomite fragments were derived from member A dolomite. North coast of Varangerfjord, west of Nesseby.

usually tightly folded. It is thus impossible to measure long continous sections or accurately measure the thickness of these members.

Facies

Stage 2 comprises a continuum of facies, from conglomerates and coarse sandstones in the south around Varangerfjord, to fine-grained sandstones interbedded with shales over the central part of the study area, to drab siltstones in the north around Trollfjord (Fig. 30). Most of these sediments compare closely with turbidites and related deposits; they are interpreted here in terms of a submarine fan depositional model.

The four facies recognized are:

1) coarse, pebbly sandstone with minor conglomerate. Sandstones are massive to coarsely horizontally stratified, usually with an erosive base (Fig. 34). Conglomerates are moderately to poorly sorted, and also have steeply erosive bases. Pebbles may show imbrication. This facies was observed only at a few outcrops along the northern coast of Varangerfjord, in the vicinity of Hammarnes (Fig. 3).

2) thin- to thick-bedded sandstones, somewhat lenticular, mostly massive, rarely graded or inversely graded, but with concentrations of granules near the base. Cross-stratification, horizontal lamination and ball-and-pillow structure are rare. This facies was observed at Hammarnes (Fig. 35) and along the east bank of the Tana River at Tana Bru. Paleocurrents flowed to the north and northwest.

3) thin- to medium-, rarely thick-bedded, sandstone, laterally continuous and parallel-sided, interbedded with shale. This facies has the appearance of classical turbidites, however study is impeded by tectonism. Sandstone beds tend to occur in bundles, 10 to 30 m thick, with each bundle composed of a thickening upward sequence at the base (Fig. 36), and a thinning upward sequence at the top. In inland exposures, internal sedimentary structures are obscure, but at the coast, Bouma sequences (1962), characteristic sequences of sedimentary structures in turbidite beds, are seen. (In Bouma's classification, 'A' refers to the massive division, or structureless sandstone, 'B' to the lower parallel-laminated division, 'C' to the ripple cross-laminated division, and 'D' to the upper parallel-laminated division. The D division often grades up into the interbedded shale, division 'E'. The notation 'Tx' indicates the sequence of structures in an individual turbidite bed; 'x' refers to one or more

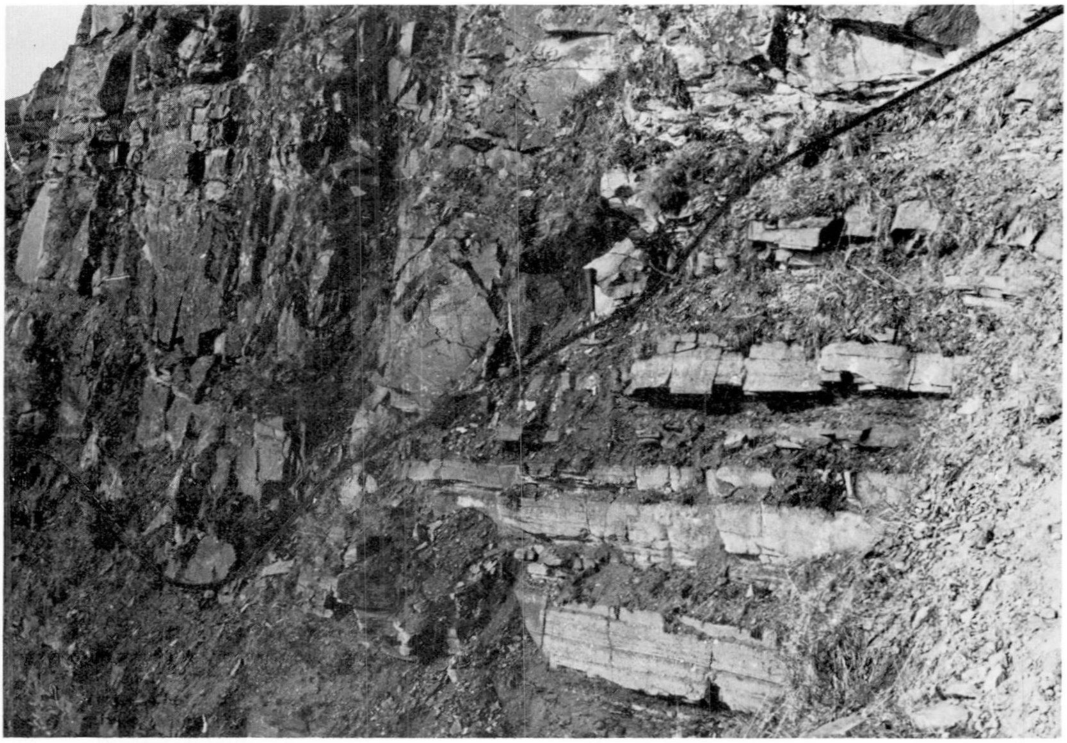


Fig. 35. Medium-bedded turbidite sandstones (facies 3) on the right, steeply cut out by medium- to thick-bedded sandstones (facies 2) on the left; member B, Nyborg Formation. The channel margin trends approximately north. Higher in this outcrop, the Nyborg Formation is unconformably overlain by the Mortensnes Tillite. Hammarnes, Varangerfjord, estimated at about 75 m from the base of member B.

Bouma divisions). Thicker beds have Ta-c sequences, while thinner beds show Tc. Beds have a sharp or erosive base, occasionally showing flute casts, a sharp top, and usually do not show grading well, especially where there is a limited range of grain sizes present.

From Varangerfjord to Tanafjord the grain size becomes increasingly finer (Føyn 1937), with very fine sand and coarse silt predominant at Stappugieddi on Jåkkanjargga (Digermul Peninsula). Bed thickness, up to about 1 m in the south, also decreases to the north. At Šuoššjåkka (Sjursjok), west of Vestertanafjord the intercalated mudstones have small-scale cross lamination. Facies 3 makes up most of members B and C, and outcrops widely in East Finnmark. It reaches its greatest thickness in the Vestertana district, about 200 m. Paleocurrents generally flowed north or northwest.

4) laminated siltstones with thin clayey partings and abundant ripple marks and cross lamination. This facies occurs at Ruoksadas, Lille Leirpollen and Trollfjord. At Trollfjord it reaches a maximum observed thickness of about 100 m, and the alternating purple and grey-green colors make it impossible to distinguish members B and C.

Facies 1, 2 and 3 are interpreted in terms of a relatively deep-water (i.e. base-of-slope and basin floor) submarine fan depositional model. Facies 4 represents relatively shallower conditions on the north and northeast sides of the depositional basin. Facies 3 closely resembles classical turbidites, with variable proximality (see Reading & Walker, 1966). It is similar to facies C and D of Walker & Mutti (1973), which are deposited on middle fan depositional lobes to the outer fan and basin plain. Facies 2 is similar to facies B2, sandstones without dish structure, of Walker & Mutti, and facies 1 resembles their facies A4, organized pebbly sandstones. Facies 1 and 2 accumulated upcurrent from facies (3) and considering the coarse grain-size and frequent channeling were deposited by strong currents in inner fan channel complexes.

Fig. 36. Bundle of thickening-upwards turbidite sandstone beds in member B of the Nyborg Formation, Ellaloabmi (Ellakløften), Vestertana.

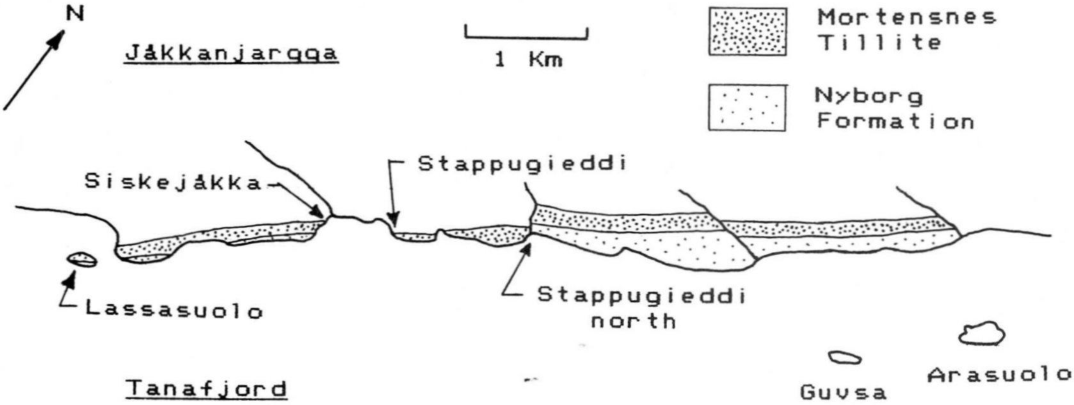


Fig. 37. Outcrop of Nyborg Formation and Mortensnes Tillite, Jåkkannjargga.

Depositional Model

The increasing water depth and initiation of large-scale submarine fan deposition marks a change from stage 1 conditions. The coarse proximal facies are restricted to the southern part of the study area. A significant component of facies 1 conglomerates is plate-shaped clasts of dolomite apparently derived from erosion of member A dolomite. This is consistant with high rates of isostatic uplift in the south, concurrent with and continuing after rapid post-glacial eustatic rise in sea level. The development of submarine fans may have been due to: 1) the relatively great depth of the basin, limiting the affect of shallow-water transport agents, 2) the enormous supply of sediment immediately following deglaciation, as a result of moderation of the climate and isostatic uplift, and 3) the presence of a signficant paleoslope along the southern margin of the basin, which developed by northward tilting of the area, and reflected the relatively high relief of the basement-to-basin transition zone. Selective glacial erosion along this zone probably higlighted the relief.

STAGE 3, REGRESSIVE TRANSITION TO SHALLOW WATER: TOP OF MEMBER C

Along the southeast coast of Jåkkanjargga a narrow strip of outcrop (Fig. 37), broken into disjointed segments by normal faults, has excellent exposures of the upper part of member C, and part of the overlying member D. The section at

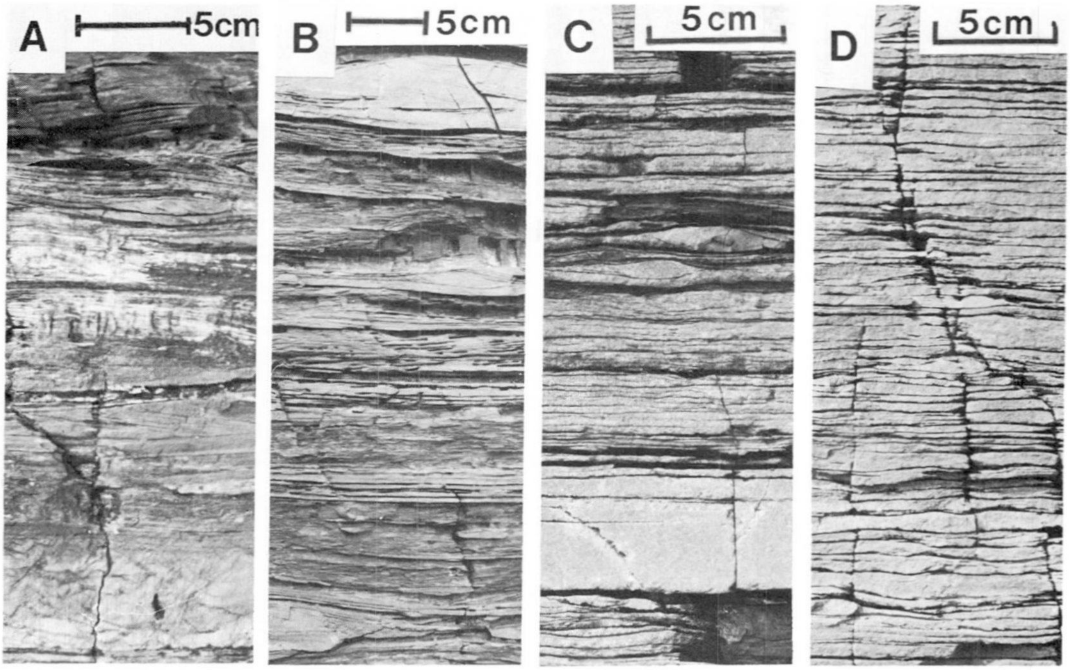


Fig. 38. Background facies in stage 3, Nyborg Formation, Stappugieddi north, Jåkkannjargga. A) 52 m below top of stage 3, lower slope environment, background is mostly facies 1 parallel-laminated mudstone with minor rippling. B) 25–30 m below top, top of upper slope, background is facies 3 siltstone laminae occurring in facies 1 laminated mudstone. C) 18 m below top, outer shelf, facies 3 laminae of siltstone with silty drapes and thin horizons of facies 2 siltstone with small-scale ripples. D) 10 m below top, shelf facies 3 laminae of siltstone with thin muddy drapes and occasional ripple lamination. Note laminae are thicker than in (C).

Stappugieddi north extends from the upper part of stage 2, through stage 3, up into stage 4, and is the basis for this section.

Facies

Stage 3 is a transition from basin plain, with turbidites deposited in quiet water, to high energy marine-dominated coastal conditions with intense reworking (Reading & Walker 1966). The base of stage 3 is placed at the appearance of reworking in the form of ripple lamination in the shales intercalated with the turbidite sandstones. The facies analysis is based on the distinction between two groups of facies: background sediments, which are fine-grained siltstones and mudstones representing the normal low-energy processes acting over long periods of time, and turbidite sandstone beds which represent relatively brief incursions of high-energy density underflows on the sea floor.

The three background facies are (Fig. 38):

1) finely parallel-laminated cleaved mudstone, probably deposited from suspension in very weak currents,

2) rippled fine siltstone and mudstone. In the lower part of the section, bedding plane exposures show mainly straight-crested ripple marks, whereas a wide variety, straight- to sinuous-crested and linguoid, are observed near the top. Ripples are mostly asymmetrical with rounded crests, and are less than 1 cm high and 10 cm long, much smaller than ripples in the adjacent sandstone beds. Current directions measured from ripple marks in bedding planes are bimodal bipolar, mostly ENE (Fig. 39). The ripple morphology indicates the concurrent activity of waves and currents (Harms 1969), and the overall energy of deposition was higher than for facies 1.

3) very fine sandstone and siltstone in thin parallel-sided to lenticular laminae, with thin muddy partings. Individual laminae may show internal lamination, or appear structureless. The exact mode of deposition is unclear, but it may have been either fall-out from wave-agitated suspensions (Reineck 1963), or lower flow regime traction currents. In either case, the conditions were probably of higher energy than that of facies 2.

The proportion of these facies changes vertically as a function of depth below the top of stage 3 (Fig. 40). At the base of the section only facies

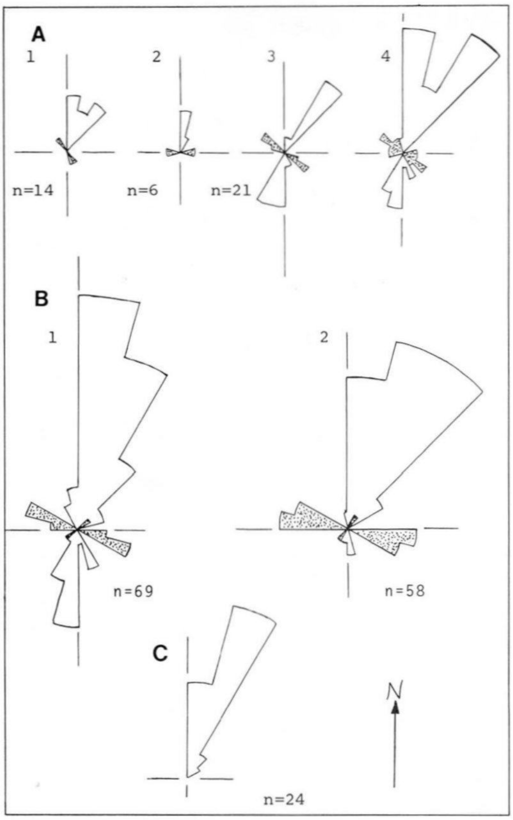


Fig. 39. Paleocurrents in stage 3, Nyborg Formation, Jåkkannjargga. **A:** ripple marks in background and on top of reworked sandstones at Stappugieddi north; 1) about 20 m below member 4, 2) about 16 m below member 4, 3) top 8 m of stage; Line omitted: 3, 4) sum of (1), (2) and (3). **B:** ripple marks in top 20 m of member 3; 1) south of Siskejåkka (Innerelv), and 2) north of Lassasuolo (Larsholmen). Plain area: current and combined flow ripples (asymmetrical). Stippled area: axes of symmetrical ripple marks. **C:** direction of sole marks of turbidite sandstones, Stappugieddi north. 'n' - number of observations.

1 is present; this is characteristic of stage 2. Sediment deposited from suspension may have been contributed from two sources: fallout of 'hemipelagic' mud, and settling from the tail region of turbidity currents. At about 55 m from the top of this stage, facies 2 appears and increases upwards to the top of the stage. At about 40 m, facies 3 appears, and it also increases in abundance upwards. Thus the background sediment indicates a gradual increase in energy of the invironment with time.

Sandstone beds are the other facies type in this stage. The 72 m long measured section contained 394 beds thicker than 1 cm (Fig. 40). The beds consist of poorly to moderately sorted silty very fine sandstone, with fine and medium sand appearing at the top of the sequence. Flute casts were observed at the bases of 30 beds, of which 24 yielded paleocurrent data (Fig. 39). On the basis of the internal sedimentary structures, almost all of the beds can be described in terms of Bouma divisions (1962), which are used to describe turbidite deposits. Four facies are recognized.

A) Massive sandstone, division 'A', occurs in Ta, Tab, Tabc, and Tac beds (Fig. 41A). This division is usually 4 to 10 cm thick, up to 32 cm thick, and is thought to have formed by rapid deposition from suspension and churning of the bed by the turbulent flow (Middleton & Hampton 1973).

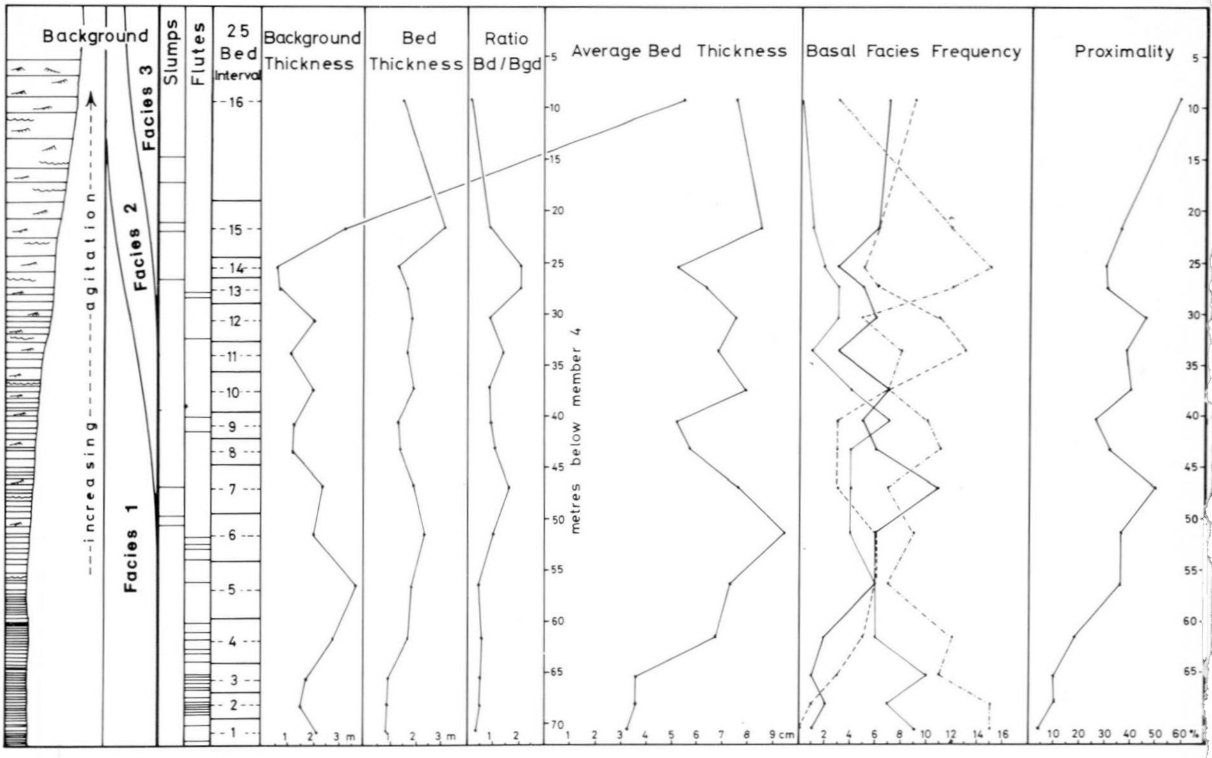
B) Parallel-laminated sandstone, division 'B', occurs in Tab, Tabc, Tb and Tbc beds, and is usually 6 to 10 cm thick (Fig. 41B). Deposition was in the lower part of the upper flow regime plane bed (Middleton & Hampton 1973).

C) Ripple cross-laminated sandstone, division 'C', occurs in Tabc, Tbc, Tac and Tc beds, and is usually 2 to 4 cm thick, reflecting the height of the ripples. Tc beds, and Tbc beds with a thin B division consist of a series of laterally spaced out ripples, which imparts a pinch-and-swell appearance to the bed (Fig. 41C). In thin beds, the ripples appear 'starved'. One bedding plane exposure of the ripples revealed a slightly sinuous, straight-crested morphology. The ripple wave length measured in section was 20–54 cm, averaging 30 cm. The 'swells' are usually constructed of one large ripple, with the lee-side laminae dipping about 10 degrees to the north. The ripples migrated forward with only minimal 'climbing'. A distinctive aspect is their rounded crests, which may reflect the presence of admixed fine sediment in the depositing current (Simons et al. 1963). Ripples form in the lower part of the lower flow regime.

A–>E) 'A' to 'E' sequences, notated as Ta–>e, are beds 1–5 cm thick, that grade rapidly upward from massive sandstone to mudstone without the intervening Bouma divisions (Fig. 41D). They appear to have been deposited rapidly from suspension, with little time for bed forms to develop (Walker 1967).

Depositional Model

Gradual upward-coarsening and inferred increasing ambient energy level of the background facies indicate a gradual shallowing of the sea through this interval. The laterally continuous, sharp- or erosive-based graded beds that dominate all but the uppermost part of the section are



interpreted as turbidites. The presence of gravity flows suggests that shallowing occurred, at least in part, by progradation of a slope across the area, rather than by aggradation alone. Reading & Walker (1966) inferred a rapid drop in sea level because of the short 9 m section between the uppermost turbidite and the shallow water tidal deposits of member D. However, as shown above, the first evidence of shallowing occurs 55 m below member D. If we assume that the effects of slow basinal subsidence and post-member 3 compaction acted to cancel each other out, and were relatively slow compared with the rate of sedimentation, then the 55 m thickness of the regressive interval provides a reasonable order-of-magnitude approximation of water depth, and a eustatic change in sea level need not be invoked.

Two assumptions allow integration of the data from 394 different beds into a coherent model:

1) during sedimentation there were no radical changes in the environment that might invalidate a sequential analysis of the beds, and
2) in any given part of the sequence, bed variability reflects somewhat different depositional circumstances for an 'average' type of current. Thus, beds at the top of the sequence reflect currents early in their development, while lower in the sequence changing conditions are seen in the changes in bed facies.

The beds' basal facies (maximum energy in a waning flow event) can be used as an indicator of relative current energy. The distribution of the basal facies as a function of depth below member D (Figs 40 & 42) shows a three-part pattern.

1) From 0 to about 25 m, A- and B-based beds decrease, while C and A->E beds increase in frequency.
2) From 25 to about 47 m, there are a number of trends, with successive peaks represented by B-, C- and then A-based beds.
3) From 47 to 72 m at the base of the measured section, A- and B-based beds almost die out, being replaced by C and A->E beds.

In the upper segment, the current was rapidly losing energy i.e., decelerating, in the middle segment there was an increase in energy (accelerating), while in the bottom segment there was again a marked decrease in energy (decelerating). While a turbidity current origin for the upper segment is possible, its position immediately subjacent to shallow water deltaic deposits suggests that this is unlikely. Rather, deposition by storm-generated bottom flows, or storm surges, seems more likely and is discussed further below.

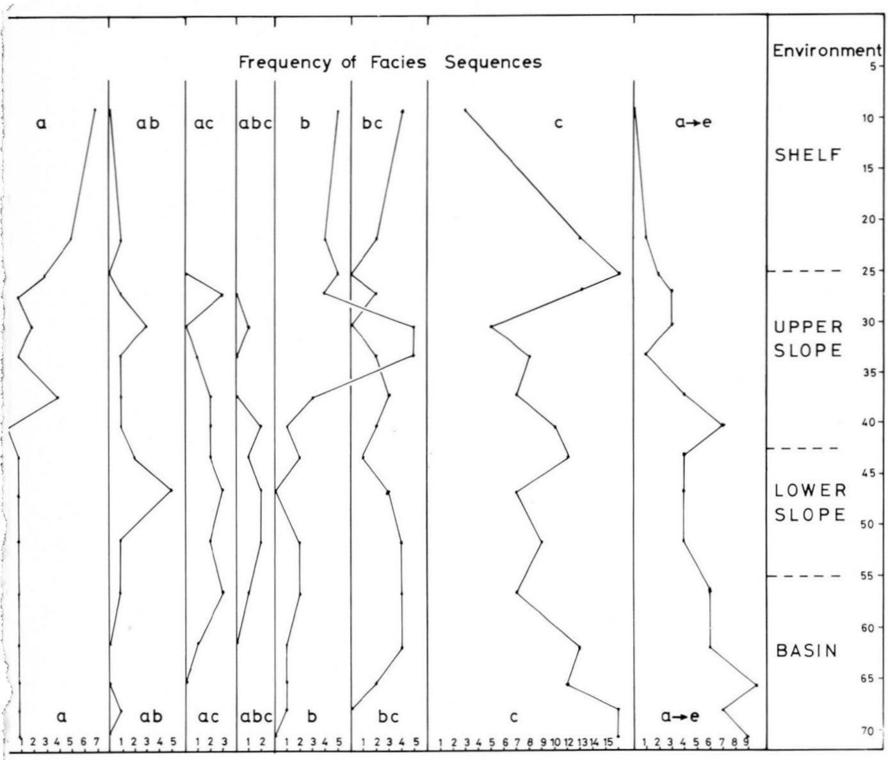


Fig. 40. Features of background and sandstone bed facies in stage 3, top of member C, Stappugieddi north, Jåkkannjargga. The relative percentages of facies in the background sediment is shown on the left. Other data is plotted at the midpoint of intervals which contain 25 beds (apart from interval 16 which contains 19 beds). In 'frequency of facies sequences' the 'C' facies at the top of Tbc beds in the upper 25 m of stage 3 represents ripples formed by reworking.

The increasing energy of the middle segment cannot, however, be explained by this mechanism, and the beds in the middle and lower parts of the sequence are interpreted as turbidity current deposits. Because such currents are gravity driven, the increase in current energy in the middle sedment indicates an increase in gradient, while the reverse applies to the lower segment.

The combined energy distribution indicated by both the background and bed sediments, suggests that the upper segment represents a shelf, the middle segment a slope, and the lower segment a lower slope apron and basin floor. (The slope-basin transition is placed at around 55 m because the trend in decreasing energy is most pronounced below that depth). These trends are clearly reflected in the proximality index (P1 of Walker, 1967, in which P1 = A + 1/2B – A–>E, and A, B and A–>E refer to the percentage of A- and B-based beds and A–>E beds; fig. 40). However, it appears that this index changed more as a function of slope than of distance from source. Assuming the validity of this pattern of basin morphology, then it is useful to correlate it with some of the other measured bedding parameters (refer to Fig. 40).

Slumps are rare, but prevail on the outer shelf where bed shear stresses were still high, and preservation potential was much higher than inner shelf. They also occur at the base of slope, favored by slope-induced stresses.

Flutes occur primarily in lower slope and basin, perhaps reflecting the high cohesivity of the fine-grained background sediments.

Bed thickness and average bed thickness first increase offshore, probably due to less reworking, and then decrease down onto the slope (Fig. 43). At the base of the slope there is a marked increase, which then decreases out onto the basin plain. These variations suggest that sediment was kept in the flow as it gained energy flowing down the basin slope, whereas sediment was deposited most rapidly where the flow encountered a decreasing slope and lost energy. These speculations are consistent with the idea of sediment bypass over relatively high gradient areas on the distal parts of 'high-efficient' submarine fans (suprafan morphology not developed), with enhanced deposition at the decrease in slope going on to the basin plain (Ricci Lucci & Valmori 1980). This type of fan has also been related to a deltaic as

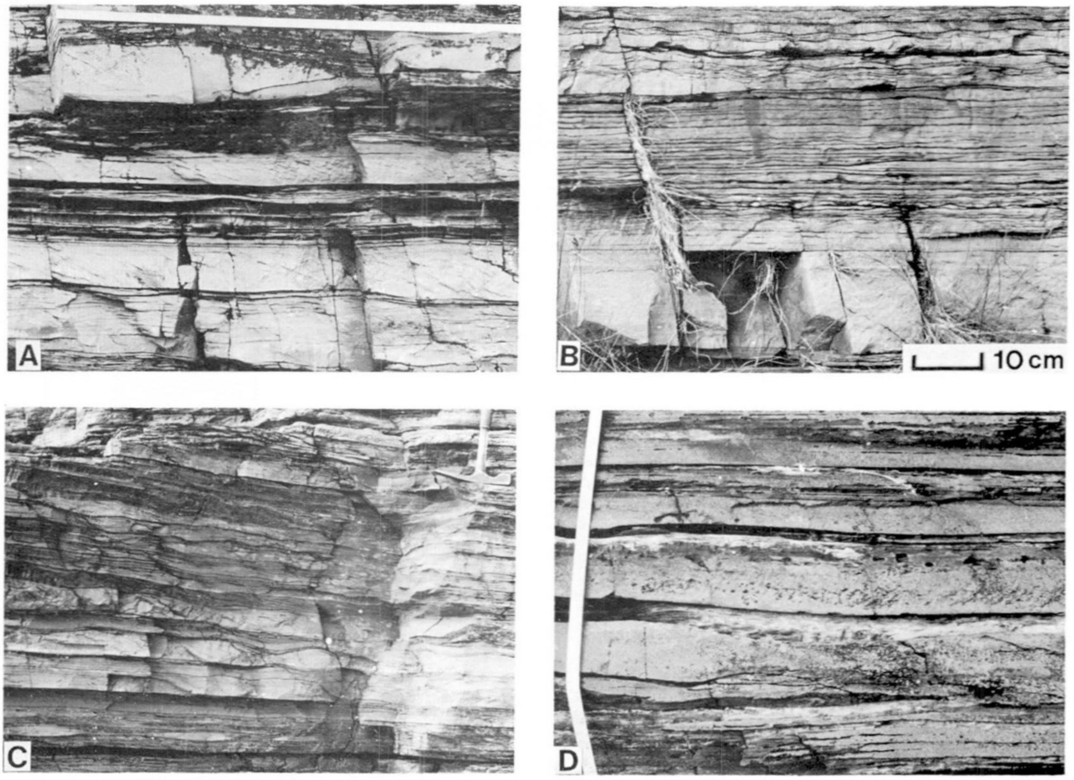


Fig. 41. Sandstone bed facies in stage 3, Stappugieddi north. A) Beds 200–205, mostly massive (facies A) at base, passing up into parallel-laminated (facies B) or ripple-laminated (facies C). About 42 m below top of stage 3, boundary between lower and upper slope environments. B) thick parallel-laminated sandstone (facies B) with rippled, reworked top. Background is intensely rippled, and reworking has truncated the sandstone bed in the center of the picture. About 11 m below member D, shelf environment. C) Pinch-and-swell sandstones primarily facies C ripple cross-laminated, with some parellel-laminated facies B sandstones. About 25 below member D, boundary between shelf and upper slope environments. D) Stage 3 opposite Guvsa (Guoholmen), showing a sequence of several Ta–>e sandstones occurring above Tc ripple cross-laminated sandstones. Background sediment is parellel-laminated mudstone. Estimated at 100 m below member D, basin environment.

opposed to beach-submarine canyon source (Normark et al. 1979).

Bed to background (sandstone/shale) ratio shows maxima at the shelf/slope break and the lower slope. The former may reflect less reworking in quieter water, while the latter reflects the decrease in gradient at the base of slope. The intervening low values may reflect sand bypass.

Facies sequences: eight facies sequences are recognized. In the shelf, the trends suggest a waning flow due to the lower gradient. The predominance of top-absent sequences (Walker 1965) may reflect frequent reworking (note that this applies to the C division in Tbc beds above 25 m). On the upper slope, there is a change to higher energy currents, but top-absent sequences such as Tab, Tac, and Tb still dominate. Further down the slope, more complete sequences are characteristic: Tac, Tabc, and Tbc. Finally, in the basin, facies A and B diminish while facies C and A–>E replace them, indicating a decrease in current energy. These observations suggest that top-absent sequences may be associated with current acceleration and bypassing in zones of greater slope (Fig. 43). Complete sequences will tend to occur in zones of deceleration where the slope is low or decreasing, and where there is maximum sedimentation. These relationships are tentative and require testing in other areas.

While most turbidite sequences are with few exceptions (e.g. Favero & Passega 1980, Nelson 1982) thought to have formed below the base of slope, usually on a submarine fan (Walker 1980), the above observations suggest that the sand-depositing currents in stage 3 did not originate as base-of-slope gravity driven flows, but rather by

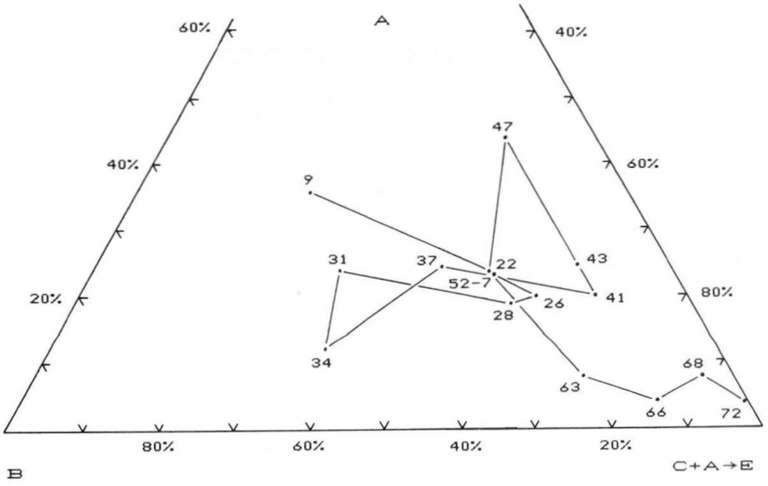


Fig. 42. The changing proportion of A-, B-, and C-based turbidites and A–>E sequences in stage 3, Stappugieddi north, Jåkkannjargga. The numbers refer to depth below the top of member C of the mid-point of 25-bed intervals as shown in figure 40. The trends are discussed in the text.

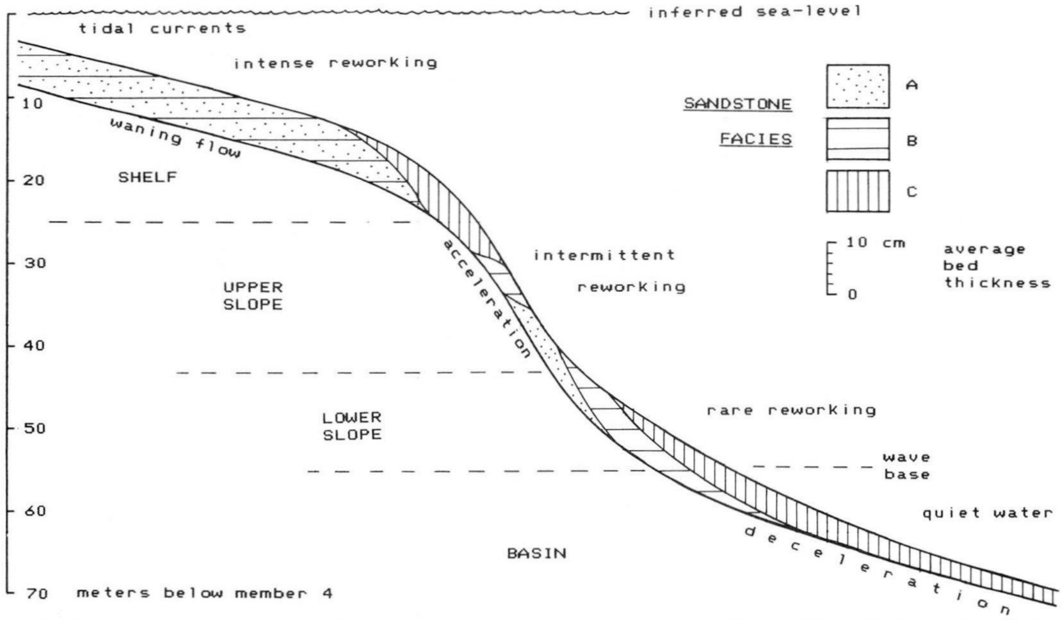


Fig. 43. Reconstructed depositional conditions of stage 3, Nyborg Formation, based on interpretation of background and beds at Stappugieddi north section. Sandtone facies depict the Bouma division sequence for an 'average' bed.

direct feeding from a delta, or by offshore and downslope movement of sediment-laden coastal waters. The strong alignment of the ripples in the background sediment and of the flutes on the turbidites, suggest a relatively simple shelf morphology as opposed to several discrete point sources which would have created a more complex paleocurrent pattern. Blanket-shaped, turbidite-like graded sands are deposited on the shallow Bering Sea shelf offshore from the Yukon Delta during large storms (Nelson 1982). The sands are carried offshore by strong bottom currents generated by returning, or ebb, water flow. This is thought to have been the dominant process in the formation of the shelf sandstones in stage 3. In contrast, wind-forced, shoreward flowing currents generate offshore-flowing bottom currents that are oriented parallel or oblique to the coastline (Morton & McGowen 1980), and thus do not resemble stage 3. Further evidence of storm activity in the coastal deposits of member D is discussed below.

The equivalent section at Trollfjord is less well exposed; however, this section, which has a red-dish color, also shows a broad shallowing-upward trend.

STAGE 4, SHALLOW MARINE SEDIMENTATION: MEMBERS D AND E

Members D and E reflect the shallow marine conditions which prevailed after filling of the basin by members B and C. Member D is present on Jåkkannjargga where up to 42 m are present, and at Trollfjord where the thickness is 70 m. Member E is preserved only at Trollfjord where 25 m are present below the Mortensnes Tillite (Figs. 30 & 44).

Facies of Stage 4, Jåkkannjargga

Member D was examined in detail at many localities along the coastline (Fig. 37), but was investigated only briefly at Trollfjord, described separately below. The extremely varied deposits in member D on Jåkkannjargga were grouped into eight facies, on the basis of sedimentary structures, color and grain size. The principle sedimentary structures are cross bedding, parallel lamination, flaser bedding, graded bedding, massive bedding, and soft-sediment deformation. Grain size falls into three groups: medium to coarse sandstone, very fine to fine sandstone, and mudstone.

Facies A, cross bedded sandstone is composed of cross sets of purple, moderately sorted, medium to coarse sandstone. The sets are mainly 5–15 cm thick, and occur in cosets up to 2 m thick. The thick cosets are laterally continuous for at least hundreds of meters, but occasionally show a strongly erosive base. Cross-bedding is planar to somewhat concave at the base of the foreset (Fig. 45). Foreset dip averages 20 degrees, and the foresets of successive sets often dip in opposing directions, imparting a 'herringbone' appearance. In vertical sections perpendicular to the current flow the sets appear parallel-laminated or slightly inclined, filling shallow troughs. Festoon bedding was not seen. The sets are interpreted to have formed by the migration of slightly sinuous to straight-crested dunes in the upper part of the lower flow regime. Penecontemporaneous ball-and-pillow structure (Potter & Pettijohn 1963) is common, and one overturned cross set was noted. More than 500 measurements of foreset orientation (determined by stereographic rotation, because regional bedding dips 25 to 30 degrees) show that most cosets have a bimodal, bipolar current distribution, with one mode dominant (Fig. 46). These modes are oriented parallel to the sole marks in the turbidites of stage 3, and suggest that the bimodal currents were directed onshore-offshore. Several sets near the base of one coset demonstrate dune shape and behavior (Figs. 47 & 48). The sets are about 15 cm high, 2 m long, and average 3–4 m crest-to-crest length. Isolated sets show rounding due to subsequent erosion, and the overlying set indicates this was related to current reversal (Klein 1970). This facies thus provides strong evidence for significant tidal currents with bidirectional bed-load transport.

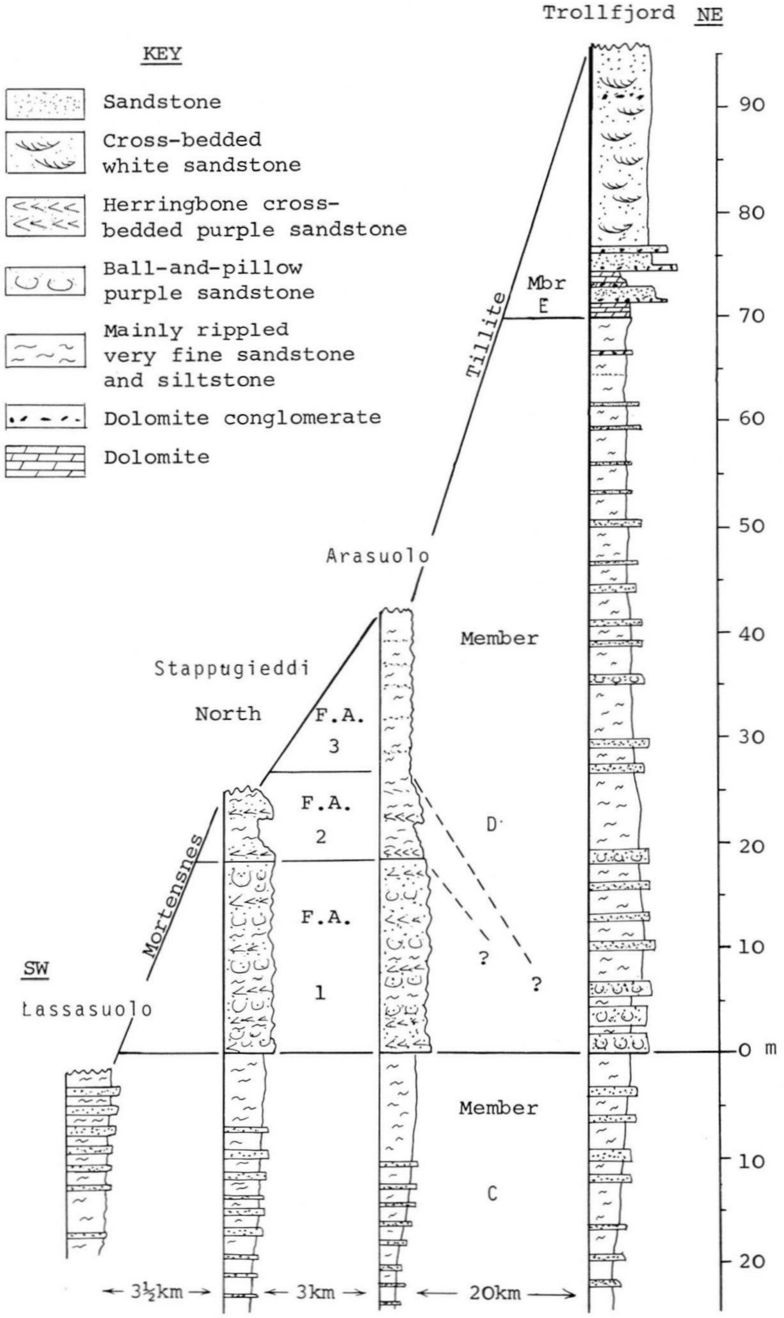
Facies B, fine to medium grained parallel-laminated purple sandstone occurs in units up to 40 cm thick. The lamination is horizontal or slightly undulating, and is laterally persistent (Fig. 45). The lamination is interrupted by rare rippled horizons, and small, shallow scours. Current lineation was not observed, but the rock does not often fracture along lamination planes. Deposition was by plane bed flow in the lower part of the upper flow regime.

Facies C, very fine grained parallel-laminated sandstone occurs in units up to 30 cm thick. The lamination is delicate and continuous and grades into the flaser-bedded facies, D. This facies was apparently deposited under similar conditions to facies B, but with finer sediment, and lower flow power.

Facies D, flaser-bedded sandstone occurs in units up to 115 cm thick, though usually less than 40 cm. The coarser component is very fine sandstone and coarse siltstone arranged into lenses and laminae up to several millimeters thick (Fig. 49). These are separated by continuous and discontinuous laminae (flasers) of mudstone usually thinner than 1 mm. Thus this facies may be termed bifurcated wavy flaser bedding (Reineck & Wunderlich 1968). Bedding planes show the ripples to have been straight to slightly sinuous crested, and asymmetrical with rounded crests which are features of combined flow ripples, described from stage 3 background sediment. This facies is a good indicator of a tidal environment; the contrast in grain sizes reflects the frequent changes in current velocity in a tidal environment (Reineck & Wunderlich 1968). Structures indicating subaerial conditions were not seen.

Facies E, graded beds includes a variety of graded beds, which are up to 20 cm thick and comprise

Fig. 44. Stratigraphy and facies outline for stage 4, shallow marine sedimentation, Nyborg Formation, Jåkkannjargga and Trollfjord. F.A. = facies association.



a sandy, often erosive, base and a top of cleaved massive mudstone (Fig. 50). Thin-sections show green grains which are apparently glauconite pellets, which is consistent with their chemical composition as determined by electron microprobe. These beds were deposited by waning flows which carried sand and mud in suspension. The thick mud layer at the top is attributed to high mud concentration of the flow rather than long periods of quiet water deposition.

Facies F, massive mudstone occurs in beds of cleaved, massive mudstone up to 40 cm thick, in sharp contact with other facies. Some beds appear to be very continuous laterally, traceable for at least hundreds of meters, while others cannot be

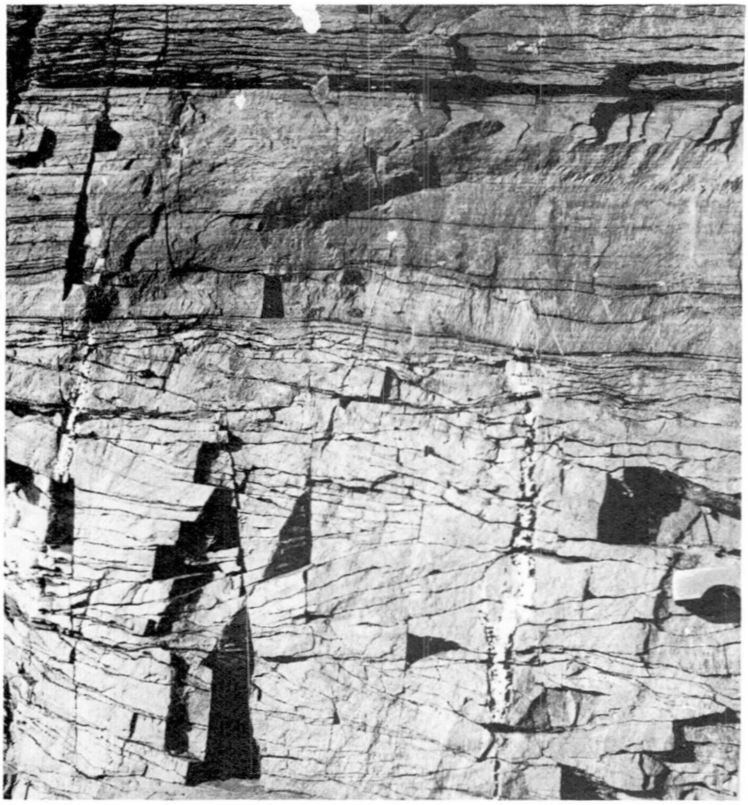


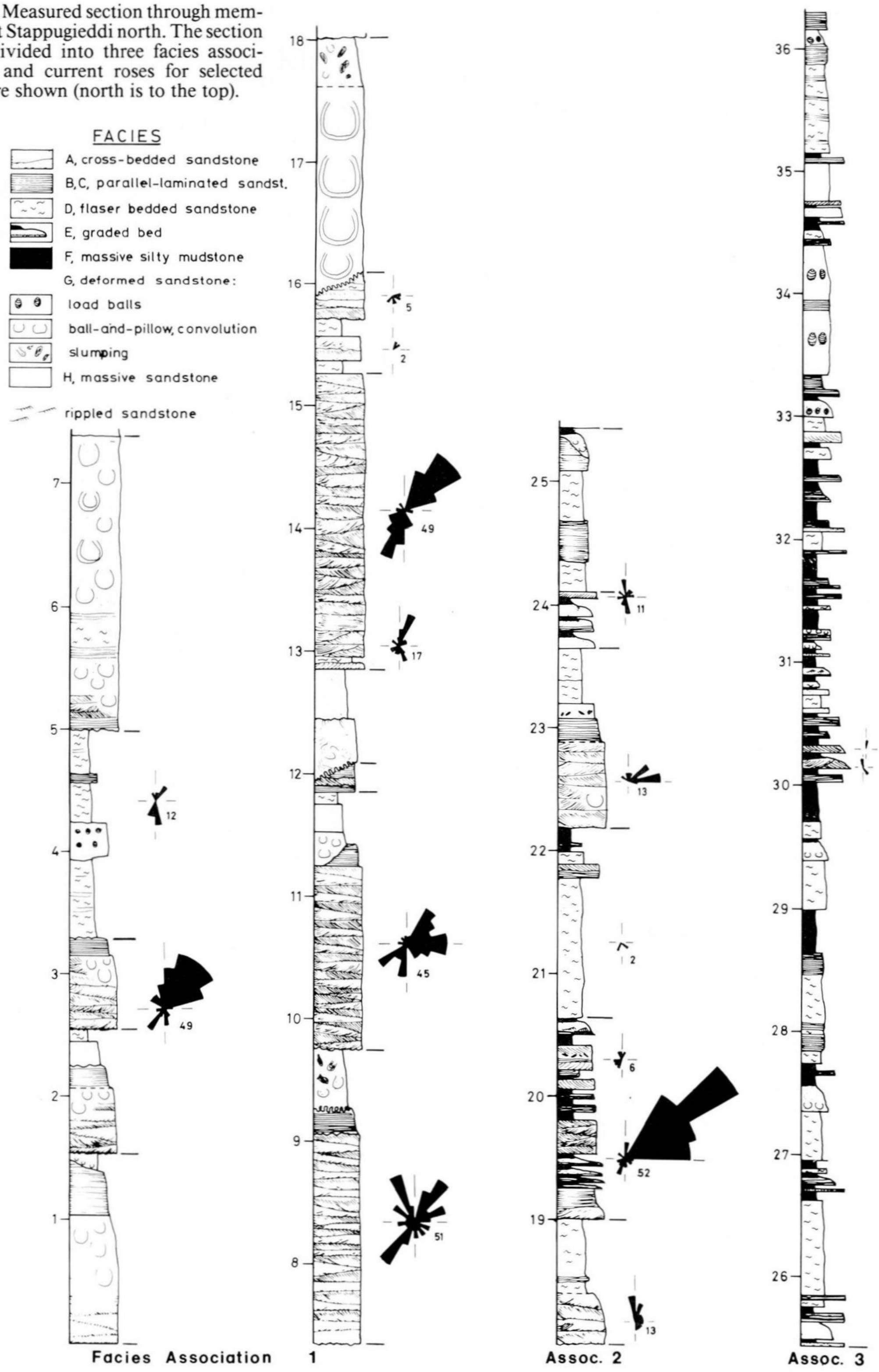
Fig. 45. Facies A herringbone cross-bedded purple sandstone overlain by facies B parallel-laminated purple sandstone, in turn overlain by facies D flaser-bedded very fine sandstone, about 3 m above the base of member D at Stappugieddi north, Jåkkannjargga. Foresets in facies A dip to NE and SW.

traced between outcrops. The base of one bed shows groove casts, suggesting that the bed was deposited by a strong current. For this reason, and the absence of internal signs of reworking, this facies is interpreted as having been deposited relatively quickly by a mud-laden current. The fine grain size is attributed to the fallout of the coarser modes at more proximal location to the source of the current, e.g. facies E.

Facies G, deformed sandstone occurs as local zones within other facies, especially facies A, as well as discrete beds composed of deformed sandstone masses with the interstices filled with massive sandstone. Four kinds of deformation were noted. (1) Small load balls, or pseudonodules, occur in fine grained massive sandstones up to 30 cm thick. They formed by vertical quasi-fluid movements in the bed (Potter & Pettijohn 1963). (2) Convolute lamination, formed by vertical movements occurs in fine sandstones. (3) On a larger scale, ball-and-pillow structure (Potter & Pettijohn) occurs as zones within facies A and B, and as discrete beds. In vertical section the balls appear symmetrical, suggesting no appreciable lateral movement. The cause of the deformation could not have been density instability, as the deformation occurs in lithologically homogeneous zones, but other possibilities are pressure changes due to water movement through the newly deposited sands, or pressure applied by strong currents. Ball-and-pillow structure is often overlain by massive sandstone. The contact appears erosive but may only reflect the tops of foundered, broken sandstone masses. (4) Slumped bedding is characterized by laminated sandstones which are chaotically bent, squeezed and sometimes broken. These deposits probably experienced substantial lateral transport. Facies G is often overlain by facies H.

Facies H, massive sandstone, fine to medium grained, occurs in beds up to 20 cm thick. This facies originated in various ways. Beds of massive sandstone and beds containing pseudonodules formed by primary deposition by strong currents, with minor intrusion by the sinking balls. Massive sandstone surrounding and overlying ball-and-pillow structure probably formed by churn-

Fig. 46. Measured section through member D at Stappugieddi north. The section is subdivided into three facies associations, and current roses for selected units are shown (north is to the top).



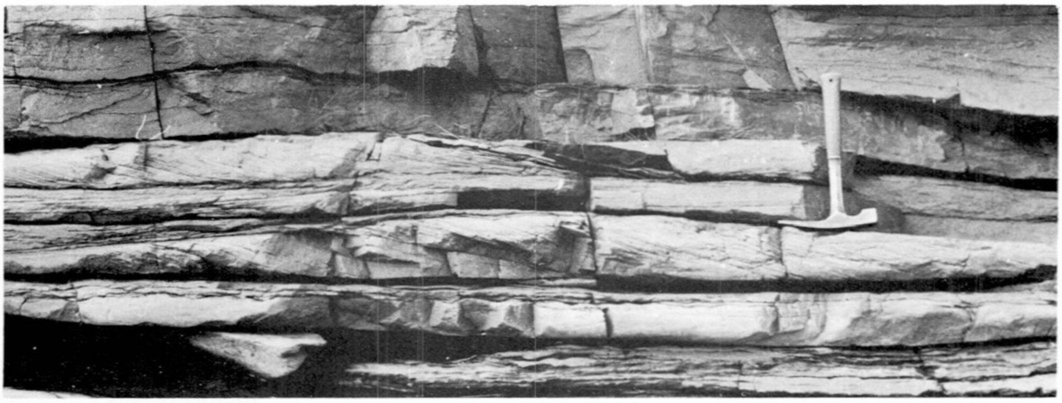


Fig. 47. Preserved dune bedform about 13 m above the base of member D, Nyborg Formation, at Stappugieddi north. Reactivation surfaces are preserved within the dune cross set. Flow was toward the NE (right).

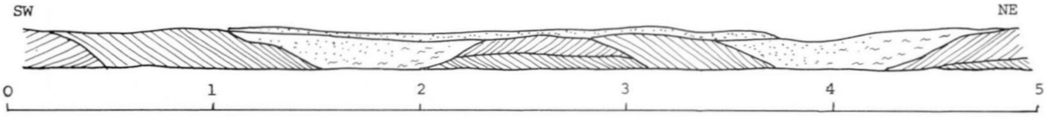


Fig. 48. Series of facies A cross sets showing current reversal and bedform modification in a bed about 13 m above the base of member D at Stappugieddi north. Currents flowed NE, SW, NE, and following a final phase of erosion the troughs were filled with massive and flaser-bedded very fine sandstone.

ing, dewatering and upward flowage of originally stratified sands.

Depositional Model of Stage 4, Jåkkannjargga

Three facies associations, that is groups of facies which tend to occur together, form the basis for interpreting stage 4, and are described below from the representative Stappugieddi north section (Fig. 46).

Facies association 1, the lower 18 m of the section, consists mainly of beds of facies A, often with ball-and-pillow deformation, which rest sharply or erosively on the underlying beds, and which pass up through facies B into facies C, D, G or H. The pattern of the fining-upwards sequence is repeated numerous times, each reflecting a gradual decrease in grain size and current energy. Fining-upwards sequences typically form by point bar migration of both fluvial channels (Allen 1965, 1970), and channels on tidal flats (Reineck 1967), although the latter often have abundant mud deposited during slack water. Paleocurrent data from shallow marine subtidal areas of the southern North Sea (Reineck 1963, Reineck & Singh 1973) showed that cross sets having bimodal current orientations oriented onshore-offshore tend to be associated with tidal channels or inlets. The appreciable continuity of the facies A cosets in thus attributed to the channel orientation having been roughly parallel to that of the exposures, rather than a true absence of channeling.

This facies association is interpreted as distributary channel and channel mouth bar deposits of a tide- and wave-dominated delta front (Fig. 51) because: (1) the tidal channels occur at the top of a regressive sequence, (2) the succession of facies A and B are coarser than most intertidal channel deposits, and (3) the paleocurrents are oriented onshore–offshore. In this model, the channels were floored with dunes (facies A), which migrated chiefly upstream or downstream depending on whether the channel was ebb- or flood-dominated. Reversing bed load transport in the form of small, 10 cm high, bed forms occurs in the mouth of the main distributary channel of the tidally-dominated Old River delta (Wright et al. 1973). Along the shallow margins of the channel the bottom was a smooth plane bed (facies B). Adjacent to the channels were shallow subtidal shoals and flats where the effect of waves and currents were damped due to the shallow water, and on which mud and fine sand were deposited (facies C and D). Episodic events leading to unusually strong currents, such as floods or storms, led to rapid erosion and deformation of

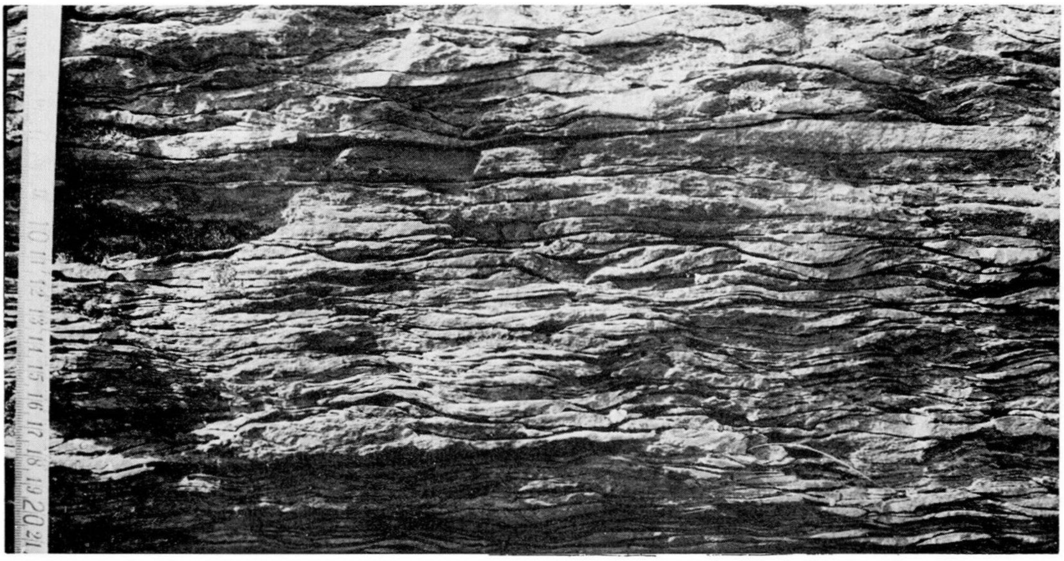
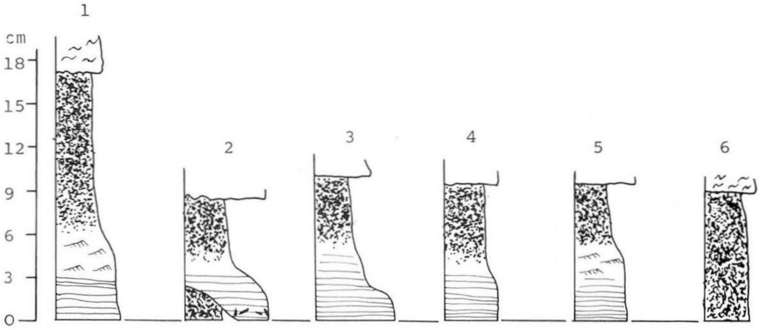


Fig. 49. Flaser-bedded very fine sandstone, facies D, about 21 m above the base of member D at Stappugieddi north. Note sinuous form of continuous flasers and frequent bifurcations. Some thin layers of facies C parallel-laminated very fine sandstone are also present.

Fig. 50. Examples of graded beds composing facies E in member D at Stappugieddi north section. Beds 1, 2 and 3 are from facies association 2, and the remainder are from facies association 3. Sandstone at the base of beds 1, 4 and 5 is fine and very fine grained, while that at the base of beds 2 and 3 is medium grained. All beds have a mudstone top.



parts of the channels (facies G), and rapid deposition of massive sandstones (facies H).

Facies association 2 is a 7.5 m thick transition between associations 1 and 3 (Fig. 46). In this interval, facies A and B diminish and become more lenticular, while facies C and D increase in abundance, and facies E and F appear. Facies A and B appear to represent smaller and shallower channels than in association 1. The environment was overall quieter, enabling preservation of 'catastrophic' storm and flood deposits as facies E, graded beds, and facies F, beds of mudstone. These are similar to other examples of sublittoral storm deposits (Johnson 1978). In a deltaic context, such environments are represented by broad, somewhat protected, shallow interdistributary bays, adjacent to distributary channels.

Facies association 3, 11 m thick at Stappugieddi north, increases to 17 m opposite Arasuolo (Areholmen). The association contains a haphazard alternation of facies C, D, and F, with intercalated beds of facies A, B, E and G. Facies C and D resulted from normal, slow, quiet-water deposition in a sub-tidal interdistributary bay or lagoon, interrupted at times by catastrophic deposition of facies A, B, E and G by relatively strong currents during storms or floods.

Description of Stage 4; Trollfjord

Near Trollfjord, west of Njargačåkka, about 20 km NNE of Stappugieddi (Fig. 30) are out-

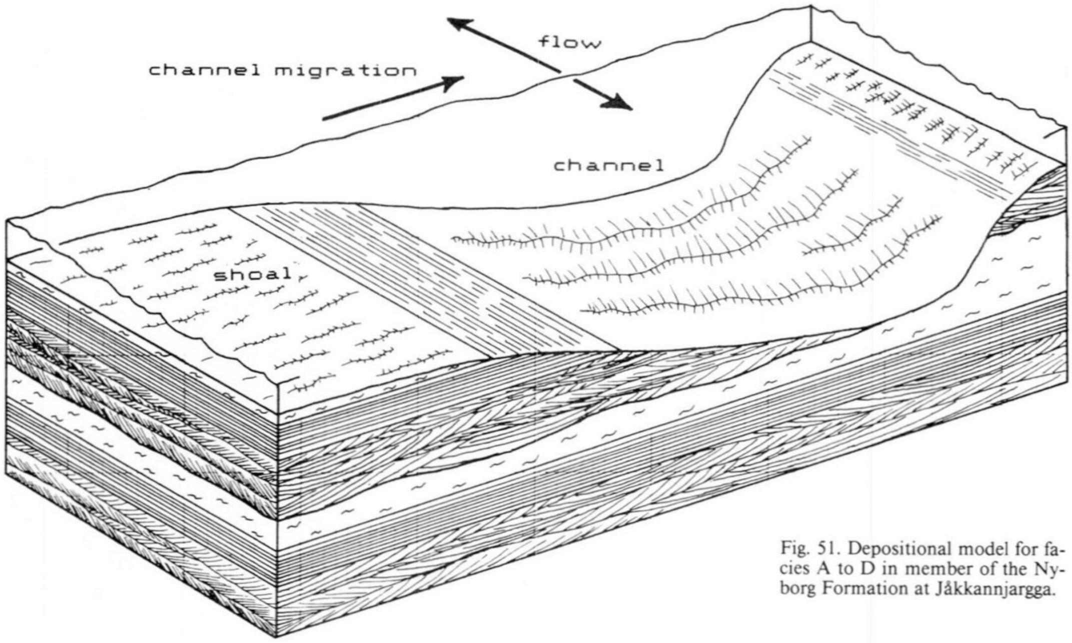


Fig. 51. Depositional model for facies A to D in member of the Nyborg Formation at Jåkkannjargga.

crops of member D, and member E, the highest part of the Nyborg Formation preserved. Member D is 70 m thick, and resembles facies association 3 at Stappugieddi. The color fluctuates between purple and grey-green. The background sediment consists of laminated mudstone, and flaser-bedded siltstone and very fine sandstone with interbeds that vary greatly in grain size, sorting and color. Noteworthy are ball-and-pillow sandstones up to 2 m thick with erosive bases. Most beds, though, are grey-green and purple, medium-bedded, poorly to moderately sorted feldspathic sandstones. Beds resembling turbidites, with Bouma (1962) divisions A and B, occur in groups. Upwards, purple color decreases, replaced by grey-green; grey-brown is characteristic at the top of the member. About 15 m from the top, laterally continuous, fine-grained white sandstones appear. These are much better sorted and have a lower feldspar content than the drab-colored sandstones. About 5 m from the top, small rounded dolomite pebbles appear in the bases of some graded sandstones.

The base of member E is marked by a 60 m bed of parallel and irregularly laminated grey-brown dolomite. Above an intervening sandstone is a second dolomite bed, massive and parallel laminated, with dolomite flakes and pebbles. The sandstone in this lower part of member E is partly cross-bedded, contains numerous wave-formed ripple marks and consists of very well sorted coarse sand, which appears very well rounded where original grain boundaries were not destroyed by pressure solution. The sandstone contains less than 1 percent feldspar and is thus a supermature quartzarenite (Folk 1974). At the top of member E is about 20 m of trough cross-bedded white sandstone with wave-formed ripples, well rounded shale flakes in scours, and a few layers of dolomite pebbles. The sandstone consists of moderately sorted, rounded fine to medium sand with a considerable amount of feldspar, and is a mature subarkose. It is overlain unconformably by the Mortensnes Tillite.

Depositional Model of Stage 4, Trollfjord

The unusually mature sandstones in the lower part of member E suggest an origin as a beach deposit, with extreme reworking of the sand grains, in contrast to the other sandstones of stage 4 which were derived more or less directly from a delta distributary. The associated dolomites which contain platey fragments that are possible eroded algal mats, were apparently deposited in a nearby protected shallow water environment.

The upward increasing maturity of member D sandstones, and the appearance of dolomite pebbles near the top of the member, suggest a change in sediment source, from delta distrbutary to marine. The latter may thus be retransported equivalents of the clean sandstones at the base of member E. Thus member D at Trollfjord is interpreted as a lagoon or bay deposit with normal quiet-water sedimentation of laminated and

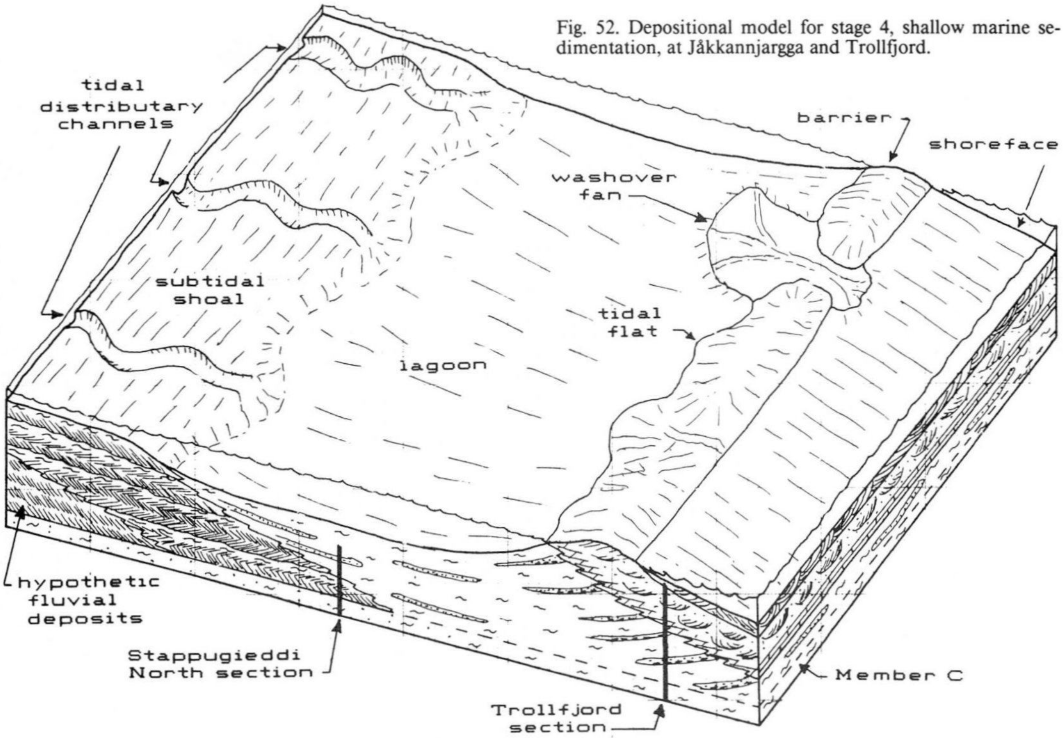


Fig. 52. Depositional model for stage 4, shallow marine sedimentation, at Jåkkannjargga and Trollfjord.

flaser bedded muds and silts, frequently interrupted by catastrophic deposition of sediments derived first from distributaries to the south, and later, increasingly from a shoreline sand body to the north. The interpretation of this sand body as a barrier is based on (1) the presence of a seaward barrier to afford protection for the inferred lagoon, and (2) the need for a local source of mature sand. Because of the limited exposure of member E, the source of the barrier sediment is unknown. It is noteworthy that some of these sandstones are much coarser than any other sandstones in stage 4.

The clean sandstones at the top of the member D are thus essentially barrier washover deposits, the interbedded dolomites and sandstones at the base of member E are interpreted as back-barrier tidal flat deposits, and the thick sandstone forming the upper part of member E is interpreted as an shoreface sand body (Fig. 52). The sharp contact at the base of this unit suggests that much of the actual barrier was eroded away during landward migration of the barrier and associated back-barrier and shoreface environments. Many of these processes were illustrated in modern environments and other ancient examples by Elliott (1978).

DEPOSITIONAL HISTORY OF THE NYBORG FORMATION

This section on the Nyborg Formation concludes with a brief synthesis of the main depositional patterns and controls (Fig. 53). The overall distribution of thickness (Fig. 30) and facies indicates that the main depocenter lay in the Vestertana district.

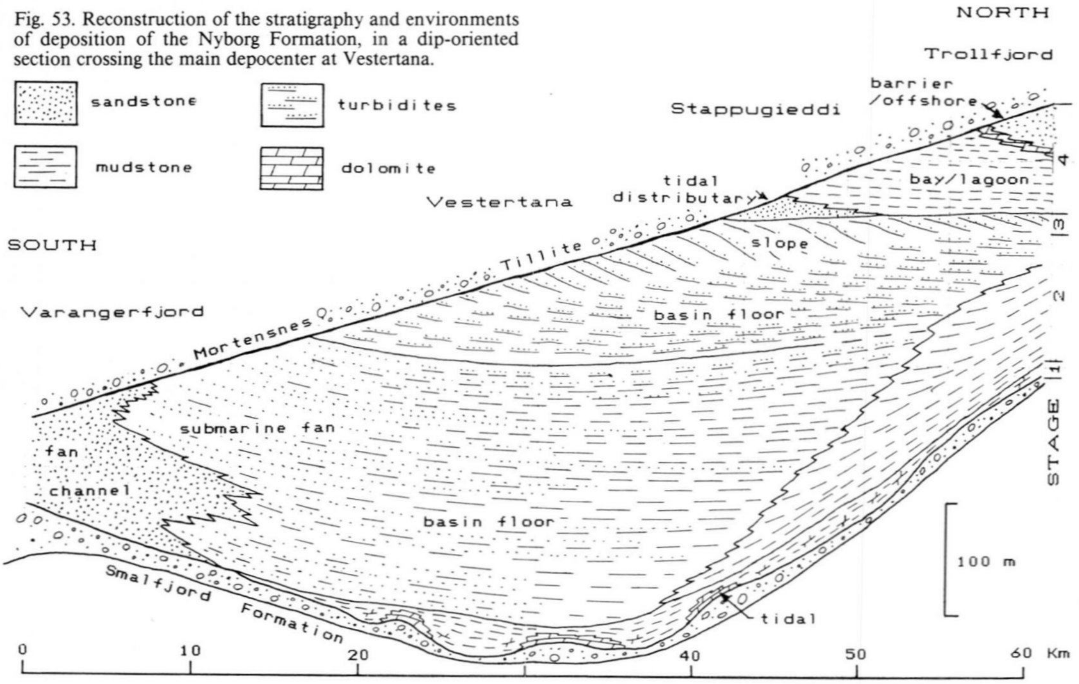
Stage 1, Transgression

The facies in member A indicate deposition during rapid transgression. In the south the Varanger paleovalley was largely filled, and sediment transport and paleoslope dip were generally to the north. In the area of the main depocenter, a depositional basin began to evolve. However, the irregular topography left behind by the preceding glaciation created correspondingly irregular thickness and facies patterns in member A, with dolomite deposited on topographic highs, and mudstone in the troughs.

Stage 2, Quiet-water basin fill

With the end of post-glacial rise in sea level, isostatic uplift of the basement south of the basin provided abundant immature sediment. Basin subsidence in the main depocenter also helped

Fig. 53. Reconstruction of the stratigraphy and environments of deposition of the Nyborg Formation, in a dip-oriented section crossing the main depocenter at Vestertana.



maintain a steep slope adjoining a relatively deep basin in the south, so that the basin filled primarily by aggradation and progradation of submarine fans. The fans extended to an area south of Trollfjord, where they encountered the gently inclined, south-sloping northern flank of the basin. Relatively shallow water mudstones and siltstones accumulated in marginal areas.

Through time, the steep southern slope of the basin prograded northwards. The changing character of the basin fill suggests that the early slope was cut by submarine canyons which supplied coarse sediment to the fan systems. Later, the gradient of the slope decreased and consequently was unchanneled as turbidity currents were no longer capable of significant erosion.

Stage 3, Regression
A late stage of the slope system is preserved on Jåkkannjargga as a transition from quiet-water turbidite deposition to high-energy sub-tidal delta front deposition. High-energy storms and floods caused enhanced transport of sediment to the shelf edge which led to the propagation of turbidity currents on the upper slope.

Stage 4, Shallow marine sedimentation
The return to shallow marine conditions was accomplished by progradation to the NNE of a tide- and wave-dominated delta. The delta front was the site of shallow, broad, tidally-influenced distributary channels and submerged mouth bars, oriented NNE. These are overlain by interdistributary bay and lagoon deposits. At Trollfjord the latter are overlain by back-barrier sandstone and dolomite, and shoreface sandstones, apparently deposited by a barrier system migrating landward to the south. This youngest preserved part of the Nyborg Formation indicates relative transgressive conditions, suggesting that the regressive conditions of stage 3 were not related to a eustatic drop of sea level at the onset of the Mortensnes Tillite glaciation (Reading & Walker 1966).

The Mortensnes Tillite Formation – Final Glaciation

The Mortensnes Tillite (Holtedahl 1918; 'upper tillite' of Føyn 1937), unlike the Smalfjord Formation, is remarkably homogeneous, consisting primarily of tillite, with minor laminated mudstones, conglomerate and dolomite. It is very widespread, extending from eastern Varanger Peninsula (Røe 1970, Siedlecki 1980) to Laksefjordvidda (Fig. 54; Føyn 1967) and Altafjord (Fig. 1; Borras Group, Føyn 1964), a distance of 280 km (Fig. 1). Observations in the Varangerfjord region have been published by Reusch

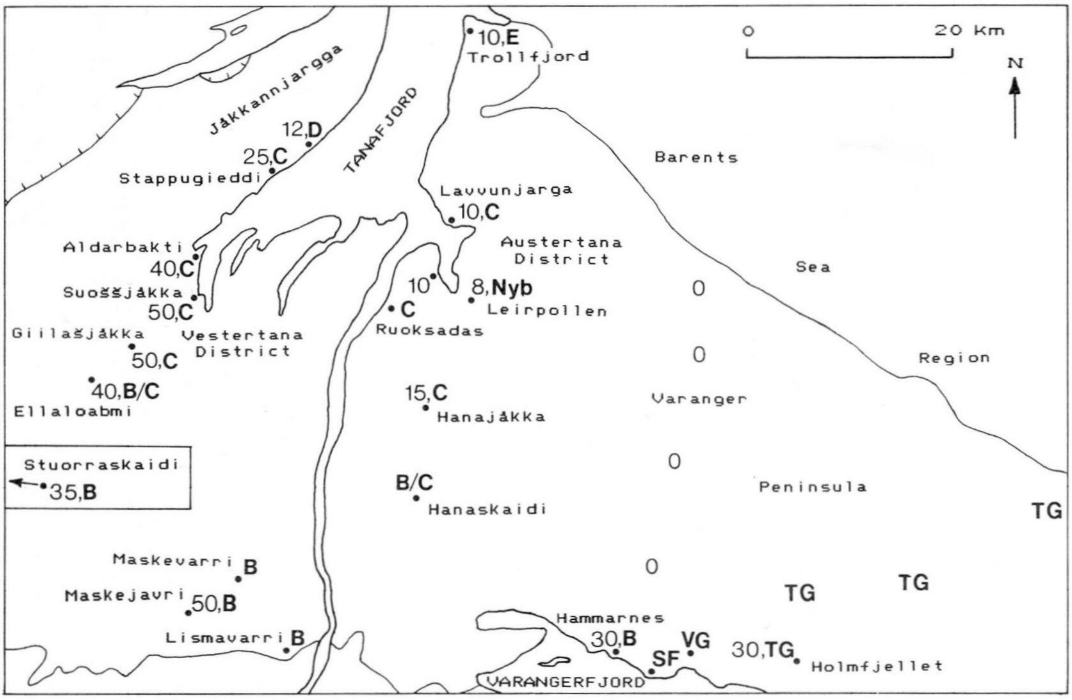


Fig. 54. Thickness, in meters, of the Mortensnes Tillite, and sub-Mortensnes Tillite geology. A through E, member of the Nyborg Formation; SF, Smalfjord Formation; VG, Vadsø Group; TG, Tanafjord Group. Correct location of Stuorraskaidi shown in Figure 3.

(1891), Holtedahl (1918) and Bjørlykke (1967), and in the Tanafjord region by Føyn (1937, 1960) and Reading & Walker (1966).

The Mortensnes Tillite progressively cuts down through the Nyborg Formation to the south, and rests on the Smalfjord Formation and the Vadsø Group to the east, north of Varangerfjord (Figs. 4 & 30; Banks et al. 1971). The slope on the unconformity is about 25' on Jåkkannjargga but appears to be somewhat lower than this elsewhere. The Tillite is overlain by mudstones of the lower submember of the Lillevatn Member.

The Formation is thickest, about 50 m, in the Vestertana area (Fig. 54). It is divided into three members on the basis of composition, structures and stratigraphic position (Fig. 55; Banks et al. 1971). The tillite facies classification was outlined in the section on the Smalfjord Formation.

LOWER MEMBER

The lower member is a northward-thinning wedge of largely massive tillite (Table 4) which rests directly on the sub-Mortensnes Tillite unconformity (Fig. 56). It is overlain by the middle member at all but the southernmost localities, where the top of the member was not seen. At Maskejavri (Masjokjavrek), (in a gorge at the north end of Måskuskaide, 10 km WNW of Lismavarri), it appears to be directly overlain by the upper member, but the tillite here is sheared.

Description

The lower member is thickest, about 30 m, north of Varangerfjord and west to Lismavarri (Fig. 56). Superior outcrops however, are present in the Vestertana area.

Basal Contact – is invariably planar, and usually parallel to, but occasionally cutting slightly into, the underlying strata. This contact is well exposed at Hammarnes, and at many outcrops in the Vestertana area. In detail, the contact often shows brecciation or homogenization of the subjacent sediment (Figs. 57 & 58), which is called deformation tillite. In many exposures in the Vestertana area such deformation tillite is usually up to 1 m thick, and is overlain by large tabular blocks, or rafts, up to 20 m long and 1 m thick, of undeformed sediment derived from member C of the Nyborg Formation. These rafts are most numerous around Šuoššjåkka.

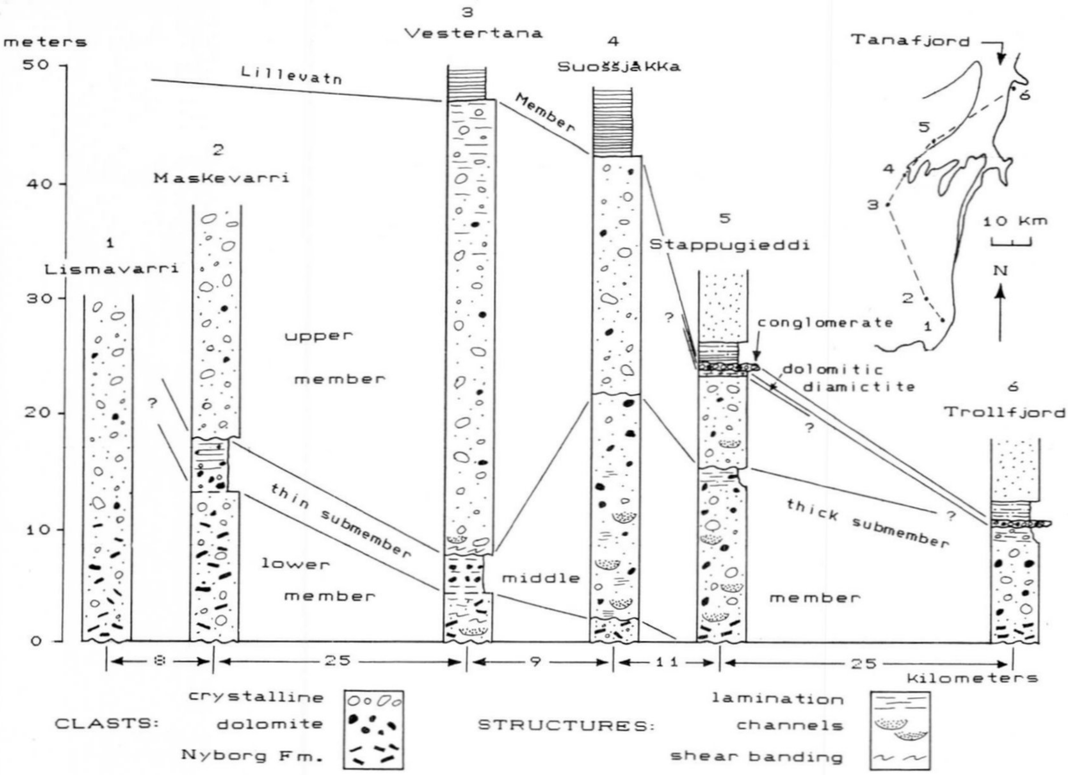


Fig. 55. Stratigraphic and facies overview of the Mortensnes Tillite, shown in a dip-oriented cross section, with the base of the tillite as datum.

Composition – of both clasts and matrix is highly variable and includes both: 1) exotic extrabasinal materials, predominantly crystalline, with minor dolomite and chert, and 2) locally derived sediment, whose color and texture closely resembles that of the strata underlying the tillite. These two materials are rarely seen in an unmixed state; the average tillite in the lower member contains about 5 percent crystalline clasts and 5 percent clasts of locally derived sediments scattered in a fine-grained, even-textured matrix derived chiefly from comminution of the subjacent sediments. Lenses and bands of relatively pure extrabasinal tillite are occasionally observed; these have a dark color, high (20–60 percent) clast content, and a matrix of poorly sorted mud with angular grains of quartz and feldspar. Crystalline clasts are composed of red granite and grey gneiss, with a few dark, fine-grained basic rocks. The latter occasionally show facets and striations (Fig. 59; Reusch 1891, Banks et al. 1971). At Hammarnes, these clasts attain a maximum dimension of over one meter, and in general, maximum clast size decreases to the north.

Color – usually green-grey or purple, is similar to that of the immediately underlying sediment, whether the Nyborg Formation or the Vadsø Group (Figs. 30 & 56). An exception occurs around Hammarnes where the purple tillite contains irregular patches of grey-green tillite, possibly due to diagenetic alteration.

Sedimentary Structures – are principally banding, and *in-situ* primary stratification, both quite scarce. Banded tillite is composed of alternating bands of extrabasinal tillite and Nyborg deformation tillite. It is diffucult to detect in the field because bands have similar colors, but is apparent in polished specimens (Fig. 60). Several outcrops display isolated bands of crystalline-rich tillite. Stratification includes *in-situ* bodies of sorted sandstones and conglomerates, and parallel lamination. Rare *in-situ* bodies of poorly sorted, bedded conglomerates and faintly laminated sandstones were observed at Hammarnes and in the Vestertana area. Conglomerates are up to 4 m thick and occur in channels cut into the tillite. Sandstone bodies are usually less than 1 m

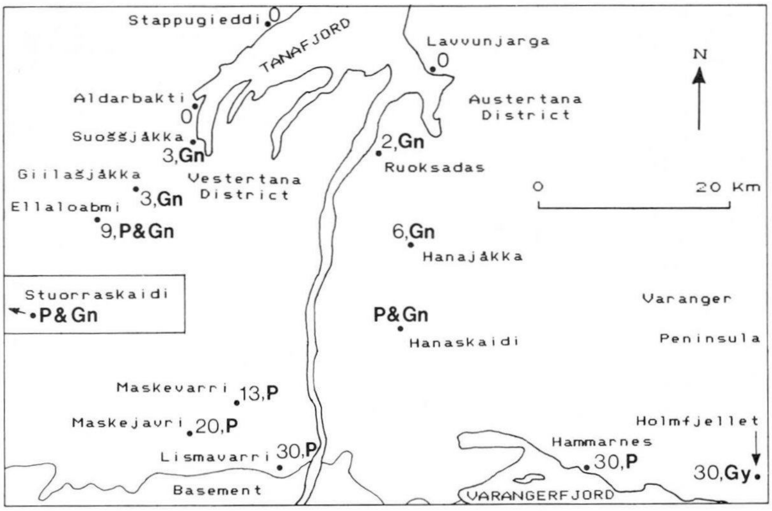


Fig. 56. Thickness, in meters, and color of the lower member of the Mortensnes Tillite. P, purple; Gn, green; Gy, grey.

Table 4. Properties of the three main tillite-bearing members of the Mortensnes Tillite.

MEMBER	AREAL EXTENT	MAXIMUM THICKNESS	COLOR	CLASTS			MATRIX	SEDIMENT SOURCE	TRANSPORTED FROM
				CONCENTR.	SIZE	COMPOSITION			
UPPER	50 x 80 Km 50 x 50 Km (lodgement tillite only)	40 m	dark grey	5-15%	average 5-10 cm; rarely >30 cm	crystallines with rare sedimentary types	sand and silt grains dispersed in mud	basement	south??
MIDDLE	60 x 90 Km 30 x 30 Km (lodgement tillite only)	30 m	buff-brown	5-10%	average 5-10 cm; max. 80 cm (cryst.)	>90% dolomite with chert and cryst.	quartz sand in dolomitic groundmass	Tanafjord Group, including Grasdalen Formation	north, northeast
LOWER	40 x 150 Km	30 m	purple, gy-grn, lt-grey; depends on substrate	5-10%	average 5-10 cm; max. 1 m (cryst.)	locally-derived substrate, and cryst. rare dolomite and chert	sandy, silty mudstone	local substrate, basement	south

high and several meters wide. One sandstone at Hammarnes grades up into a finely laminated shale with dropstones. Some examples have a gravel lag at the base. At several exposures in the Vestertana area, a distinctive laminite composed of centimeter-thick laminae, each grading upward from sandstone to mudstone, occurs in units up to 1 m thick and several meters wide.

Upper Contact – is usually gradational into the overlying middle member, and is described with that unit.

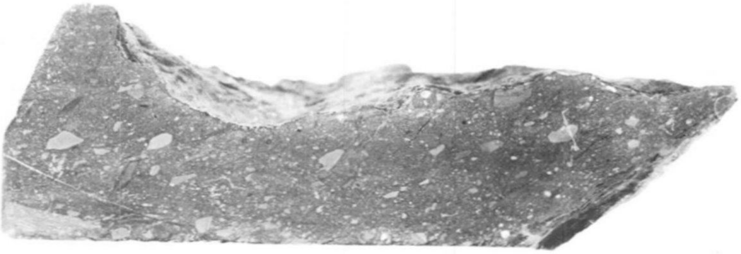
Paleoflow Directions – was determined from clast long axis orientation and deformational structures (Fig. 61A). Preferred orientation of clasts at Hammarnes appears to be transverse to flow, as deformed beds of Nyborg Formation in the tillite suggest shear directed toward the WNW. Imbrication of clasts in the Vestertana area suggests flow with both east and west components. In addition, one cross-set in an *in-situ* sandstone body suggests water flow to the south.

Deposition of the Lower Member

The lower member is interpreted as a lodgement

Fig. 57. Lower part of the lower member, Mortensnes Tillite. A raft of member C of the Nyborg Formation, partly homogenized and sheared, underlain by deformation tillite and overlain by clast-poor grey-green massive lodgement tillite. Tape is 50 cm long. Hill 405 (407, Dazajåkcåkka, 5 km west of Vestertanafjord).

Fig. 58. Deformation tillite, composed of siltstone and mudstone derived from member C of the Nyborg Formation, at the base of the lower member, Mortenenes Tillite. View is of a vertical section, the lower surface being the base of the member. Right is to the east, the apparent direction of the applied stress. Specimen is 12 cm wide. Hill 420 (425) just south of Gudnarjårrannjoaski, 7 km west of Vestertanafjord.



tillite deposited by large glaciers or a continental ice sheet because:

1) It occurs over a large area, at least 40 x 150 km.
2) The very low angle, wedge to blanket geometry is common in lodgement tills in Quaternary deposits in low-relief terrains.
3) It contains striated and faceted clasts.
4) In-situ bodies of stratified sediment indicate channelized flow of water.
5) Abundant locally derived material in both clasts and matrix is suggestive of glacial erosion and transport. Such reworking is also indicated by studies of microfossils (Vidal 1981).

The features of the tillite allow additional reconstruction of the conditions in the basal zone of the ice through time. The deformation till at the base of the lower member, and the occasional rafts of Nyborg sediment indicate a period of intensive subglacial erosion, presumably while the ice was freezing, at the pressure melting point, and the substrate could adhere to the glacier sole, or be thrust up into the glacier. The small size of comminuted Nyborg material suggests extensive

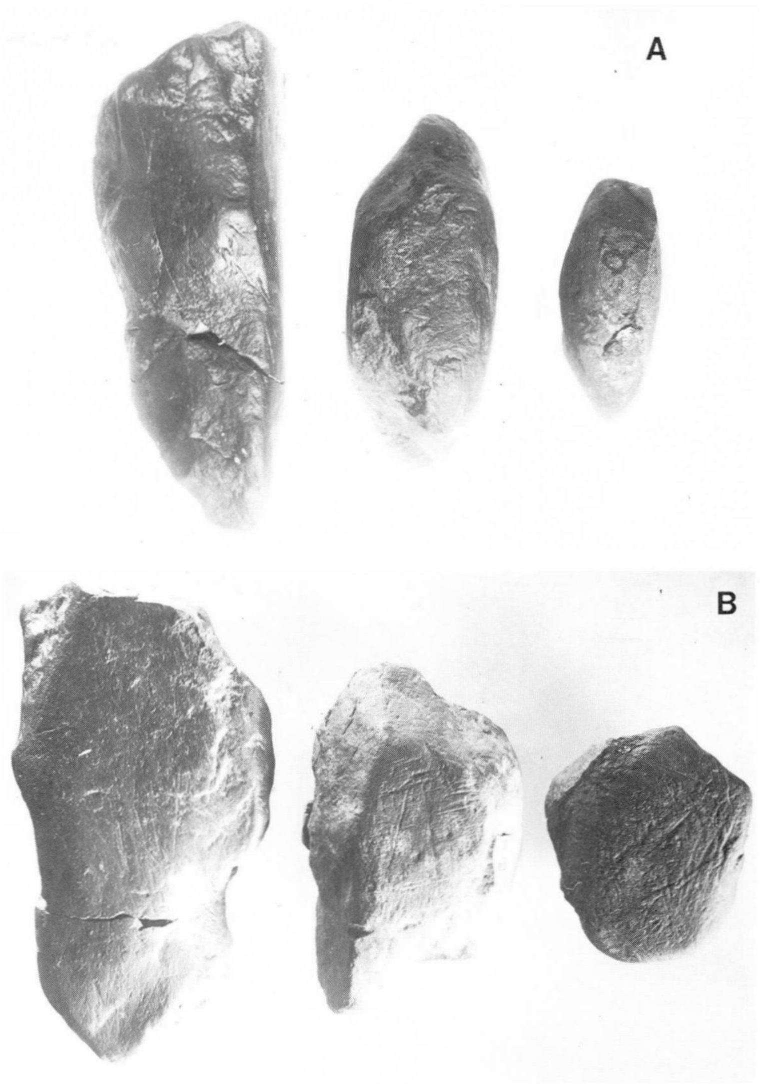


Fig. 59. Three striated and faceted clasts of altered diorite from the lower member of the Mortensnes Tillite at Hammarnes, Varangerfjord. The large clast is 16 cm long. A) View of the clasts along the b (intermediate) axis. The profiles are asymmetrical. B) View along the c (short) axis showing striated, faceted surfaces. Straie occur in subparallel groups.

breakdown of what was only poorly consolidated at the time of erosion.

Exotic extrabasinal materials were transported into the basin in the lower part of the ice, and were mixed with locally derived materials. Partial mixing resulted in banded tillite, while thorough mixing resulted in massive tillite. Deposition of till commenced when the glacier became melting-based. Also at this time, meltwater began to form subglacial or englacial tunnels where flowing water was able to sort and stratify till or debris. The ongoing deposition of lodgement till around the channels enabled preservation of the stratified sediments as *in-situ* bodies encased in tillite. The concentration of Nyborg rafts around Šuoššjåkka, and the thicker lower member in that area, may indicate the development of a small recessional moraine (see Clayton & Moran 1971).

Several observations support previous interpretations of a southern source for the ice sheet (Føyn 1937, Reading & Walker 1966): decreasing thickness of the lower member toward the north, increase in maximum clast size toward the south, available source area for certain crystalline types in the south (Føyn 1937), and purple color in lower member extends north of where purple Nyborg deposits (member D) are truncated against the unconformity with the Mortensnes Tillite.

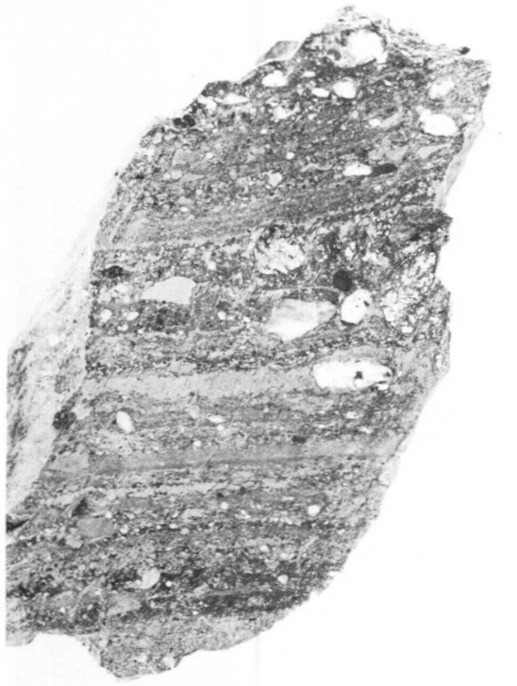


Fig. 60. Polished specimen of banded tillite, 10 cm high, from the lower member of the Mortensnes Tillite west of Giilasjåkka. Light-colored bands are finely ground Nyborg sediment, which alternate with darker bands composed of crystalline clasts and coarse sand. The finer grain size of the Nyborg bands is due to its low resistance to comminution. Primary sedimentary structures are absent.

MIDDLE MEMBER

The middle member extends widely (Fig. 62), from near the southern margin of the basin to Trollfjord in the north, and from Lauvvunjarga in the east to Stuorraskaidi (Fig. 3) in the west. It is distinguished from the adjacent members by a buff-brown weathering color, due to the predominance of dolomite and subordinate chert clasts in a sandy matrix with a dolomitic groundmass mass (Table 4). Also diagnostic is the abundant sedimentary structures. North of where the lower member wedges out near Aldarbakti (Alterberget), the middle member rests directly on the Nyborg Formation, and thus locally has a grey-green color. The thickness of the middle member increases suddenly on Låddebakti (Addasberget, west of Vestertanafjord, Fig. 62) from 0–6 m in the south, to 6–30 m in the north; these are respectively termed the thin and thick submembers.

Thin Submember – Description

The thin submember is well exposed in the Vestertana area, and south to Ellaloabmi, where it forms a nearly continuous blanket of stratified diamictite usually 2–4 m thick. The lower contact is often gradational, showing an upward change from massive grey-green, crystalline-rich tillite of the lower member to the stratified buff-brown, dolomitic diamictite of the middle member.

Both primary sedimentary and deformational structures are abundant. Most common is parallel stratification, ranging in thickness from lamination-scale of a few millimeters to bedding scale of several centimeters, and showing lateral continuity of at least several meters, and possibly much more (Fig. 63). Rare associated cross stratification indicates the tractional origin of some of the layering. Other structures include small scours and unconformities, outsize clasts with plomp-and-drape, slumped beds of chaotically deformed stratified tillite, small-scale and large-scale folding, and high-angle faulting. Many of the clasts in this zone are of massive diamictite, similar in appearance to the stratified diamictite.

The lower sandy diamictite of the thin submember locally grades up into a finely parallel-laminated mudstone with sandstone laminae and

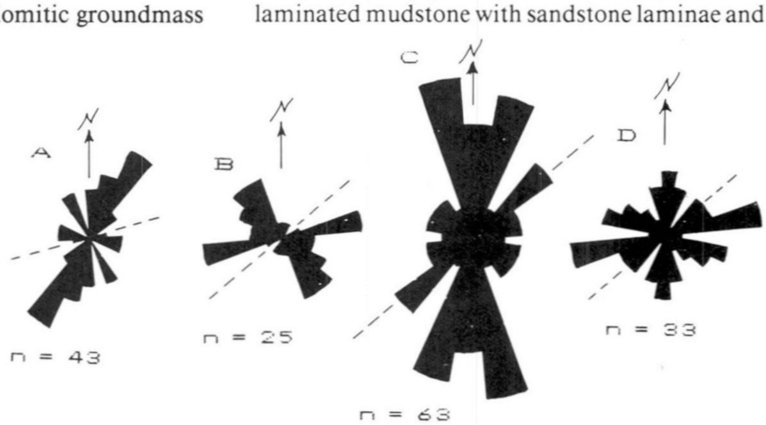


Fig. 61. Orientation of long axis of clasts in the Mortensnes Tillite. A) Lower Member, Hammarnes, B) contact between thick middle member and upper member on Jåkkannjargga, C) upper member tillite on Jåkkannjargga, and D) conglomerate bed at top of upper member, Jåkkannjargga. n = number of clasts measured, and dashed line is local cleavage orientation.

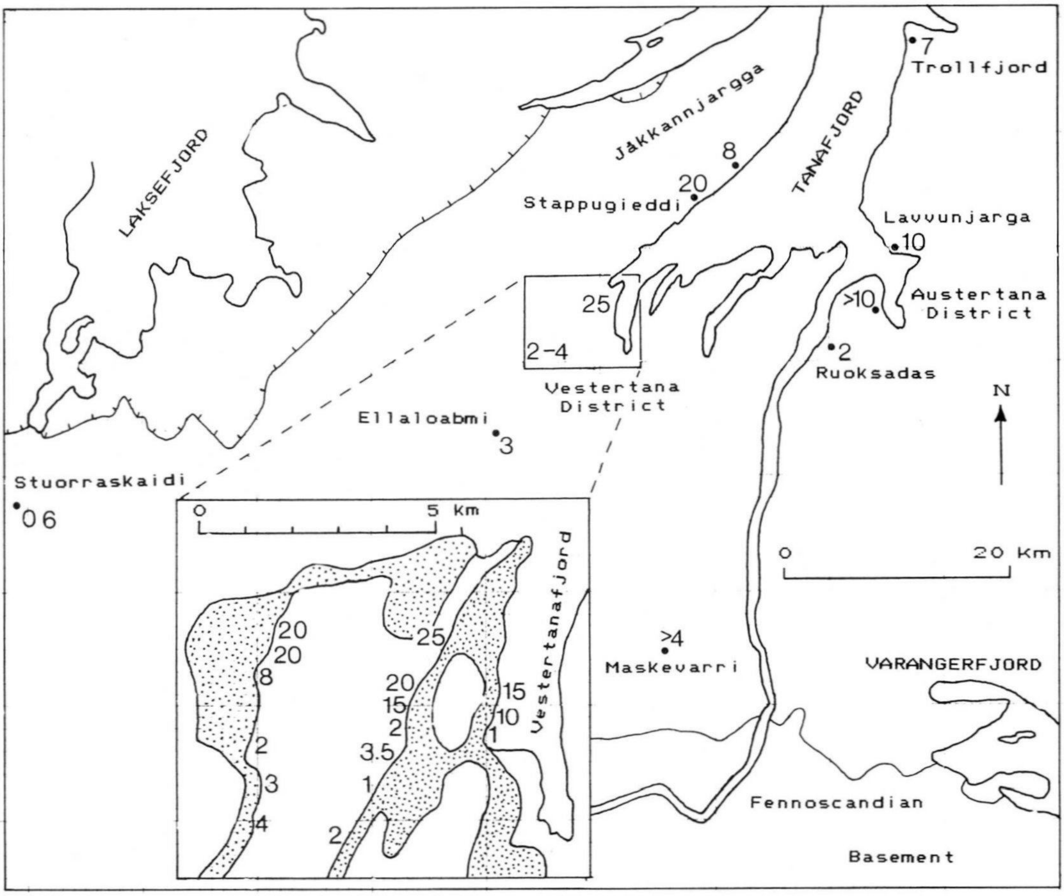


Fig. 62. Thickness, in meters, of the middle member of the Mortensnes Tillite, showing the development of the thick submember to the north and the thin submember to the south. Detailed inset map also shows simplified outcrop of the Mortensnes Tillite in the Vestertana district, based on Føyn (1960).

beds, and small dropstones (Fig. 64). This lithology is up to 1 m thick, occasionally folded and sheared, and is overlain sharply by the upper member.

On the southwestern slope of Maskevarri, to the south, the lower gradational contact of the thin submember is about 3 m thick, and the submember itself is at least 4 m thick. It consists of thin, 3–4 mm thick, symmict (Sauramo 1923) graded laminae, each faintly and finely parallel-laminated (Fig. 65). The top is not exposed.

At Stuorraskaidi, the thin submember consists of about 60 cm of parallel-stratified, brown-weathering diamictite, which rests gradationally on the lower member and grades up into the upper member.

Thin Submember – Interpretation

The change from the lower member to the middle member indicates both new source area and depositional environment, apparently subaqueous as reflected by the ubiquitous stratification and dropstones. The sandy texture suggests selective removal of fine sediment, probably in low salinity meltwater plumes, which was deposited distally in graded laminae, as seen at Maskevarri. Poor sorting and scattered clasts suggest weak, sporadic currents, with some ice rafting. Occasional beds with deformed laminated blocks indicate slumping and mass flow. The peculiar style of deformation which is laterally restricted and which does not resemble the products of glacial overriding as described elsewhere in this paper may be due to the grounding of icebergs. The finely laminated mudstone at the top of the member suggests gradually decreasing current strength. The deformed top of the member, and the frequent absence of the complete sequence

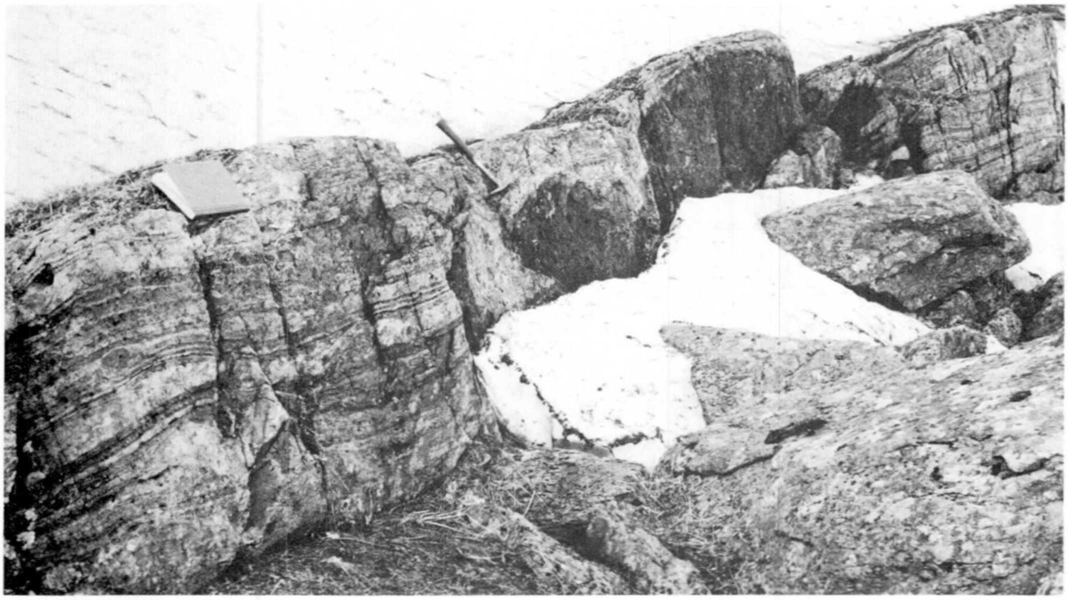


Fig. 63. Thin submember of the Mortensnes Tillite, Ellaloabmi. The coarse, parallel stratification visible here is typical. To the right of the hammer is a large flattened block of massive sandy diamictite, apparently dropped into place. Adjacent to the block, the stratification in the diamictite has been destroyed.

Fig. 64. Thin submember of the Mortensnes Tillite, near Ellaloabmi. Transition from thickly stratified, sandy diamictite up into finely stratified, laminated mudstone with dropstones. The sandy diamictite beds contain chaotically deformed sediment fragments and are interpreted to be sediment gravity flows.

indicate that the contact with the overlying upper member is erosive.

These considerations suggest that the thin submember formed by a retreating marine ice sheet (i.e. terminus below sea-level), analogous to the submarine glacial retreat sequences described

Fig. 65. Thin submember, Mortensnes Tillite, Maskevarri, developed as a rhythmite consisting of thin graded laminae with dropstones.

from phase 2 of the Smalfjord Formation. The vertical sequence reflects a change from subglacial deposition, to proximal subqueous deposition to distal subaqueous deposition. Horizontal facies changes suggest more distal deposition, with regard to the ice margin, to the south. The interpretation of this unit is augmented below.

Thick Submember – Description
The thick submember is best exposed on Jåkkannjargga where a complex sequence is preserved. It also outcrops west of Vestertanafjord, at Trollfjord, and at Lavvunjarga (Fig. 62). Emphasis here is given to the 3 km of excellent coastal exposures between Lassasuolo (Larsholmen) and Stappugieddi north (fig. 37). Member C of the Nyborg Formation subcrops below the tillite only at Lassasuolo, while member D subcrops over the remainder. Large rafts of Nyborg sediment in the tillite can be tied to specific horizons in member D. Below the tillite, the Nyborg Formation shows no signs of the overriding ice sheet, apart from one small thrust fault which dips to the northeast.

The thick submember on Jåkkannjargga is divided into five lithofacies units, defined by composition, structure and stratigraphic position (Fig. 66).

Unit 1 forms a nearly continuous blanket of massive deformation tillite over the unconformity. The tillite is purple and grey-green, with less

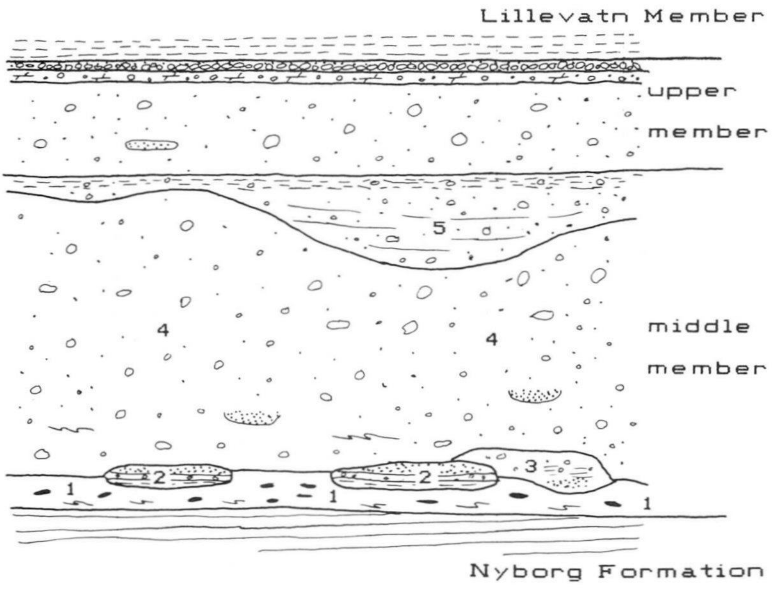


Fig. 66. Schematic portrayal of the stratigraphic and depositional units distinguished in the Mortensnes Tillite on Jåkkannjargga.

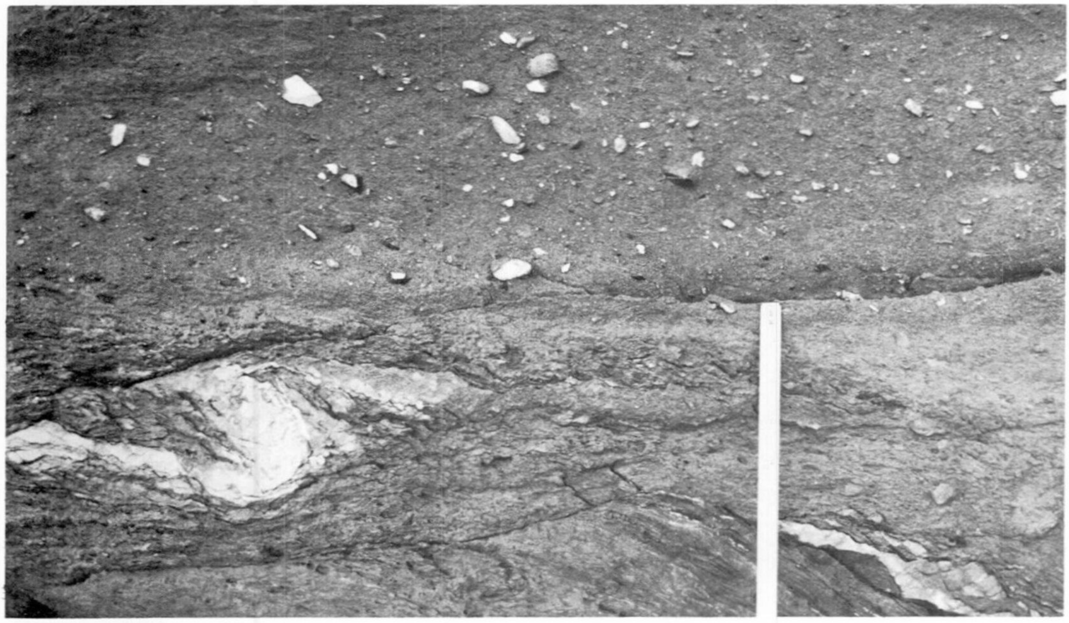


Fig. 67. Thick submember, Mortensnes Tillite, showing unit 1, deformation tillite, composed of Nyborg rafts (at bottom) and deformed Nyborg sediment (overfold at left). Small clasts are imbricated. Inferred flow was to the left (southeast). 300 m NE of Lassasuolo, Jåkkannjargga.

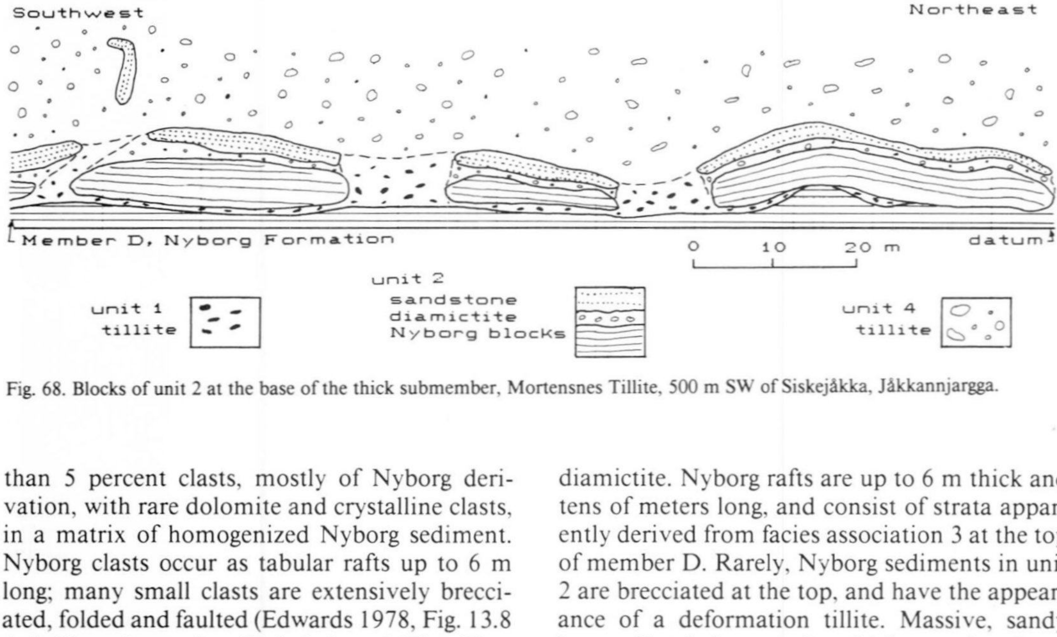


Fig. 68. Blocks of unit 2 at the base of the thick submember, Mortensnes Tillite, 500 m SW of Siskejåkka, Jåkkannjargga.

than 5 percent clasts, mostly of Nyborg derivation, with rare dolomite and crystalline clasts, in a matrix of homogenized Nyborg sediment. Nyborg clasts occur as tabular rafts up to 6 m long; many small clasts are extensively brecciated, folded and faulted (Edwards 1978, Fig. 13.8 A & C), and occasionally imbricated (Fig. 67).

Unit 2 comprises large tabular blocks near the base of the middle member, many of which include three lithologies: Nyborg rafts, diamictite and white sandstone (Fig. 68). The blocks usually have fairly well defined margins with the adjacent diamictite. Nyborg rafts are up to 6 m thick and tens of meters long, and consist of strata apparently derived from facies association 3 at the top of member D. Rarely, Nyborg sediments in unit 2 are brecciated at the top, and have the appearance of a deformation tillite. Massive, sandy brown diamictite up to 2 m thick rests sharply on Nyborg sediment. Clasts are mainly dolomite. Its most striking features are the non-erosive basal contact and its high dolomite content and lack of Nyborg material. White sandstone present at the top of most of the blocks is medium-grained and moderately sorted, and occurs as lenses and

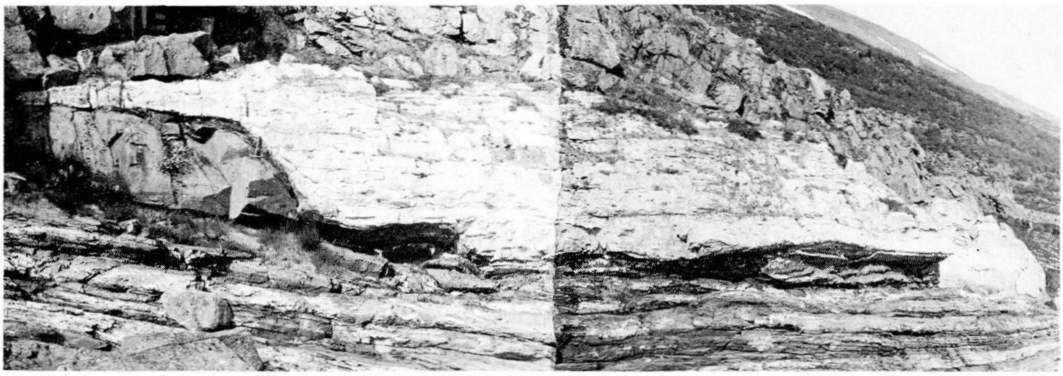


Fig. 69. A block of unit 2 showing allochthonous Nyborg sediment overlain by sandy brown tillite (visible on the left) and white sandstones resting in a steep-sided channel. Above is unit 4 tillite. Siskejåkka, Jåkkannjargga.

sheets up to 4 m thick, often eroding channels into the underlying tillite (Fig. 69). In some cases, unit 2 has been severely deformed and is present as blocks in unit 4.

Unit 3 consists of stratified dolomitic diamictite and sandstone observed at only a few localities. The diamictite is distinguished by its high clast content, 10 to 30 percent, and clasts mostly of dolomite and chert. The matrix is a fine-grained dolomitic groundmass with scattered sand grains. The unit rests on units 1 and 2, and is erosively overlain by unit 4. The sandstone tends to occur in well-formed channels. Graded sandstone laminae at the channel base contain dropstones, and pass upwards and laterally into massive tillite.

Unit 4, the most prominent in the thick submember, consists of buff-brown tillite with a very sandy matrix, predominant dolomite clasts, and abundant sedimentary and deformational structures. The unit thins from 20 to 8 m toward the northeast. North of Stappugieddi north it rests directly on the Nyborg Formation, and the lower 1 to 2 m contains Nyborg sediment and has a grey-green color. Crystallines compose about 15 percent of all clasts, including boulders of grey granite up to 1 m across. The most distinctive feature of unit 4 is the presence of numerous oval clasts, aligned parallel to regional bedding, and composed of a dolomitic sandy diamictite having a lighter weathering color than the enclosing massive tillite (Fig. 70). The clasts are 5 to 10 cm across and massive internally. A second type of unusual clast is bodies of dolomite breccia up to about 1 m long and tabular in shape. Two forms of stratification of unit 4 tillite are noteworthy. Light weathering sandstone with scattered clasts occurs as wisps, lenses and lenticular beds, most commonly near the base of the unit (Fig. 71). In the basal part of unit 4 are channels filled mostly with parallel-laminated or massive sandstone, occasionally with diamictite (Fig. 72). Most channels are 1 to 2 m high, and up to 10 m wide. They are oriented within 45 degrees of north (Fig. 73). Deformational structures in unit 4 are remarkable for their variety and frequency, and include folded lamination (Fig. 74), faulted diamictite clasts, sandstone layers deformed into boudins, brecciated sandstone bodies, sandstone with mullion structure, step-faults (Edwards 1978, Fig. 13.8 B), and overfolded rafts of bedded dolomite derived from the Grasdalen Formation or equivalent.

Unit 5 at the top of the thick submember includes two facies, bedded diamictite in the lower part up to about 5 m thick, and laminite at the top usually less than 1 m thick. Both are similar in color and composition to unit 4, and are infrequently preserved beneath the erosive base of the upper member. Unit 5 is thickest, 6 m, between Stappugieddi and Stappugieddi north. Here, the base of the unit is a sharp bedding plane with well developed grooves and striations oriented east-west (Fig. 73). The beds are up to 1 m thick, lenticular and amalgamated, and consist of diamictite with irregularly deformed lamination and rip-up clasts, and lenses and blocks of various types of diamictite. Laterally the beds wedge out onto the margins of a shallow channel cut into unit 4 tillite. A nearby outcrop shows a shallow channel about 12 m wide cut into unit 5 and floored with conglomerate and sandstone. The channel is partly filled with deformed blocks of

Fig. 70. Light-weathering clasts of sandy tillite immersed in massive and slightly stratified tillite of unit 4, thick submember of Mortensnes Tillite, Jåkkannjargga.

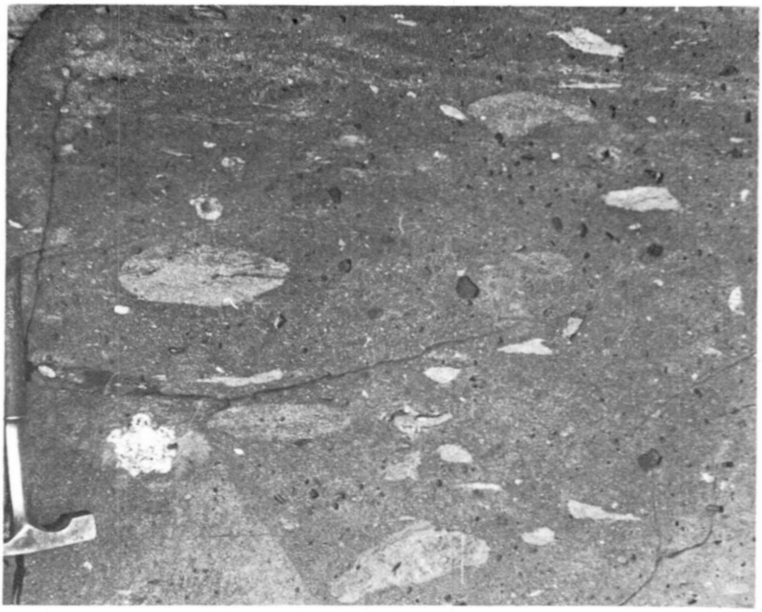


Fig. 71. Lenticular bed of stratified sandstone which grades into surrounding tillite containing lenses and wisps of sandstone. Thick submember, Jåkkannjargga.

sandy diamictite. The laminite at the top of unit 5 consists of alternating sandy and muddy laminae up to several millimeters thick with rare grading and numerous dropstones.

The thick submember which occurs west of Vestertanafjord (Fig. 62) is similar to unit 4 as described above, however the inland exposures do not bring out subtle features. Bodies of dolo-

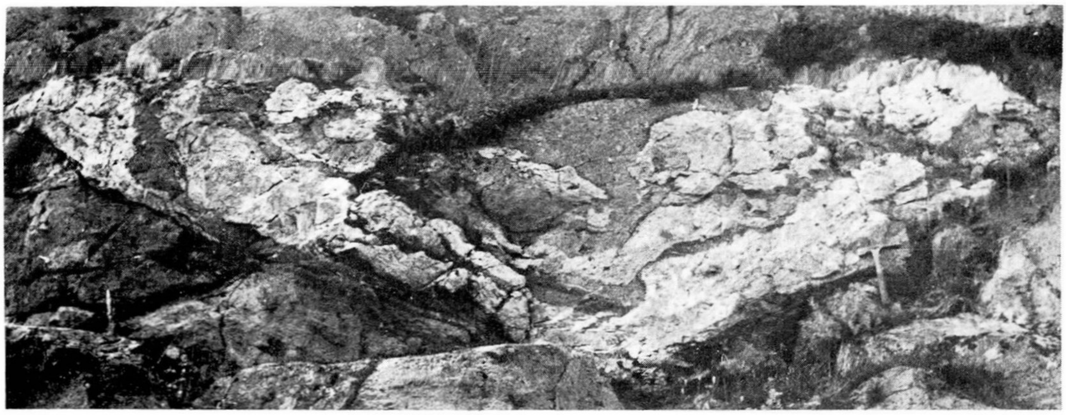


Fig. 72. Channel filled with alternating moderately sorted sandstones and massive diamictite. No lag was observed at the base. Several meters from the base of unit 4, thick submember. Between Lassasuolo and Siskejåkka, Jåkkannjargga.

mite breccia are common, while blocks of bedded dolomite up to 10 x 3 m in size are occasionally seen. *In-situ* sandstone bodies are widespread and show varying degrees of post-depositional deformation.

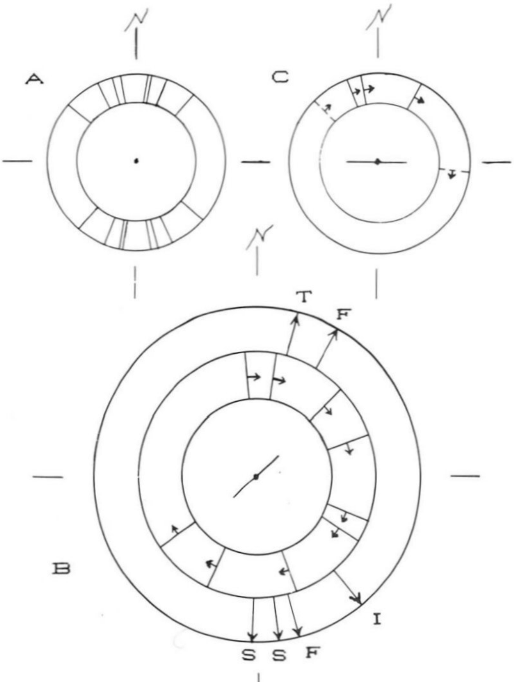


Fig. 73. Directional features in the thick submember, Jåkkannjargga. A) Orientation of channel axes, unit 4. B) Deformational structures in and at the base of unit 4: center, mullion structure; inner circle, fold axis orientation with direction of overturning, and outer circle, direction of stress inferred from normal (step) fault system (F), thrust (T), shear planes (S), and clast imbrication (I). C) Overfolds in unit 5, solid line, bedded tillite; dashed line, dropstone laminite.

At Lavvunjarga, the thick submember composes most of the Mortensnes Tillite. It rests erosively on member C grey-green mudstones of the Nyborg Formation which imparts this color to the lower 2 to 3 m of the tillite. Irregular, discontinuous lenses of sandstone occur throughout the tillite. The brown sandy tillite grades up into 3 m of dropstone laminite, which is overlain by the upper member.

At Trollfjord, west of Njargaccåkka, the Mortensnes Tillite is made up chiefly of the thick submember which resembles unit 4 of the sequence at Jåkkannjargga. At the base is a 35 cm thick breccia of the underlying member E sandstones and shales of the Nyborg Formation. The upper 3 m of the tillite has highly deformed stratification, and at one locality the tillite was overlain by 30 cm of laminated mudstone with dropstones and symmetrical sandstone ripple lenses. This is overlain by the upper member.

Thick Submember – Interpretation

The thick submember of the middle member was deposited primarily as a lodgement tillite because it shares many features with the lower member of the Mortensnes Tillite. Furthermore, *in-situ* bodies of stratified sandstone are more numerous than in any other lodgement tillite in the Vestertana Group in Finnmark. This general interpretation can be refined by reference to the complex section at Jåkkannjargga.

Unit 1 is a deformation tillite because of its high Nyborg content and ubiquitous deformation structures. The presence of several unit 2 blocks, each showing similar lithologies and sequences suggest that they were originally deposited as one continuous unit which was then eroded and

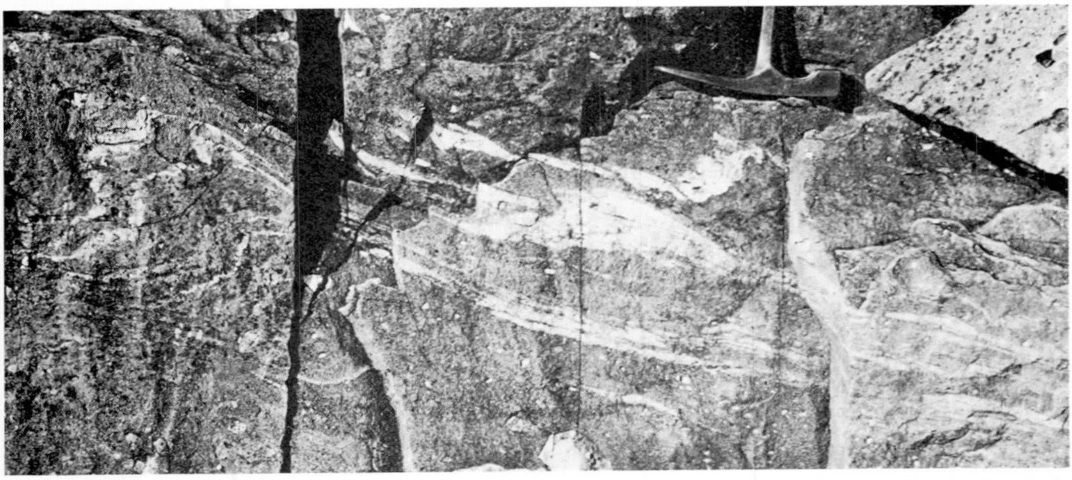


Fig. 74. Sandstone laminae overturned to the left (south) and thickened and compressed due to shear from overriding ice sheet. Unit 4 of thick submember. 300 m SW of Siskejåkka, Jåkkannjargga.

broken into pieces during transport *en masse*, some of which were preserved and deposited elsewhere (Fig. 75). Unit 2 diamictite, in contrast to unit 1, lacks evidence for intense subglacial erosion. Unit 2 sandstone was deposited by water flowing in channels scoured into unit 2 diamictite. Following the emplacement of unit 2 blocks, unit 3 diamictite and sandstone in channels was deposited on top of units 1 and 2. The coarse texture and dropstones in the channels contrasts with unit 2 sandstones. In addition, locally observed shear-like deformation structures along the unit 1 – unit 3 contact suggest a subglacial origin for unit 3 (Fig. 75).

Unit 4 represents the main depositional event in the thick submember, and is a lodgement tillite. The numerous examples of stratification attest to abundant glacial meltwater. The deformation of many of the *in-situ* bodies suggests that deposition of both till and sandstone alternated with periods of subglacial shearing. The sandy diamictite clasts may have been derived by erosion of an older till.

Unit 5 represents a major change in depositional environment. The irregular beds of diamictite were clearly resedimented as gravity flows. The presence of lenses and occasional beds of sandstone and conglomerate indicate that periods of water flow alternated with mass flows. One conglomerate-floored channel in which unit 5 occurs was scoured out by powerful water currents. The dropstone laminite at the top of the unit was deposited in relatively quiet water by deposition from weak currents and ice rafting. This suggests that the lower part of unit 5 represents subaqueous rather than subaerial mass flow processes. The orientation of many sedimentary and deformational structures strongly indicates that the ice flowed from the north or northeast. The composition of the clasts and matrix both indicate that the dominant sediment source was the Tanafjord Group.

Broadly, the thick submember preserves a record of subglacial erosion and deposition, and subaqeous proglacial deposition:

1) Period of major glacial erosion (pre-lower member), possibly removing as much as 200 to 300 m of Nyborg Formation. The end of the erosive phase probably coincided with a change from freezing-based to melting-based conditions.
2) During rapid retreat of the ice margin, a thin lodgement or melt-out till (unit 2 diamictite) was deposited on the autochthonous Nyborg Formation. The abundant glacial meltwater collected in proglacial streams, eroded channels into the tills, and filled them with relatively clean, well sorted sands (unit 2 sandstone) derived from the very sandy debris carried in the glacier (Fig. 75A).
3) As the climate cooled, the ice sheet again advanced southwards over a thin permafrost layer, eroding away large slabs of the newly deposited sediments and their autochthonous Nyborg substrate. At the same time, vigorous subglacial erosion formed the deformation till of unit 1 (Fig. 75B).
4) A change to wet-based conditions causes dep-

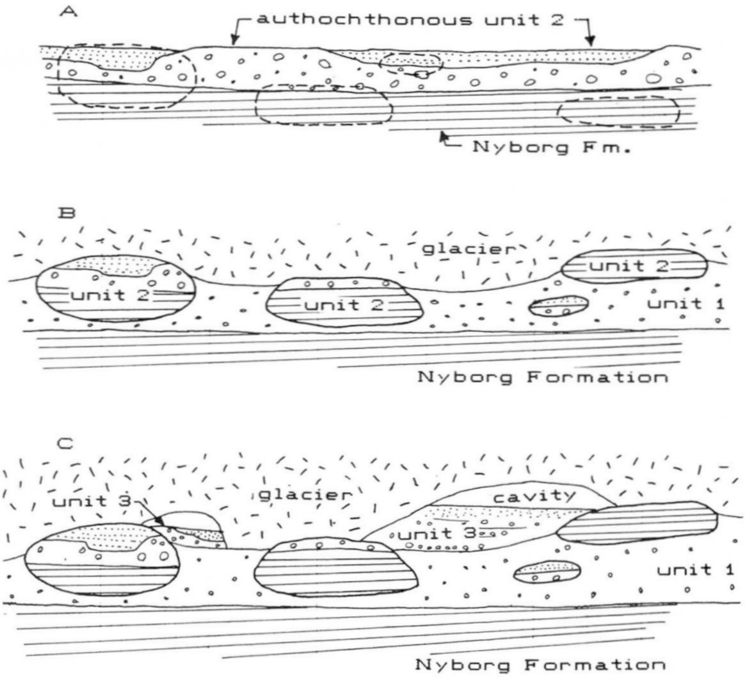


Fig. 75. Proposed depositional sequence for the thick submember, middle member, Mortensnes Tillite, based on studies of the outcrops on Jåkkannjargga. A) deposition of lodgement till on autochthonous Nyborg Formation during glacial retreat; then partial reworking by fluvioglacial streams into sandstones of unit 2. Dashed lines indicate portions of unit 2 that will form rafts in the lower part of the middle member. B) Rafts of unit 2 entrained in the ice, resting on unit 1 tillite. C) Subglacial streams develop at the base of the ice, depositing stratified, poorly sorted sandstones and coarse laminites with dropstones. These deposits rest on units 1 and 2, and are erosively overlain by unit 4, a lodgement tillite.

osition of rafts of sediment (unit 2) and unit 3 tillite (Fig. 75B), while subglacial meltwater streams formed channels in which unit 3 stratified sediments were deposited (Fig. 75C).

5) There now followed a major glacial advance which led to sustained subglacial erosion and deposition of lodgement till (unit 4). However, thermal conditions remained temperate, and large amounts of water circulated through and at the base of the ice sheet.
6) Finally toward the close of the glacial episode, eustatic rise in sea level submerged the ice margin, causing calving of icebergs. Subglacial meltwaters maintained channels near the margin of the ice sheet; these were filled with till slumping in from the sides of the channels, and with ice dropped particles (unit 5, lower part). Slump structures in unit 5 suggest transport was to the east, but regional considerations, discussed below, suggest that it may have been to the west. Away from the ice margin, in deeper water, the laminated mudstones with dropstones of the upper part of unit 5 were deposited.

Deposition of the Middle Member

Integrating the interpretations of the thin and thick submembers indicates that the thick submember was deposited primarly as lodgement till by a southward flowing, wet-based ice sheet, while the thin submember was deposited subaqueously over a bathymetric depression as the ice sheet began to float and gradually broke up due to iceberg calving. Subglacial meltwater flowed southward beneath the ice sheet to the grounding zone, where both it and entrained sediment were discharged into the sea, to be deposited as the thin submember. Fluctuations between subglacial erosion, deposition and both channelized and sheet-like flow of subglacial water in unit 4 suggest occasional lifting of the marine ice sheet, perhaps due to ice thinning or changes in sea level. The main processes that were attributed to the thin submember: sporadic strong currents, sediment gravity flows, isolated deformation related to grounding icebergs, can thus be explained in the context of a marine ice sheet. Increasingly distal conditions from the ice margin, preserved as dropstone-bearing laminites at the top of both the thin and thick submembers, suggest that a rise in sea level eventually pushed the submerged ice margin to the north, outside of the study area. The abrupt line separating the thin (subaqueous, proglacial) and thick (subglacial) submembers was probably topographically controlled, and the lateral differentation of these facies reflects a lengthy pause in the overall retreat of the marine ice sheet.

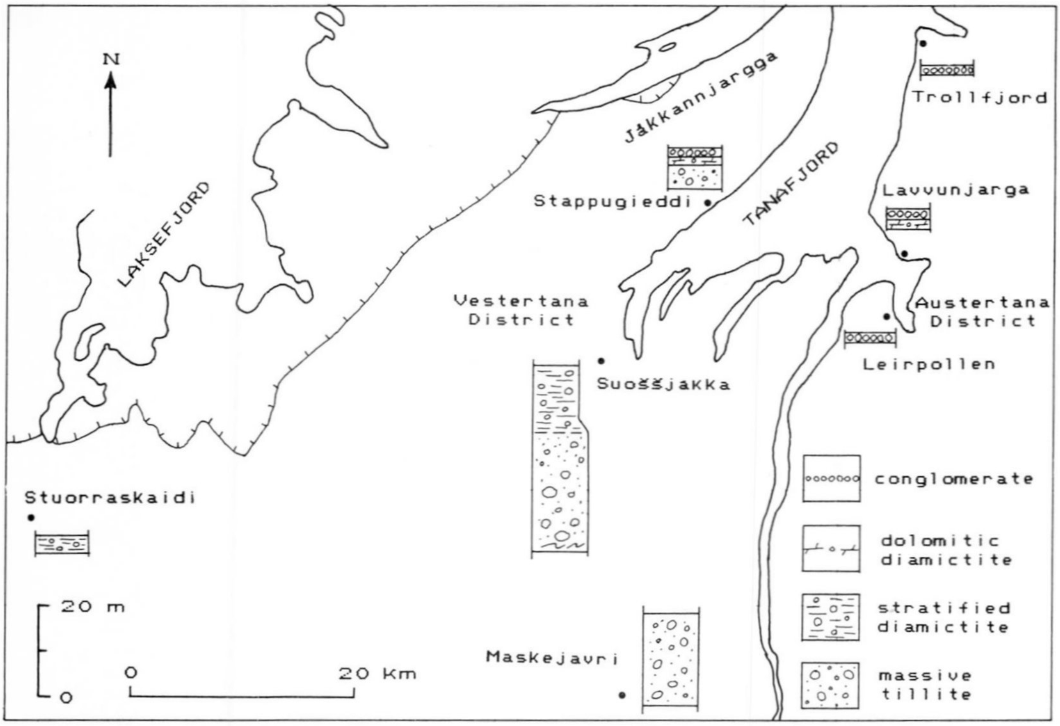


Fig. 76. Thickness and facies of the upper member, Mortensnes Tillite.

The distinctive features of the unit 4 tillite resemble in some respects those of 'undermelt' diamictites described from other ancient and Pleistocene sequences (Gravenor et al. in press).

UPPER MEMBER

The upper member is best developed in the Vestertana area, and extends to Trollfjord in the north, Austertana in the east, and Stuorraskaidi in the west (Fig. 76). It consists mostly of dark grey, massive tillite, which contrasts with the underlying middle member (Table 4). At northern and eastern localities the upper member includes two additional lithologies: dolomitic diamictite composed of predominantly dolomite clasts and matrix, and polymict conglomerate, both only tens of centimeters thick. The upper member is overlain by mudstones of the lower submember of the Lillevatn Member, Stappogiedde Formation.

Description

Grey tillite composes the bulk of the upper member in the Vestertana area, where it reaches its maximum thickness of about 40 m (Fig. 76).

Basal contact – generally appears sharp above the middle member. It may appear erosive when it overlies middle member laminites that are highly sheared and folded, in which case the basal part of the massive tillite contains small rafts of deformed laminite derived from the middle member, and also shows shear banding. Locally, where the thin submember of the middle member is absent, the upper member rests directly on the lower member.

Composition – dark grey tillite consists of about 5 to 15 percent clasts, mostly crystallines, in a muddy matrix with scattered sand grains (Table 4). Most clasts show signs of rounding.

Sedimentary structures – tillite appears massive at almost every outcrop. *In-situ* bodies of stratified sediments are very rare; one such deposit composed of cross-bedded and parallel-laminated sandstone was seen at Jåkkanjargga. In addition, several irregularly shaped, small masses of gravel-rich diamictite occur in the lower part of the member. The most significant structure is lamination which appears in a long road cut where of Šuoššjåkka farm. Here, the upper part of the diamictite is very faintly laminated in the top 10 to 15 m, becoming more readily discernible toward the top, concomitant with a decrease in clast size and abundance. Laminae are up to 1 cm thick; the thicker laminae are more continuous than the thinner ones. About 30 percent of the laminated diamictite consists of greenish-grey mudstone, the remainder is brownish-grey with dispersed sand grains and small clasts. The laminae show moderately dipping folds, and isoclinal recumbent folds, both small-scale. The top of the laminated diamictite is interstratified over an interval of about 1 m with parallel-laminated mudstone, lacking dropstones. This zone is overlain by the laminated mudstones of the Lillevatn Member. At Stuorraskaidi the upper member is represented solely by about 4 m of finely parallel-laminated mudstone with abundant dropstones. The unit rests gradationally on the middle member, and grades up into the laminated mudstones of the Lillevatn Member.

Upper Contact – in normally weathered outcrops in the Vestertana area, massive-appearing upper member tillite is sharply overlain by the Lillevatn Member laminated mudstones. It is unclear though whether the gradational conditions at Šuoššjåkka are representative. Sharply above the massive tillite at Jåkkanjargga is a distinct bed of *dolomitic diamictite.* The 20 to 40 cm thick bed of light buff-brown structureless diamictite consists of about 5 percent dolomite and crystalline clasts in a fine-grained dolomite matrix. At one locality the underlying tillite showed dolomite laminae which increased in frequency and thickness upwards, suggesting a gradational contact with the dolomite tillite. A similar diamictite occurs above the thick submember of the middle member at Lavvunjarga. The 20 cm thick bed is finely laminated in the lower part. A thin *conglomerate* bed, usually 20 to 30 cm thick, occurs at the top of the Mortensnes Tillite at Jåkkanjargga, Store Leirpollen, Lavvunjarga (loose block) and Trollfjord. On Jåkkanjargga, the conglomerate fills small pockets and depressions in the dolomitic diamictite below. The conglomerate is polymict, with composition similar to that in the upper member tillite, and clast supported, usually with a sandstone matrix. Locally the conglomerate is well sorted with very well rounded pebbles. It is overlain by up to 15 cm of sandstones which grade rapidly up into the Lillevatn Member. On the west side of Store Leirpollen, the conglomerate is at least 50 cm thick, and appears to overlie the thick submember of the middle member. The conglomerate is clast-supported and clasts are composed of dolomite. At Lavvunjarga a loose block of conglomerate, closely resembling that which occurs at Jåkkanjargga, was found on the beach, opposite outcrops of the upper part of the Mortensnes Tillite. At Trollfjord the conglomerate overlies the middle member, but it consists of rounded dolomite and a variety of crystalline pebbles. It is sharply overlain by mudstones of the Lillevatn Member.

Interpretation

The upper member consists of five distinct facies. Massive tillite is dominant and very widespread. The erosive base, and rare *in-situ* sand bodies suggest an origin as lodgement till, similar to the lower member tillite.

The stratified diamictite was seen only at one outcrop, but is assumed to be more widespread. The alternation of fine mudstone and diamictite laminae without any signs of current reworking suggests subaqueous conditions, with the mudstone deposited by suspension settling from dilute meltwater plumes, and the diamictite deposited by rafting of poorly sorted glacial debris from floating ice. This facies is similar to 'compound glacial marine sediments' described from the Antarctic continental shelf (Anderson et al. 1980). Sub-ice shelf conditions are possible because the lack of slumping and scouring due to iceberg grounding, and the absence of appreciable bottom currents, contrasts with the deposition of the thin submember of the middle member in front of a marine ice sheet.

In contrast to the laminated diamictite described above, the laminated mudstone with dropstones observed at Stuorraskaidi resembles, and had a similar origin to, the laminites seen at the top of the middle member, and in members D and E of the Smalfjord Formation.

The dolomitic diamictite is a unique lithology of uncertain origin. A diagenetic origin seems unlikely because of the planar contact with the underlying lithologies. Alternatively the diamictite may have formed very slowly by ice rafting of clasts and simultaneous precipitation of carbonate in a relatively shallow area, far from the ice front.

The conglomerate bed at the top of the upper member is a high energy facies apparently formed by reworking of tillite and removal of fine-grained matrix. The development of the conglomerate above the dolomitic diamictite at Jåkkanjargga suggests that subtantial lateral transport of the clasts may have occurred. At Trollfjord the presence of the crystalline-rich conglomerate above the middle member suggests that the upper member may originally have been deposited here, and then reworked to form the conglomerate. However remnants of upper member grey tillite are not preserved at Leirpollen or Lavvunjarga.

Deposition of the Upper Member
The upper member is similar to many of the other glacial sequences in Finnmark in containing an early phase of lodgement till deposition, followed by a later phase of subaqueous deposition. The sequence of depositional events is summarized below.

1) The glaciation represented by the upper member followed the submarine glacial retreat represented by the laminites of the middle member.
2) The ice sheet was grounded in the central part of the study area where lodgement till was deposited, but was floating in the west where dropstone laminite was deposited. The source of the ice is unknown because deformation structures are rare.
3) With time, the ice sheet began to float over increasingly larger areas, and the grounding line retreated. In quiet water, possibly under an ice shelf, laminated diamicton accumulated as a 'compound glacial marine sediment'. Away from the ice shelf in the north, dolomitic diamicton accumulated in relatively shallow water.
4) Following deglaciation, the northern and eastern parts of the study area were isostatically uplifted, possibly but not necessarily above sea level, and intense reworking of the underlying tillites led to the formation of a thin lag conglomerate. This was preserved during postglacial rise in sea level. In the main depocenter, deposition of laminated tillite gave way rapidly to the marine shales of the Lillevatn Member.

DEPOSITIONAL HISTORY OF
THE MORTENSNES TILLITE
The stratigraphy and facies of the Mortensnes Tillite indicate that the Formation includes two phases of ice sheet advance and retreat, which were preceded by a lengthy period of subglacial erosion. The lower member formed beneath extensive piedmont glaciers, or an ice sheet which flowed northward off of the Fennoscandian shield. Possibly during the same glacial episode, but later in time, the middle member was deposited beneath an ice sheet which flowed from the north; a thin development in the southern part of the basin formed in front of the submerged ice margin. The upper member represents the second glacial advance, with a major change in provenance, but the source of the ice is unknown. After the final retreat of the marine ice sheet, local isostatic uplift at the northern margin of the basin formed a lag conglomerate which caps the Mortensnes Tillite over a large area.

The Lillevatn Member, Stappogiedde Formation – Postglacial

The Lillevatn Member (Banks et al. 1971; 'dark-coloured shale and light-coloured sandstone' of Føyn, 1937; 'quartzic sandstone member' of Reading, 1965) is significant in Finnmark because it correlates readily from the eastern Varanger Peninsula (Røe 1970) at least to Halkevarre south of Porsangerfjord (Føyn 1967, member 1 of the Dividal Group), about 200 km. Reading & Walker (1966) suggested a fluvial origin for the sandstones in this member. The name 'Lillevatn' has been replaced by 'Uccajavri'.

The Lillevatn Member includes a lower submember, 3 to 55 m thick, consisting largely of mudstones, and an upper submember of sandstones and shales which are about 40 m thick over most of the study area. At Stuorraskaidi (Fig. 3) it reaches a maximum of 55 m. The lower submember comprises a thick submember which occurs in the south (Fig. 77). The zone across which the rapid change in thickness occurs coincides closly with where the middle member of the Mortensnes Tillite rapidly thickens to the north (Fig. 62).

THICK LOWER SUBMEMBER
Description
The thick submember rests sharply or with rapid transition above the upper member of the Mortensnes Tillite. The lower part consists of grey parallel-laminated mudstone, in which the thickness and frequency of silty laminae increase upwards. Towards the top it grades into a siltstone and very fine sandstone, primarily parallel-laminated but with ripple cross-lamination. At the top few meters thin lenticular fine to medium grained sandstones appear; these are sharp based and are massive or stratified. Usually the upper

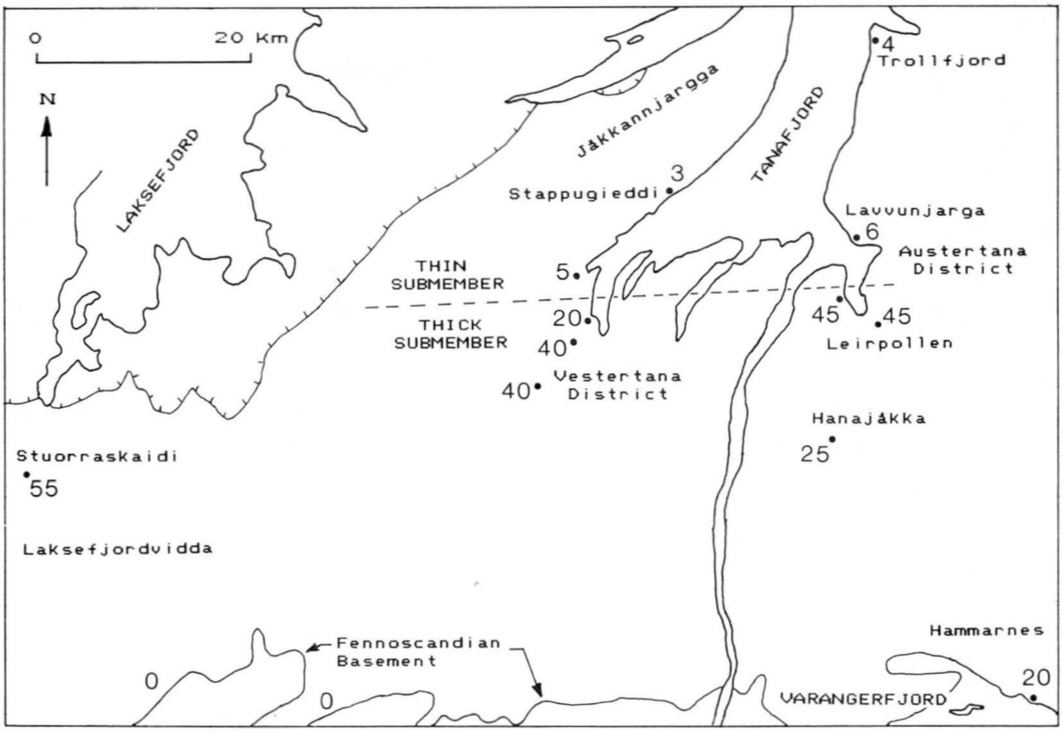


Fig. 77. Thickness of the lower submember, Lillevatn Member, showing the development of the thick lower submember to the south and the thin lower submember to the north.

contact of the submember is sharp, but at a few locations it is strongly erosive with channels cutting down as much as 1 m.

Interpretation
This unit is a large-scale coarsening-upward sequence that reprents a transition from quiet water sedimentation at the base to shallow water, high energy conditions at the top. Such sequences form by progradation of a delta into a quiet water, marine environment (Elliot 1978), and is analogous in this regard to stage 3 of the Nyborg Formation.

THIN LOWER SUBMEMBER
Description
The thin submember consists of silty or sandy grey mudstone, usually parallel-laminated, with some ripple cross-lamination. Intercalated with the mudstones are medium-grained sandstones, mostly parallel-laminated or cross-bedded internally. The unit rests sharply on the conglomerate at the top of the Mortensnes Tillite. The section at Lavvunjarga is unique in that it shows a coarsening-upward trend, analogous to that seen in the thick submember.

Interpretation
The general occurrence of sandy interbeds and ripple lamination in the thin submember suggests that depositional conditions were somewhat shallower and higher energy than in the lower part of the thick submember. The abrupt decrease in grain size from the underlying Mortensnes Tillite conglomerate supports Reading & Walker's (1966) ideas of a major transgression following the deposition of the Tillite. The greater thickness of the lower submember in the south, and the association of quiet water facies in that area probably reflect the presence of a depositional basin in the south, which shallowed rather quickly to the north. This represents a continuation of the subsidence and basinal trends inferred for the upper member of the Mortensnes Tillite.

UPPER SUBMEMBER
Facies
The upper submember is a complex assemblage of facies: sandstones (facies A through D) and shales (facies E and F). The base of the overlying Innerelv Member is marked by the appearance of purple shales (Banks et al., 1971). In general,

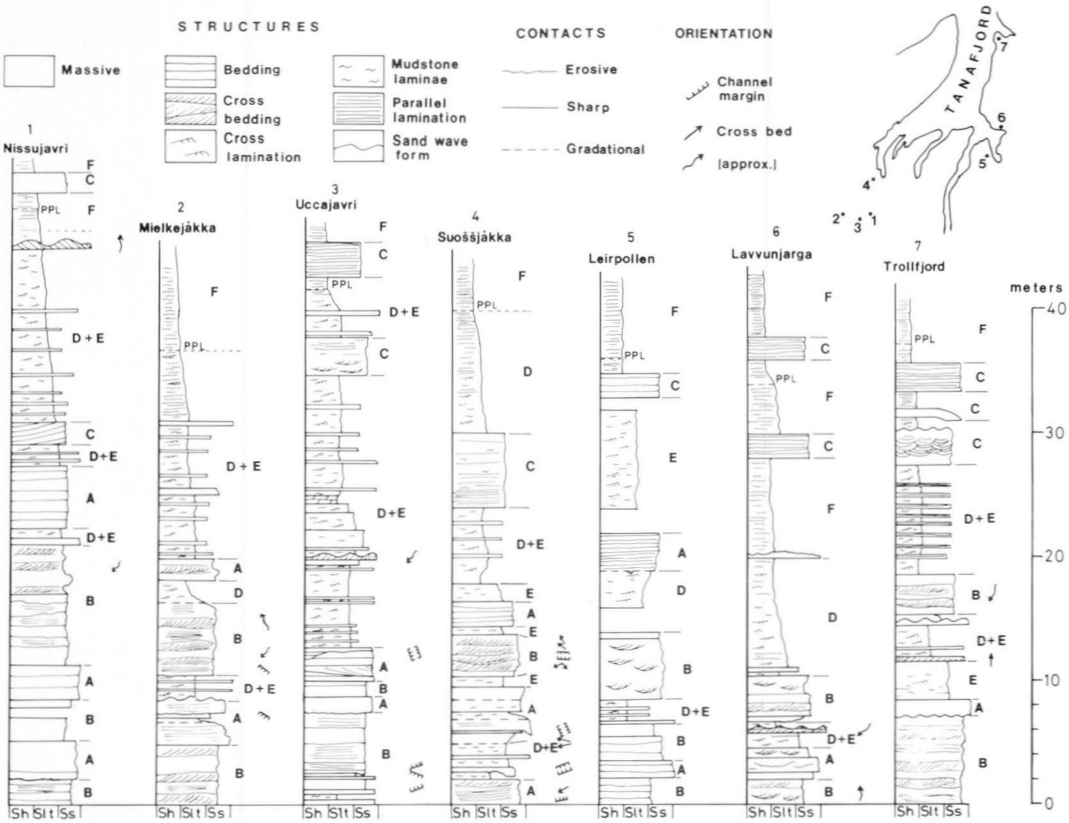


Fig. 78. Measured sections through the upper submember, Lillevatn Member. Paleocurrents oriented with north to the top.

sandstones are predominant in the lower part of the submember, and shales in the upper part (Fig. 78). The facies are described briefly below.

Facies A is very poorly sorted, coarse, subarkosic sandstone with granule conglomerate and, frequently, a muddy, micaceous matrix. Pebbles up to 3,5 cm long were seen at Mielkejåkka (Melkelven), but average 2–4 mm. Beds are medium to thick, and parallel-sided to lenticular, with occasional scoured bases. Almost all beds are massive internally, but a few show trough cross-bedding, and one showed faint, irregular subhorizontal lamination. This facies is considered to have formed in strong tractional flows, probably upper part of the upper flow regime.

Facies B consists of medium-grained, moderately sorted subarkosic sandstone, usually in medium beds 10 to 40 cm thick. Beds are parallel-sided to slightly lenticular and are usually parallel-laminated, but also massive, and planar and trough cross-bedded. This facies formed by moderate currents associated with migrating dunes and plane bed flow.

Facies C sandstones are relatively well-sorted and well-rounded, usually fine-grained and occur in units 2 to 6 m thick, with sharp, planar bases and tops. Internally they are mostly parallel-laminated, but show a range of other structures. These sandstones also occur in the base of the Innverelv member. The relative maturity of these sandstones, and their occurrence in the upper part of the member suggests a marine influence.

Facies D comprises thin to medium beds, intercalated with facies E mudstone, of variable grain size (fine to very coarse sand) which are almost always sharp, planar-based, and occasionally lenticular and highly erosive. Tops of beds are usually sharp, and may show evidence of reworking. At Trollfjord many of these beds contain numerous shale flakes. Internally, coarse sandstones are usually massive, while fine and medium sandstones are parallel-laminated or trough cross-bedded. One variety of this facies consists of very coarse sand to granule material in beds that exhibit a large scale wave-like morphology, which because of their internal bi-directional cross bedding may represent antidune deposits (Hand, 1969). These beds represent a variety of bed forms, formed in moderate to strong, episodic flows.

Facies E consists of dark grey, brown weathering rippled and finely parallel-laminated, micaceous silty and sandy mudstone. Silt and sand are concentrated in laminae, lenses and thin lenticular beds, which are often ripple cross-laminated. A few sections displayed small-scale coarsening-upward sequences 3 to 5 m thick, overlain by facies B sandstone. Such sequences tend to occur in the middle part of the upper submember. Units of facies E contain very variable proportions of interbeds of facies D sandstones. These mudstones formed in a shallow, somewhat agitated area, characterized by suspension settling of mud, subject to frequent waves and currents.

Facies F consists of finely parallel-laminated grey mudstone, which occurs at the top of the submember and grades up into purple mudstone of the Innerelv Member. This mudstone, which is much finer grained than facies E mudstone, often contains intercalations of facies C sandstone. This mudstone formed in very quiet water.

Interpretation

The upper submember is broadly interpreted as shallow water, delta front to delta plain deposits because the unit occurs on top of a broad regressive coarsening-upward sequence, and the sandstones are coarser, more feldspathic and micaceous, and muddier than shallow marine sandstones in the Tanafjord and Vestertana Groups. A more refined interpretation of some of the facies is difficult. The main sandstone units rest erosively on the delta front and prodelta deposits of the lower submember and may have formed in either coarse grained point bars of meandering streams (McGowen & Garner 1970) or braided streams (Miall 1977).

Facies E mudstones, often with intercalated facies D sandstones, correspond to the shallow water environment of a submerged delta plain. The abundant mica suggests proximity to rivers. The sandstones indicate significant interruptions of the tranquil environment, perhaps as related to breaching of the channel during flooding, and the transport of coarse sediment out onto the floodplain (Allen 1965).

The clean sandstones of facies C occur in the upper part of the submember, usually within facies F, fine-grained mudstones (Fig. 78). The combination of lower energy conditions of facies F, and intensive reworking of sand seen in facies C suggest a transition to coastal marine environments, such as barrier or chenier. This is consistant with the occurrence of small scale coarsening-upward sequences in the middle to upper part of the submember. These form in the lower delta plain during flooding, when fresh, sediment-laden water exiting through crevasse channels flows out over brackish water in interdistributary bays (Oomkens, 1970). Thus, several lines of evidence point to the impending upward transition into the shallow marine Innverelv Member (Banks 1973).

The limited paleocurrent data do not indicate the flow directions of the Lillevatn Member streams. However, the southward increase in maximum grain size suggests that the Fennoscandian shield was the main source area.

DEPOSITIONAL HISTORY OF THE LILLEVATN MEMBER

Study of the Lillevatn Member reveals a complex depositional history.

1) The eustatic and isostatic adjustments which followed the Mortensnes Tillite glaciation resulted in relatively deep water in the south, and relatively shallow water in the north.
2) During the onset of deltaic progradation into the basin from the south, mudstones of the thick submember were deposited in the south, and sandy mudstones were deposited in the thin submember in the north.
3) The widespread development of the upper submember indicates that delta plain conditions developed over the entire area. The blanket geometry of the unit suggests that there was little delta plain aggradation as the delta prograded northwards. The erosive contact between the submembers may represent a drop in alluvial base level, perhaps reflecting a slight fall in relative sea level due to continuing isostatic recovery.
4) Following establishment of the broad alluvial plain, a relative rise in sea level initiated both minor but uniform aggradation, and transgression, which are represented in the facies and their corresponding environments: 1) facies A and B in delta plain, fluvial channels, 2) facies D and E in a delta plain, fresh water

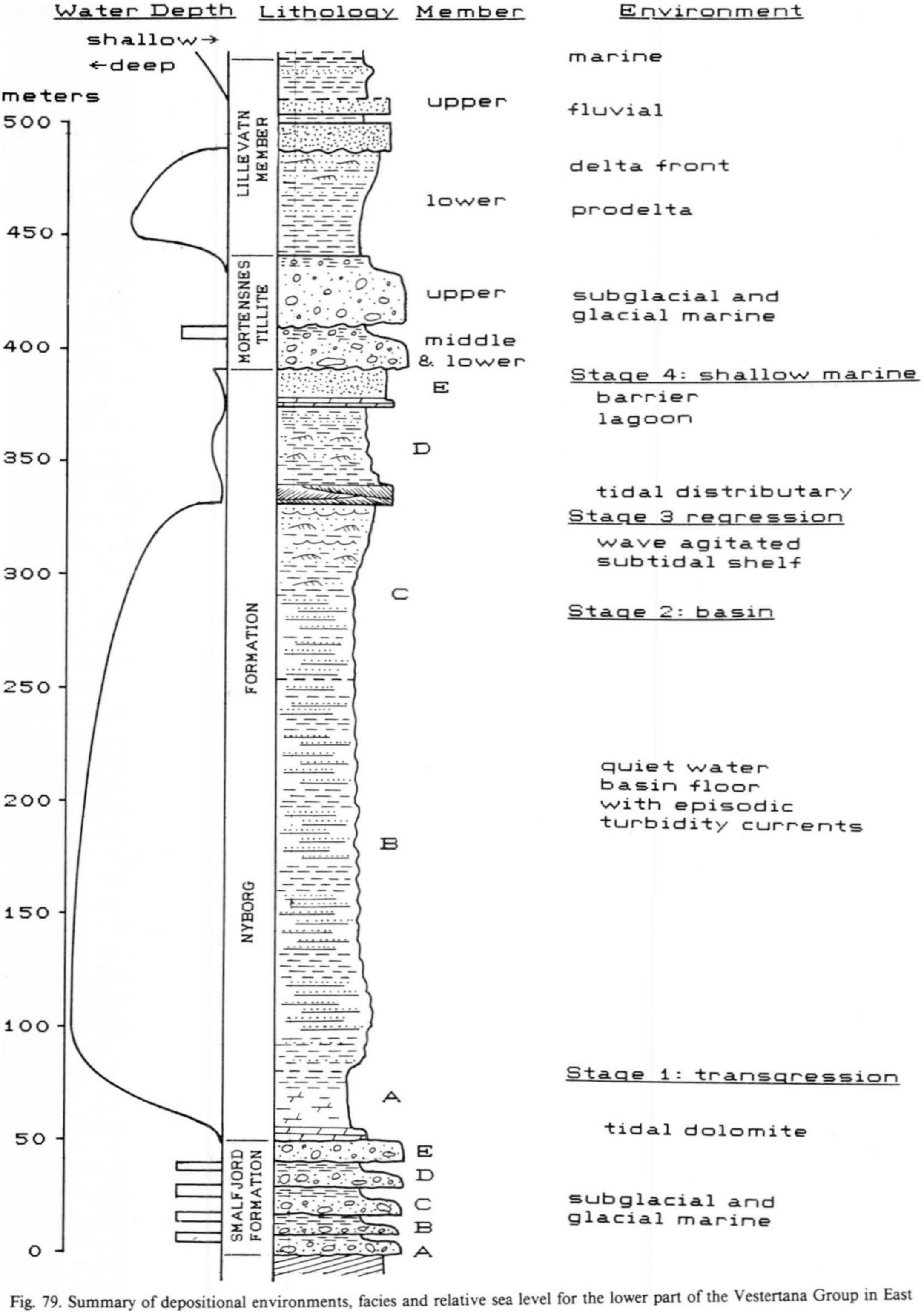


Fig. 79. Summary of depositional environments, facies and relative sea level for the lower part of the Vestertana Group in East Finnmark.

floodplain, 3) facies E coarsening-upward sequences in a lower delta plain, brackish interdistributary bay, 4) facies C on a delta destructinal coastline, either chenier or barrier bar, with facies F, shelf muds.

Synthesis

CONTROLS ON SEDIMENTATION

Major controls on sedimentation (Fig. 79) were: 1) regional rectonics, 2) climate, 3) eustasy, and 4) isostasy (Reading & Walker 1966). To *regional rectonics* can be ascribed the development of this small epicontinental basin with its main depocenter in the Vestertana area, as well as the broad trends of thickness and facies changes, and unconformities.

Local structure may also have controlled the abrupt north-south changes in thickness and facies observed in the Mortensnes Tillite and the Lillevatn Member. The change in facies in the middle member of the Mortensnes Tillite from grounded ice in the north to floating ice in the south, and in the lower submember of the Lillevatn Member from shallow water and erosion in the north to thick basinal deposits in the south both suggest a rapid change in subsidence rate over a very short distance. This zone also corresponds to a major change in the strike of Caledonian structures (Føyn 1937). It is possible that a small high-angle fault underwent slight vertical offset during the Upper Proterozoic and was later reactivated during Caledonien tectonism.

Climate was the chief control of sedimentary facies, having caused the glacial and non-glacial episodes, as well as the stadials and interstadials represented by the member-scale fluctuations preserved in both glacial formations.

Eustatic sea level rise would be expected to approximately coincide with the wasting of the ice sheets. The abrupt facies changes between the glacial and non-glacial formations suggest that this may have been due to rapid deglaciation. However, this may also be typical for retreating marine ice sheets which deposit submarine glacial retreat sequences (Edwards, in press). The facies changes associated with the top of both of the glacial formations shows signs of sea level rise. In the Smalfjord formation at Trollfjord, loessites are overlain by laminated mudstones which are probably marine, and the basal dolomites of the Nyborg Formation indicate temporary starvation of terrigenous sediment in the basin (Reading & Walker 1966). The polymict conglomerate at the top of the Mortensnes Tillite abruptly overlain by Lillevatn Member mudstones may also indicate a late glacial rise of sea level. Evidence for sea level falling with the onset of glaciation was not observed.

Isostastic uplift ensued as the ice sheets thinned and retreated, resulting in slow, delayed unloading of the crust. Signs of isostatic uplift are preserved in the lower part of the Nyborg Formation, where dolomite deposited during the transgression was eroded and retransported in member B, north of Varangerfjord. Similarly, the development of the conglomerate bed at the top of the Mortensnes Tillite in the north appears to suggest temporary uplift and reworking of the tillite, prior to eventual submergence due both to continuing rise in sea level and basinal subsidence. A delayed isostatic uplift may be represented by the erosive contact at the base of the upper submember of the Lillevatn Member.

PALEOGEOGRAPHY

Several different lines of evidence can be combined to reconstruct the paleogeography of the study area (Fig. 80): 1) variations in thickness, 2) distribution of depositional environments, 3) sediment transport directions, and 4) sediment composition and texture. All of the formations studied here are thickest in the region around Vestertana. In addition, facies relations in stage 2 of the Nyborg Formation, the middle member of the Mortensnes Tillite and the lower submember of the Lillevatn Member all indicate deeper water conditions in this area, indicating that it was both a depositional and structural basin.

Paleoflow data obtained from ice deformation structures revise previous concepts of the paleogeography, which referred to a southern source area only (Føyn 1937, Reading & Walker 1966). While the Fennoscandian shield was a major source area, especially in the south, there was also an important source to the north, which was active primarly for some of the glacial units in the Smalfjord and Mortensnes Formations. Paleocurrents and regional variations in grain size of both the Nyborg Formation and Lillevatn Member, and geometry and basal composition of the lower member of the Mortensnes Tillite, suggest derivation mainly from the south. The source of the coarse-grained clean sandstones in member E of the Nyborg Formation at Trollfjord is unknown.

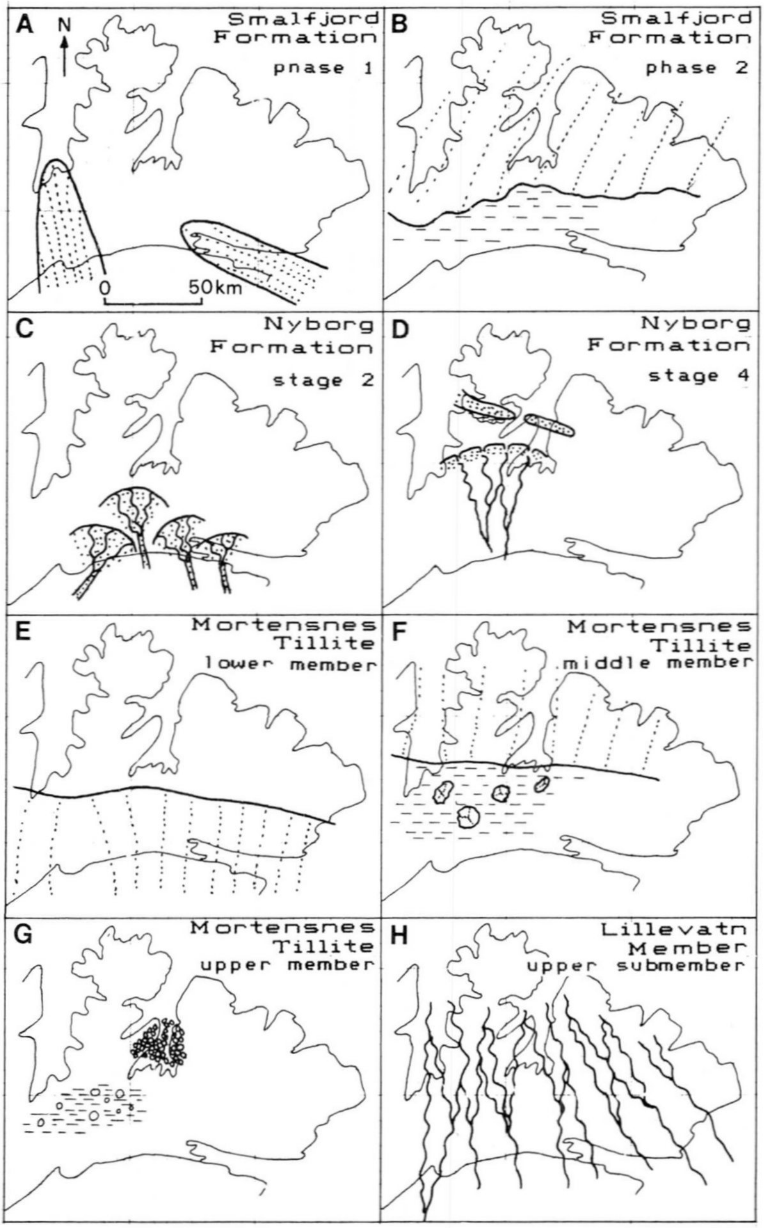


Fig. 80. Summary of paleoenvironments in the lower part of the Vestertana Group, East Finnmark. A, Krokvatn Paleovalley in the west and Varangerfjord Paleovalley in the east are scoured by broad valley glaciers; flow lines are suggested by dots. The valleys were filled primarly with subaqueous sandstones and conglomerates. B, Several times during phase 2 of the Smalfjord Formation, large ice sheets advanced from the north. During retreat, the ice sheets terminated in the sea, where laminated mudstones accumulated. C, Submarine fans prograded north from a steep slope adjacent to the Fenoscandian Shield. D, As the depositional basin filled, a tide- and wave-influenced delta prograded northwards (member 4), and a barrier lagoon system was established (member 5). E, A large piedmont glacier or ice sheet advanced from the shield in the south. F, A large ice sheet advanced from the north; during retreat, it terminated in the sea, where large icebergs were released. G, In the latter stages of Mortensnes Tillite deposition, glacial marine laminated diamictites were deposited in the deep water of the basin center, while isostatically uplifted portions of the northern basin margin were reworked, forming a conglomerate lag. H, During maximum regression associated with the Lillevatn Member, a large fluvial system extended over the entire study area.

The composition of clasts and matrix in the tillites further supports a northern source area, particularly the abundant dolomite in the Smalfjord Formation, member B, and both dolomite and sand in the Smalfjord Formation, members C and E, and the Mortensnes Tillite, middle member. These sediments were almost certainly derived from the Grasdalen Formation and equivalents (dolomite and chert) and the Tanafjord Group (sand). On the southern part of the Varanger Peninsula the Mortensnes Tillite rests unconformably on the Tanafjord Group (Siedlecki 1980), and is a further indication that outside of the basin, large quantities of older sediments were eroded by the ice sheets.

Additional information on the paleogeography is provided by changes in sedimentation style across the basin. Paleovalleys preserved at the base of the Smalfjord Formation, and high-energy base-of-slope deposits in the Nyborg Formation north of Varangerfjord indicate that the southern margin of the basin was relatively rugged, while the northern margin was much gentler. Significant basement topography is preserved west of Varangerfjord (Holtedahl 1918, Bjørlykke 1967). It appears that during deposition of the lower part of the Vestertana Group there was a relatively high-relief basement area south of the basin, which at times fed valley glaciers (phase 1 of the Smalfjord Formation) or piedmont glaciers (lower member of Mortensnes Tillite) to the north and northwest (Fig. 3). In contrast, the lower relief northern margin of the basin was the site of southward flowing ice sheets. The variation of tillite compositon through time indicates that the southern and northern ice streams varied in relative size, and probably coalesced in different parts of the basin, depending on factors such as climate and relief.

The postulated large ice sheets flowing from the north raise the question of the paleogeography of the southern Barents shelf. Reconstruction of this area suggests the presence of a Pechora craton, separated from the Fennoscandian craton by a narrow seaway, the Timanian aulacogen (Siedlecka 1975). The presence of shallow marine facies in these Upper Proterozoic strata suggest that the shallow seaway would have been no barrier to glacial advance, especially during periods of eustatically lowered sea level. Furthermore, the presence of similar glacial sequences in eastern Svalbard (Edwards 1976), suggests regional glaciation of the Barents Sea region at that time.

QUATERNARY DEPOSITIONAL ANALOGUES

While it would futile to try find a particular area of Quaternary glaciation to illustrate all facets of the Finnmark Upper Proterozoic sequence, it is possible to use the North Sea in this fashion for the glacial units. Significant similarities are: 1) deposition and structural basin developed in an epicontinental setting, between two glacier sources. 2) The topographic depression created by the basin served as a confluence for ice streams. 3) glacial erosion of a type called «selective linear erosion» (Sugden 1977) was concentrated where soft basin sediments lapped onto the resistant basement rocks of the basin margin, forming the Norwegian Trench in the northeastern North Sea (Rokoengen and Rønningsland, (in prep.), and the Varanger Paleovalley in Finnmark. 4) Successive advance and retreat of the marine ice sheets resulted in sequences composed of lodgement till overlain by glaciomarine muds (e.g. Milling, 1975).

As the North Sea has not had major deltas active during the Quaternary, it is not pertinant to the Nyborg Formation and Lillevatn Member. While it is considered that stages 3 and 4 of the Nyborg represent progradation, and shallow marine and coastal deposition that would characterize a wave- and tide-influenced delta, analogous deposits from modern examples are poorly known. On the other hand, delta front deposits do not seem well represented in the Lillevatn Member, which therefore defies interpretation of delta type.

A major problem is the contrast in basin fill styles between stage 2 of the Nyborg Formation, which was dominated by turbidite sandstone deposition, and the lower submember of the Lillevatn Member, which consists almost entirely of mud deposited from suspension. The reason for this contrast may have been the high relief of the southern margin of the basin following the Smalfjord glaciation, which would have aided propogation of turbidity currents, whereas after the Mortensnes glaciation, the basin margin had much lower relief.

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Appendix

Name	*Old name*	*Map sheet*
Aldarbakti	Alteberget	Smalfjord
Arasuolo	Areholmen	Langfjorden
Fadnuvaggi	Grasdalen	Trollfjorden
Jåkkanjargga	Digermul Peninsula	Langfjorden
Laddebakti	Addasberget	Smalfjord
Lassasuolo	Larsholmen	Langfjorden
Maskejavri	Masjokjavrek	Polmak
Mielkejåkka	Melkeelven	Smalfjord
Nissujavri	Nesvatn	Smalfjord
Ruoksadas	Rødberget	Tana
Selešjarga	Saelenes	Varangerbotn
Siskejåkka	Innerelv	Langfjorden
Skjåholmen	Skjaaholmen	Varangerbotn
Šuoššjåkka	Sjursjok	Smalfjord
Oiabaččannjarga	Bigganjargga	Varangerbotn
Uccajavri	Lillevatn	Smalfjord
Vieranjarga	Kvalnes	Nesseby