CHAPTER 5

SMALFJORD TILLITE FORMATION, TANAFJORD AND LAKSEFJORD

5.1 Area of Study

The investigation of the Smalfjord Tillite was concentrated in the area between Vestertanafjord and Smalfjord (fig. 35), where there are frequent, often very continuous, exposures. Outside of this area, the tillite was studied west of Njukcagaissa, east of the Tana River at Rødberget, and west of Leirpollen (fig. 37). More distant outcrops, briefly examined, include Trollfjord, and south of Laksefjord at Uccaskaidde and Ruksisbakvarre.

5.2 Stratigraphy and Sedimentary Framework

The Formation around Smalfjord comprises more than a dozen sedimentary units, some of which are readily traced and laterally continuous, and other which appear only in a small area, and change rapidly in thickness. An understanding of the stratigraphy is hampered by the lenticularity of many of the units, and the complex tectonic structures. In addition to the large asymmetrical folds, characteristic of the sedimentary rocks of East Finnmark, there are low angle overthrusts with a demonstrable displacement of at least 2 km, and possibly as much as 5 km (fig. 3). Tillite believed to occur on klippe, has not been related to autochthonous exposures. Working out the stratigraphy is facilitated by two facts: 1) the Smalfjord Tillite includes two contrasting facies, tillite and siltstone, and 2) successive units of tillite differ in colour, composition, and other features.

Radiocarbon dating, the study of palaeosols (Morrison, 1968), and a great deal of other evidence have shown that multi-till sequences in the Pleistocene were formed by the successive advance and retreat of an ice sheet. For example, successive till horizons deposited by separate glacial advances typically differ in colour, clast and matrix composition, and grain size distribution (e.g. Westgate and Dreimanis, 1967; Gillberg, 1969; White et al. 1969). In the Smalfjord Tillite in this area

1) Four out of five tillite units are laterally continuous, and relatively uniform in composition, colour, grain size distribution, and other features.
2) Successive tillite units differ from each other in composition, colour, grain size distribution, and other features.
3) Four of the tillite units have demonstrably erosive bases.
4) All the tillite units are locally separated from each other by laminated or varved siltstone units with varying amounts of dispersed, outsize clasts. The siltstones conformably overlie the tillites, but are overlain erosively by the tillite above.

In view of the characteristics listed above, an erosion surface followed by a tillite to siltstone succession may represent a glacial retreat sequence, and is the framework for the interpretation of the Smalfjord Tillite. Similar sequences are developed in the Mortensnes Tillite.

The observation of different types of tillite at the same locality lead Føyn (1937, p.133) to suggest more than one advance of the ice. On the basis of this recurring sequence, the Smalfjord Tillite Formation is subdivided into members, which include a tillite unit at the base, siltstones at the top, and other lithologies such as sandstone and conglomerate as they occur (fig. 30). Five members, A to E are recognised, four of these of considerable lateral extent. Two tillite units are of uncertain status, they are included as components of other members.

The stratigraphic scheme presented here is tentative in many parts. Nevertheless, it does not sacrifice the prime intent of this study which is to understand the processes of glacial deposition, and not to simply record the number of advances and retreats in this area.

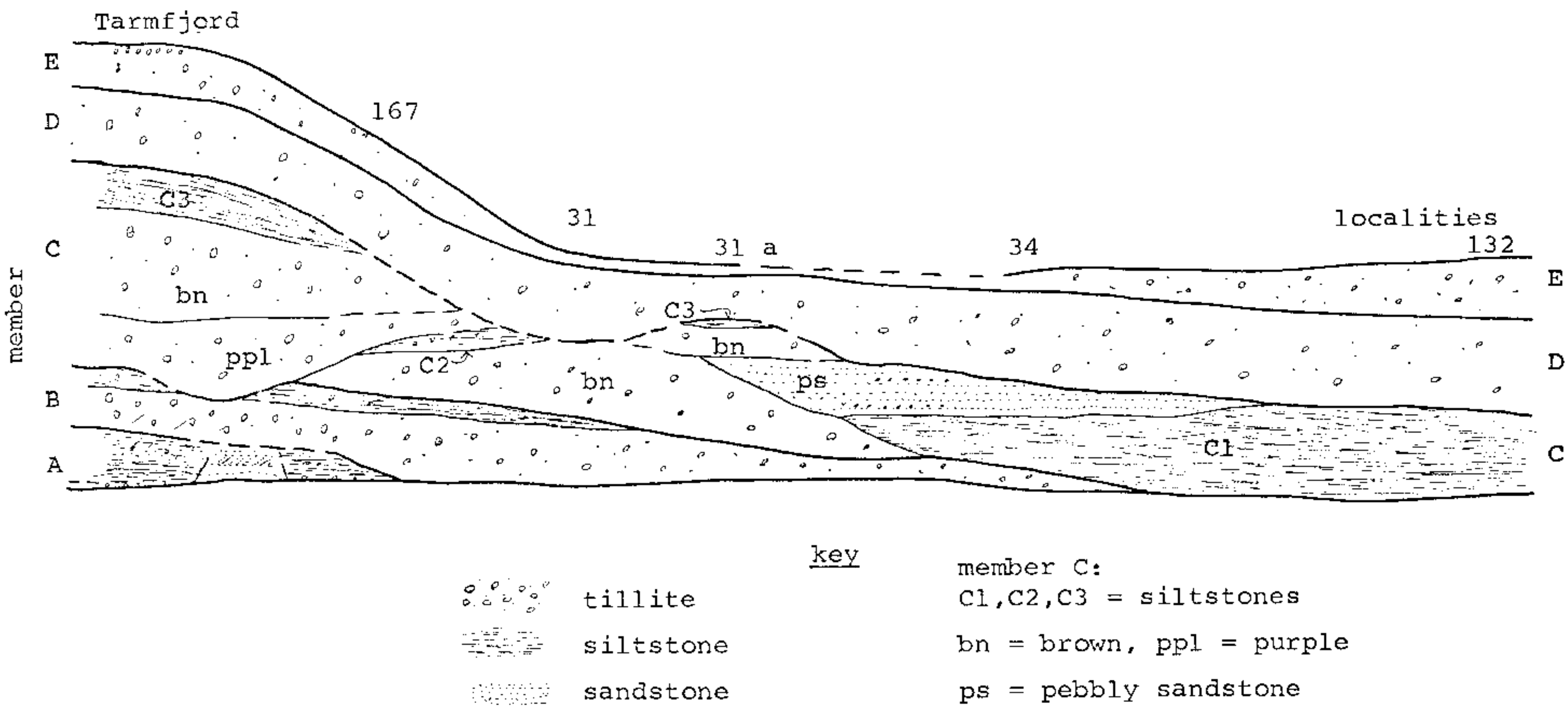


Figure 30. Diagrammatic sketch of relationships between the members of the Smalfjord Tillite, around Smalfjord. Thickness of the formation varies from about 50-100 m.

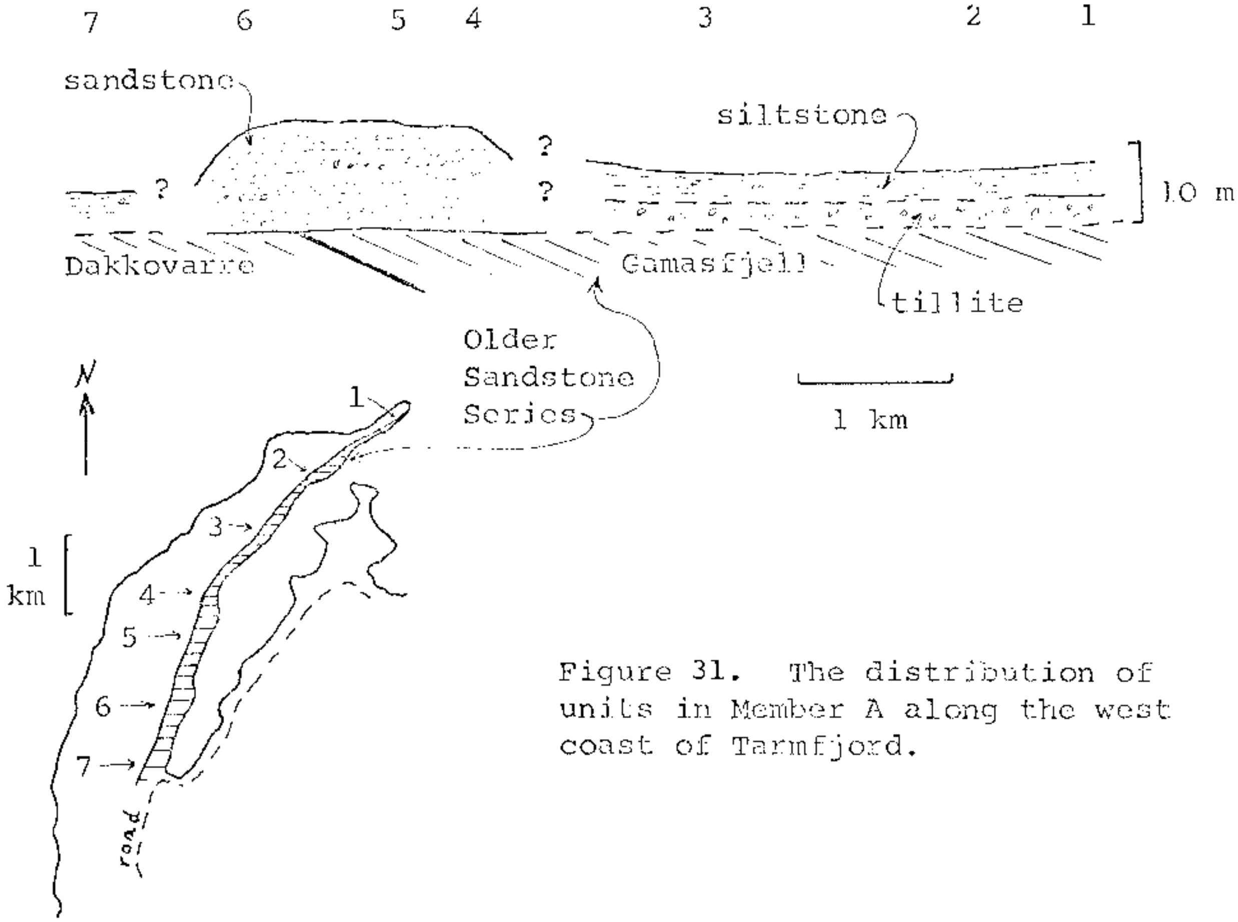


Figure 31. The distribution of units in Member A along the west coast of Tarmfjord.

5.3 Sedimentology

5.3.1 Member A

Description

Member A was observed only along the west side of Tarmfjord (fig. 31). It consists of three units : tillite (Table 3), sandstone, purple siltstone (Table 4).

Table 3*, Member A Tillite, Tarmfjord, Locality 1, Fig. 31.

Colour: purple and green
Clasts:
- Concentration: 5-10%
- Composition: fine sandstone
- Size: average about 5 cm
- Shape: equant

Matrix:
- Size: sandy-siltstone
- Cement: ferruginous

Thickness: 2 m exposed
Contacts: not exposed
Structure: massive

---

* The important features of the tillite units are compared in

Table 4*, Member A Siltstone, Tarmfjord, Locality 1, Fig. 31.

Colour: purple
Structures:
Lamination: very thin to thick laminae of silty mudstone, variable in sorting, colour and grain size. Local 2-4 mm graded laminae with a lower coarse poorly sorted part, and an upper fine part (Pls. 17, 40 a and b). These may be weakly parallel-laminated. Several isolated rows of current ripples, current direction to the south, or southwest. Plomp-and-drape.
Deformation: at the top only, along the junction with member B tillite.
Dropstones:
Distribution: dispersed, and in rows.
Concentration: very low, except in occasional rows.
Composition: mainly dolomite, several types of crystallines.
Size: mostly less than 2 cm, several up to 8 cm.
Thickness: 2 m maximum exposed.
Contacts: Lower not exposed, upper is erosive.

The Sandstone Unit

At locality 5 (fig. 31), the sandstone unit is about 10 m thick, and is brown-yellow, poorly sorted and medium-grained. Structures include parallel lamination and cross-bedding in beds up to 50 cm thick. The weathered surface shows concave pits indicating a carbonate-rich matrix. A few pebbles of dolomite, chert and siltstone are dispersed in the sandstone. The unit is overlain sharply by the member B tillite.

At locality 4 (fig. 31) the sandstone unit is about 15 m thick. It is parallel-laminated and massive in beds up to about 50 cm thick, and contains a few small, rounded crystalline pebbles scattered about, and concentrations, parallel to bedding, of dark brown ferruginous, nodule-like pebbles, mostly smaller than 1 cm, and tabular in shape. Sorting is variable, but is

* The important features of the siltstone units are compared in Table 16.

generally very poor. The sandstone weathers dark brown, to purplish brown, and also appears to contain a carbonate cement. The dark brown weathering colour, and the presence in thin section of dark bands surrounding the carbonate grains suggests that the grains are composed of siderite. It is not clear whether the grains are primary, or a recrystallized cement, or both.

The relationship between the sandstone and the other units could not be definitely established.

Interpretation

Due to the paucity of exposure it is impossible to argue strongly for any particular origin of the tillite. A subglacial origin may be conjectured on account of the massive appearance of the tillite, its position directly on top of the Older Sandstone Series, and its almost uniquely local derivation. The unit is similar in these respects to unit A of the Smalfjord Tillite at Kvalnes, Varangerfjord (section 4.2.1 fig. 19), which was interpreted as a ground moraine.

The sedimentary structures in the sandstone unit suggest deposition by aqueous currents. It may have been outwash derived by the winnowing of a sandy till, while the ice margin was stationary, or gradually wasting back.

The symmict (poorly sorted) texture of the varves suggests a marine origin for the purple siltstone unit. Ice rafting, by shore ice, bergs, or possibly an active ice margin is indicated by the outsize clasts.

Derivation of Sediment

The sandstone content of the tillite, both in clasts and matrix, and of the sandstone unit suggests a local derivation for these units. In addition, the siderite cement and the ferruginous clasts in the sandstone unit suggest derivation from the Dakkovarre Formation (Table 2) as it is the only part of the Older Sandstone Series known to contain appreciable quantities of iron (Føyn, 1937; Siedlecka and Siedlecki, 1971). Ice movement with a component of movement south is required as the Dakkovarre Formation is buried beneath younger strata of the Older Sandstone Series to the north, but is unconformably overlain by the Smalfjord Tillite to the south (fig. 5).

5.3.2 Member B

Member B rests on the Gamasfjell and Dakkovarre Formations, and locally on member A, and it is overlain by both members C and D. It may tentatively correlate with tillite at Areholmen (fig. 37), Rødberget, and Laksefjord.

The member comprises tillite, pebbly sandstone, and siltstone (fig. 32), and is distinguished by the high concentration of clasts composed almost entirely of dolomite and chert in the tillite (Table 5). At most exposures, the tillite is massive, but two important exceptions occur, and are described below in detail. On the west side of Tarmfjord the tillite contains many deformation structures and locally derived siltstone, and northeast of Auskarnes the member includes stratified sandstone and massive and layered tillite.

Mouth of Tarmfjord

Description

Along the northern part of Tarmfjord, the tillite of member B rests on member A siltstone. This contact and the overlying tillite shows many interesting features:

1) the tillite unit is a complex zone about 10 - 15 m thick composed of purple siltstone derived from member A, purple tillite, and buff-yellow tillite. The latter is described in Table 5.

2) at the base of the zone there may be a sharp, planar surface separating undeformed siltstone below, from highly deformed siltstone mixed with tillite above (Pl. 16).

3) the siltstone at the top of member A may be faulted (Pl. 17). The faults strike NW-SE, dip to the northeast, the dip increasing

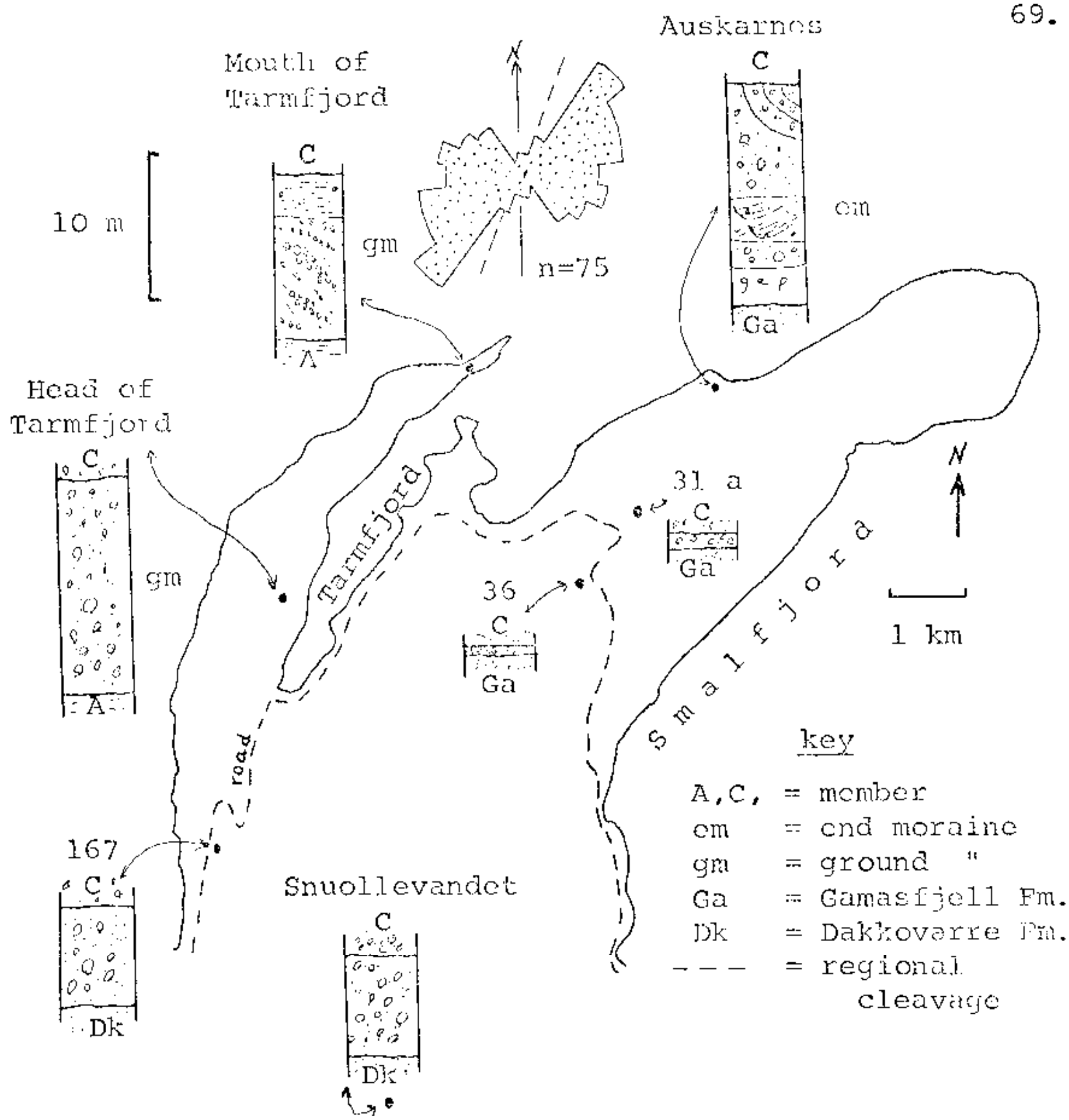


Figure 32. Distribution of units of member B in the Smalfjord area. Rose diagram of clast long axes in horizontal plane.

downwards, and the faults die out downwards.

4) the siltstone and intermixed tillite in the zone is folded and faulted. Most folds are isoclinal with subhorizontal axial planes (Pl. 18).

5) the mixture of siltstone and tillite may be layered (Pl. 19), or may be a massive purple tillite with scattered dolomite clasts and blebs of yellow dolomite-rich tillite.

6) locally the tillite has a well developed fabric (Pl. 20). The pebbles are imbricated and the long axes of most pebbles dip to the northeast.

Table 5

Member B Tillite, Characteristic Properties, Smalfjord Area.

Colour: buff-yellow
Clasts:
Concentration: 25-60%, usually high.
Composition: dolomite and chert, rare crystallines towards top at Tarmfjord.
Average diameter: variable, 5-20 cm.
Maximum diameter: usually 60-80 cm: in allochthonous tillite east of Auskarnes are single dolomite blocks 2 m across, and areas that may be brecciated masses of dolomite which are about 100 m long and up to 20 m high.
Shape: angular to rounded, dolomite clasts are usually slightly elongate, while crystallines tend to be equant.
Matrix:
Size: mainly unsorted grains and groundmass of carbonate, with few scattered sand grains (Pl. 39a). Sand content is variable.
Thickness: up to 15 m, thickest around Tarmfjord, decreases in all directions.
Lower Contact: erosive at Tarmfjord, elsewhere poorly or unexposed.
Upper Contact: grades into purple silstone unit, or is eroded into by member C or D tillite.
Structures: varied: mostly massive, also banded, stratified, described in detail in text.

7) a single sedimentary dyke occurs near the base of member B, cutting through massive purple tillite. It consists of dolomitic tillite with purple shale flakes. It is < 5 cm wide, about 2 m high, and is nearly vertical, striking roughly E-W (at a high angle to the regional tectonic cleavage). The top is truncated by massive dolomitic tillite in the zone.

8) viewed from across the fjord (Pl. 21), at a distance of about 1½ km, the zone has the appearance of a series of imbricate slabs of dolomitic tillite separated by layers of purple tillite and siltstone, and dipping gently to the northeast.

9) at the top of the zone is up to 2 m of horizontally layered tillite. It consists of alternating layers up to 5 cm thick of drab-purple and drab-yellow silty tillite. The layers are undeformed and continuous when viewed close up (Pl. 22). However,

from a distance the thicker layers are seen to lens out laterally. The contacts between layers may be sharp or diffuse. No sedimentary structures were observed.

10) the zone is overlain by up to 4 m of varved and laminated purple siltstone (Table 6).

Table 6

Member B Siltstone, Tarmfjord

Colour: purple
Structures:
Lamination: variable in appearance, faintly parallel-laminated throughout, excellent varves about 1 cm thick with horizontal, or loaded base, massive, moderately-sorted fine sandstone grades up into parallel-laminated silty mudstone. This passes sharply into the mudstone background with faint lamination and scattered load pockets of coarse and medium sand grains.
Deformation: internal loading at the bases of some varves, and deformation in association with the overlying tillite.
Dropstones:
Distribution: scattered throughout the siltstone.
Concentration: low, several percent.
Size: mostly < 5 cm, few up to 20 cm.
Composition: mostly dolomite, few crystallines.
Thickness: up to 3 m.
Lower Contact: gradational.
Upper Contact: erosive.

Interpretation

The complex zone of member B tillite as described above is a result of the intermixing of purple siltstone and dolomitic tillite. The siltstone was derived by the erosion of the directly underlying siltstone of member A, while the dolomite was transported a considerable distance, as the nearest known occurrence of the Grasdal Formation against the unconformity is near Trollfjord, 25 km to the northeast. An effective means of incorporating large quantities of material into a glacier is upthrusting at the base (see Chapter 3, fig. 13). The process also has the effect of bringing together locally and distantly derived material. The areas of mixed siltstone and dolomitic tillite, with abundant deformation structures, represent thrust zones of the glacier, in contrast to massive dolomitic tillite, with imbricated pebbles which would represent debris-laden ice between thrust planes.

The combined long axis orientation of clasts, imbrication and orientation of the deformation structures in the mixing zone all indicate a direction of ice movement to the southwest. The several slabs of dolomitic tillite indicate that several thrusts developed, but it is unlikely that all of them were active simultaneously. Rather, a direction of propogation opposed to the direction of transport is probable, and is analogous to the development of back-limb thrusts above a sole thrust as suggested by Jones (1971) for certain structures of the Canadian Rocky Mountain orogeny, and is similar to the process of "plastering-on" inferred by Slater (1927b) from British Pleistocene glacial deposits. According to Slater, irregularities formed on the ice-substrate surface have a drumloid shape. These are built up on the stoss side, as a series of minor thrust planes, which eventually lead to a major thrust plane (p. 213). In the present case an obstacle to glacier movement may have been the sandstone unit of member A. Thrust planes first developed at the northeast margin of the body, and then the site of their formation moved to the northeast, leaving a stagnant mass of dolomite-rich ice beneath the new thrust plane.

The layered tillite above the deformed, complex tillite zone appears to be a banded tillite formed by the continued shearing of purple and yellow tillite. A lack of sedimentary structures supports this. The continuation of ice motion above the thrust zone suggests that the thrusting occurred within, rather than at the margin of the ice sheet. If the overburden of ice were great, then the inclination of the thrusts would be low (see Boulton, 1970, p.219). Alternatively, the lower inclincation may have been caused by the melting out of interstitial ice. The sedimentary dyke of tillite indicates the presence of some fluidized till under pressure, following the period of deformation.

The conformably overlying varved purple siltstones indicate that proglacial subaqueous conditions immediately followed subglacial conditions.

Auskarnes

Description

Northeast of Auskarnes (fig. 32) member B contains four units (Pl. 23) separated by a gap of 3-4 m from the Gamasfjell Formation. These units are:

4) 0-3.5 m bedded and layered tillite resting in a convex-downward depression (Pl. 26). Definite effects of sorting by currents were not observed. The layering is truncated at the top by the tillite of member C.

3) 2-5.5 m tillite with local variation in texture clearly shown by variations in the clast concentration.

2) 2.5 m pebbly sandstone with scour-and-fill structures, laterally interfingers with stratified tillite (Reading and Walker, 1966, p.183, fig. 3), (Pl. 24). The scours are asymmetrical with the steeper side on the northwest margin, are up to a metre deep, and are filled with low angle cross-stratification which dips predominantly to the northwest, but tends to drape over the scour (Pl. 25). The top is gradational.

1) c. 3 m horizontally stratified tillite (Pl. 24). The top is sharp.

Interpretation

The scour-and-fill structure and the pebbly sandstone texture suggest a braided fluvial origin for the second unit, as present day braided stream deposits contain similar structures

(Doeglas, 1962; Williams and Rust, 1969). The uniform asymmetry of the scours in unit 2 and the style of filling suggests that there was a component of flow to the northwest (Augustinius and Riezebos, 1971). The braided stream deposits which presumably originated as glacial outwash, suggest that the stratified tillite, units 1 and 3, is supraglacial, or proglacial in origin, rather than subglacial, and have formed by melt-out, mass flow, or winnowing of till. Unit 4 may be a stratified tillite preserved in a hollow formed by the melting of buried ice. This interpretation of member B at Auskarnes contradicts that of Reading and Walker (1966) who suggested deposition beneath a wet-based ice shelf (p. 186, 204).

If we assume that stream flow was parallel to the ice margin, then the palaeocurrent evidence from unit 2 suggests that during retreat the ice margin was stationary to the northeast or southwest of Auskarnes.

Other Localities

At other localities of autochthonous member B the tillite is usually massive throughout and is similar in composition and texture to that described in Table 5. Occasionally, restricted zones of current activity have formed local gravels and sandstones (locality 36, fig. 32), or where the member is thin, < 1 m, it may consist entirely of reworked sediment.

Such deposits may represent either primary ablation moraines, or subsequently reworked ground moraines. The absence of sections with probable ground moraine overlain by a winnowed horizon suggests that the former is more likely.

Derivation of Sediment

Directional indicators show that ice movement in the study area was to the southwest. A possible source is the Grasdal Formation (fig. 4) which underlies the Smalfjord Tillite south of Trollfjord. Derivation from the south has been suggested by earlier workers (Føyn, 1937; Reading and Walker, 1966). This may be supported by the palaeocurrent evidence in the outwash facies, but can also be reconciled with an ice margin to the northeast (fig. 33).

5.3.3 Member C

Member C rests on member B in the west, and generally on the Older Sandstone Series in the east, cutting down from the Vagge Formation to the Dakkovarre Formation from north to south. It is overlain by member D.

Member C is complex, consisting of at least two known tillite units, three siltstones, and a pebbly sandstone (figs.30 and 34). The presence of two tillite units is demonstrated by their occurrence in the same section, but the tillites have similar properties (Table 7), and thus there may be more than 2 tillite units as correlations cannot be checked between all sections. In the southeast of the area (e.g. Spot Height 132, fig. 34) a parallel-laminated siltstone, unit C1, lacking clasts (Table 8) makes up most of the member. This thins towards the north above a basal tillite unit, and beneath member D. In the northwest of the area a purple and green siltstone with rare varves and outsized clasts, unit C2, occurs above a basal tillite unit (Table 9). The pebbly sandstone occurs above the clast free parallel-laminated siltstone (locality 34, fig. 34), and below a second tillite unit or member D. In the west of the area purple tillite, the overlying brown tillite and the siltstone above (unit C3) have been tentatively assigned to member C.

Base of the Member

Northeast of Auskarnes, at the base of the tillite unit is a layer, about 50 cm thick, of well-rounded crystalline

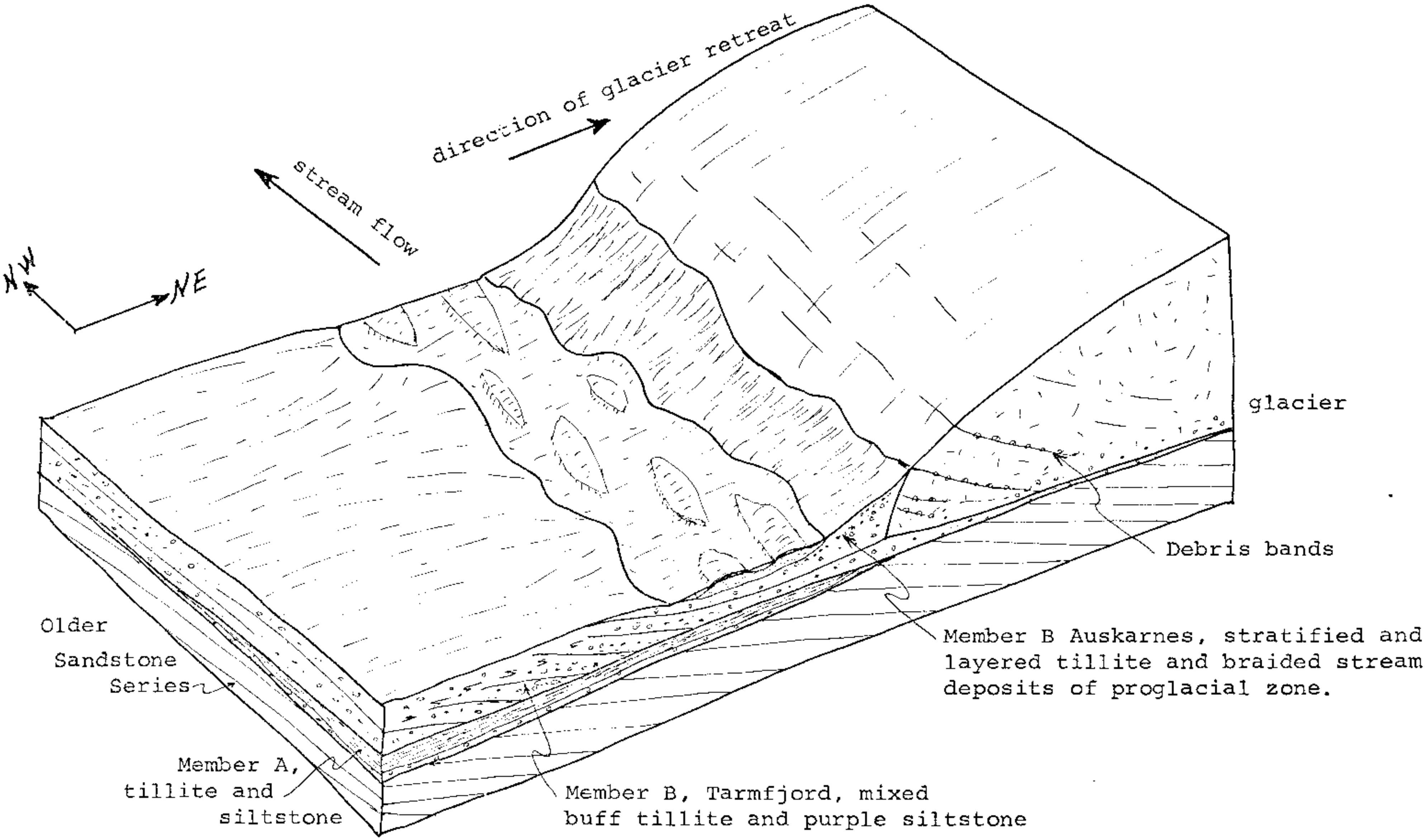


Figure 33. Suggested relationship between member B at Tarmfjord and at Auskarnes based on interpretation of structures, and palaeocurrent evidence. At Tarmfjord clasts have long axes aligned NE-SW and dip to NE.

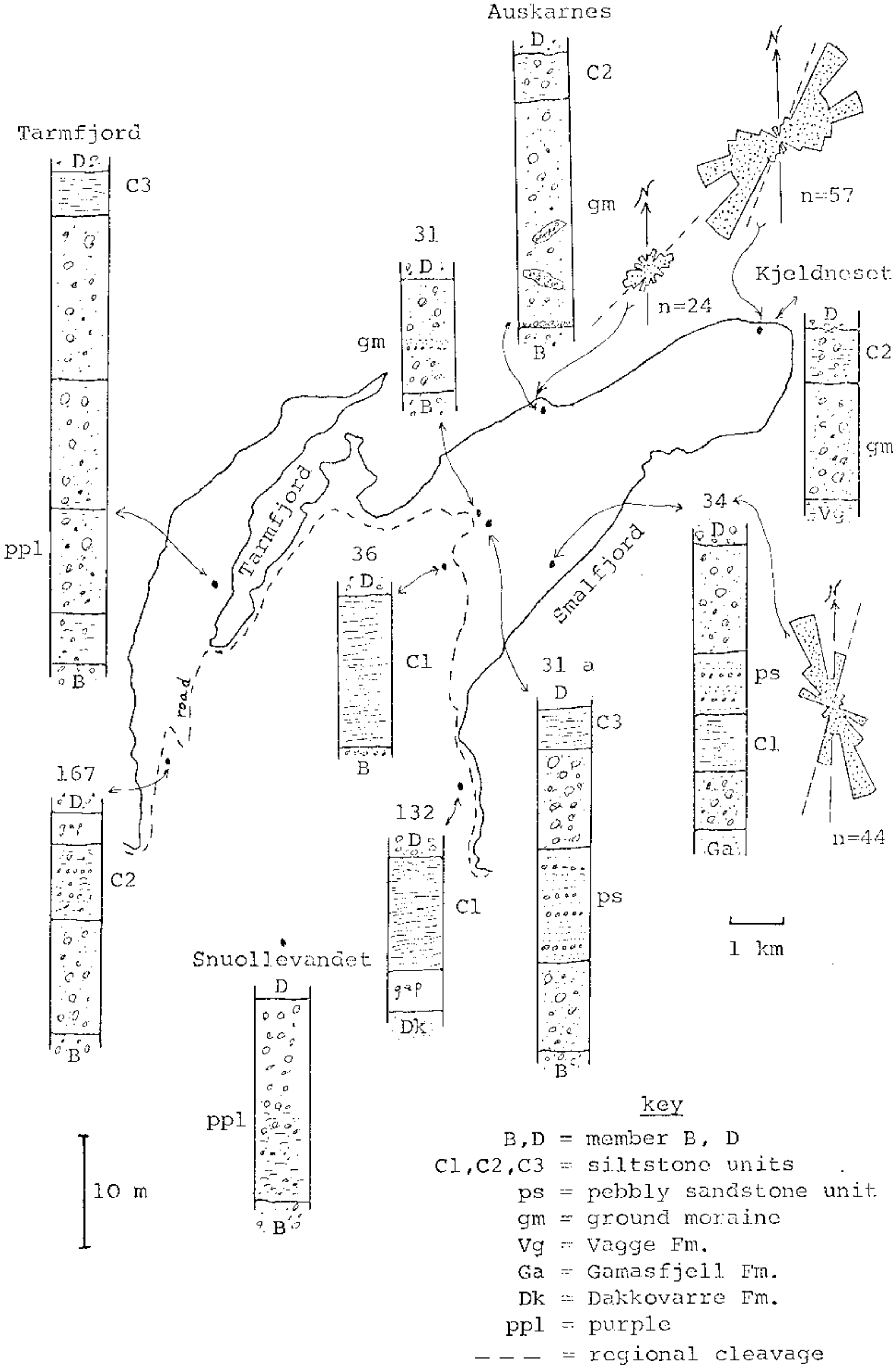


Figure 34. Distribution of units in member C in the Smalfjord area. Rose diagrams of clast long axes in bedding plane.

Table 7. Member C, Brown Tillite

Colour: weathering: buff-brown, fresh: green-grey.
Clasts:
- Concentration: usually 10-20%.
- Composition: 75-95% dolomite and chert; 5-20% crystallines, including red granite, grey gneiss and granite, and greenstone, little green sandstone.
- Average Diameter: about 2-10 cm.
- Maximum Diameter: about 70 cm.
- Shape: most clasts equant, or slightly elongate or tabular, depending on internal properties. Angular to well rounded, crystalline boulders are usually well rounded.

Matrix: fine sand and silt grains scattered in carbonate groundmass (Pl. 39b). Scattered large sand grains.
Thickness: 0-15 m in main area, thicker to west.
Lower Contact: erosive (see text).
Upper Contact: grades into siltstone, pebbly sandstone, or eroded into by member D tillite.
Structures: almost entirely massive but for inclusions of dolomitic tillite, and rare deformed lamination.

Table 8

Member C, Parallel-Laminated, Clast-free Siltstone, Unit Cl.

Colour: mainly grey-green, occasionally purple.
Structure: Fine parallel-lamination, silt grains in rows in silty mudstone.
Dropstones: none seen.
Thickness: up to about 10 m, wedges out to the north and west.
Lower Contact: not seen.
Upper Contact: eroded into by member D tillite, sharply or erosively overlain by pebbly sandstone unit.

Table 9, Member C, Siltstone with Clasts, Unit C2

Colour: purple and green.
Structure:
- Lamination: fine to coarse parallel-lamination, mainly mudstone to siltstone, few graded laminae seen northeast of Auskarnes. Boundaries between laminae sharp. Variable in appearance.
- Deformation: seen only in conjunction with overlying tillites. Plomp-and-drape structure.

Dropstones:
- Distribution: in rows parallel to bedding.
- Concentration: usually low, 0-5%. Absent at base, increase upward.
- Size: usually < 5 cm, up to c. 20 cm.
- Composition: largely dolomite, few crystallines.

Thickness: up to 7 m, base and top not seen in same outcrop.
Lower Contact: gradational above tillite.
Upper Contact: eroded into by member D tillite.

boulders (Pl. 26). The boulders are up to 60 cm long and consist mainly of grey granite and gneiss, with some dolomite. The matrix is unsorted tillite, and the boulders are in contact with each other.

At Kjeldneset (fig. 34), member C tillite rests directly on the grey-green and purple fine sandstones and shales of the Vagge Formation. The contact is erosive, the extent of which is obscured by disruption of the shales probably by both glacial and regional tectonism. The lower 2 m of the tillite is drab green with irregular subhorizontal layers of buff-brown tillite. The green tillite is rich in tabular clasts of Vagge sandstone and shale.

Features of the Tillite Units

At Auskarnes and Kjeldneset the tillite contains several large blocks of dolomitic tillite all of which closely resemble the tillite of member B (Pl. 27). The blocks are about 3-4 m long, and up to 1 m thick. They are orientated roughly parallel to the regional bedding, but the block in Plate 27 dips about 20° to the north compared to the regional bedding. A few thin sandy laminae less than 1 cm thick, extending about 10 m, were observed at Auskarnes. In some places these are deformed into irregular folds (Pl. 28).

In the second tillite horizon in the centre of the area at locality 31a (fig. 34), small irregular patches of tillite with dolomite and crystalline clasts, but with high clast concentration occur in the lower part of the tillite. These do not appear similar to other tillite units known to the author.

The contact between the lower tillite unit and the clast free parallel-laminated siltstone was never observed, but at both Auskarnes and Kjeldneset the tillite is seen to grade up into the varved siltstone with clasts, unit C2. Between the tillite and the siltstone is about 2-3 m of massive grey-green sandstone with almost no clasts, and very faint horizontal lamination. At 167 , this siltstone unit, C2, is free of clasts in the basal few metres, but clasts occur sporadically in rows higher up (Table 9).

Interpretation

The erosive base of the tillite, and the incorporated blocks of Vagge Formation and member B tillite indicate the origin of the lower tillite unit as a ground moraine. This is consistant with the deformed sandy laminae which may have formed by the sorting action of running water at the base of the ice sheet, subsequently disrupted by the motion of the ice. The tabular shape of the blocks of tillite may reflect derivation along thrust zones, or the action of laminar shear within the moving ice sheet.

The boulder layer at the base of the tillite at Auskarnes appears to be a lag deposit such as has been described as a concentrate derived by the reworking of till (e.g. Kaye, 1964a). However, the composition of the bed is such that it could not have been derived from the underlying tillite of member B, and it is more likely that the bed was a product of glacial deposition, related to member C.

The upward transition into varved siltstone indicates the change from subglacial to proglacial subaqueous conditions, probably in a quiet marine, or lacustrine environment.

Pebbly Sandstone Unit

Description

This unit is prominant in the central and eastern parts of the area where it is up to 8 m thick and consists of stratified sandstone with occasional pebbly horizons. The sandstone weathers buff-brown, but is grey-green or green when fresh. It is commonly parallel-laminated or massive, and crudely medium bedded. Soft-sediment deformation into small high-angle micro-faults is common (Pl. 29). Graded bedding is seen occasionally. The sandstone is medium to coarse grained, poorly-sorted, and consists of quartz grains with considerable amounts of microcline and plagioclase in all stages of weathering. The grains are chiefly angular, but are also rounded. The degree of rounding may be diagenetically controlled. The matrix consists of a fine grained groundmass with much carbonate. The carbonate and sericite rims on feldspar grains may be diagenetic in origin.

At locality 34, the unit rests erosively or sharply on the clast free, parallel-laminated siltstone, unit C1, and nearby at locality 31a it rests gradationally above the lower tillite unit. The sandstone is overlain by the second tillite, or by member D tillite.

Interpretation

Although the sandstone was apparently deposited by aqueous currents, the absence of channels and cross stratification, and the poor sorting suggest that the currents may have flowed in standing water rather than over a subaerial surface. No vertical or lateral interfingering with either the siltstone or tillite was observed. The unit probably formed in proglacial subaqueous conditions, but the nature of the currents is uncertain. Faulting is likely to have been caused by a subsequent glacial advance.

Tillite Between Members B and D in the Western Part of the Area

The inclusion of purple tillite (Table 10) and overlying brown tillites in the western part of the area within member C is based on the fact that they are similar in composition to brown tillite of the eastern part of the area and on interpretational evidence given below. About 5 m of purple tillite is seen at the south end of Tarmfjord, while near Snuollevandet to the south about 15 m are present. No purple tillite was observed on the road west of 167 between members B and D. About 30-40 m of brown tillite overlie the purple tillite at Tarmfjord, and several metres at Snuollevandet.

Table 10

Member C, Purple Tillite, Western Part of the Area

Colour: purple, occasional brown streaks and bands.
Clasts:
- Concentration: 10-20%.
- Composition: dolomite, crystallines, including red granite and greenstone.
- Average Diameter: 2-8 cm.
- Maximum Diameter: at least 40 cm.

Matrix: sandy silt, much carbonate.
Thickness: 0-15 m.
Lower Contact: banded, much incorporation of purple siltstone.
Upper Contact: alternating bands of brown and purple tillite, gradually becomes brown upwards.
Structure: banding in relation to contacts, no internal structures seen.

siltstone of member B. In both cases the tillite is banded. At Snuollevandet purple siltstone grades up into purple tillite over about 10 m. The siltstone, which appears parallel-laminated at the base develops thin tillite layers which increase in thickness and frequency upwards. Towards the top of the zone the rock is mainly purple tillite with thin continuous purple siltstone bands (Pl. 40c). Over the next few metres the colour of the tillite becomes brown. Purple tillite west of Tarmfjord often shows the presence of brown areas within the tillite. These observations suggest the importance of incorporated purple siltstone in altering the colour of the tillite from brown to purple. The upward transition to brown tillite indicates that the effect was limited to the lower layers of the tillite. As the purple tillite rests erosively on member B, and the original colour appears to be brown, similar to member C tillite in the eastern part of the area, it is considered to be part of member C, along with the overlying brown tillite.

At Tarmfjord the brown tillite is overlain by about 4 m of intermixed brown and grey-green tillite, which is succeeded by 15 m of massive greenish-brown tillite with dolomite and sandstone clasts. The tillite is followed by about 5 m of parallel-laminated and varved grey-green siltstone with no clasts (Table 11).

Table 11

Member C, Varved, Clast-Free Siltstone, Unit C3

Colour: grey-green
Structure: thin, up to 1 cm graded laminae, mainly fine sand and silt. Lower sandy part relatively well-sorted. Soft-sediment deformation due to subsequent over-riding.
Dropstones: none observed.
Thickness: up to 5 m.
Contacts: rests gradationally above second tillite in the east, (loc. 31a) and above sandstone and dolomite tillite in the west (Tarmfjord). Overlain erosively by Member D tillite.

The tillites are considered to be part of member C, and the siltstone may correlate with the varved siltstone without clasts, unit C3, above the second tillite at locality 31a.

Derivation of Sediment

The importance of local material in influencing the composition of tillite is shown by the purple tillite. Similar observations have been made by students of Pleistocene tills. The same relation is seen with the Vagge Formation sandstones and shales, which probably supplied the green fine-grained sandstone material to the tillite west of Tarmfjord, and in smaller quantities to the brown tillite. As the case for member B, the dolomite and chert were probably derived from Grasdal Formation.

The occurrence of clast from the Vagge Formation south of where it has been eroded beneath the unconformity with the Smalfjord Tillite suggests that there has been a southward component of flow of the ice sheet. However, on a regional scale the material may have come from any direction. This applies to the dolomite and chert component as well.

On the other hand, the only known source of crystalline material is the basement to the south, where rock types similar to some of the clasts are known to crop out (Føyn, 1937, p. 129; Reitan, 1960; Bugge, 1960).

Clast orientation (fig. 34) sheds little light on the palaeoflow direction, as modes may be longitudinal or transverse to flow (see Chapter 3).

5.3.4 Member D

This is the most laterally continuous member in the Smalfjord area (fig. 35). It rests on the Dakkovarre Formation southwest of Vestertana, 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 by member 1 of the Nyborg Formation. The member also occurs at Rødberget and Areholmen.

The member comprises two units, a grey-green tillite with few clasts (Table 12), and an overlying grey-green and purple siltstone with dropstones (Table 13), seen only southwest of Vestertana.

Table 12

Member D Tillite, Main Study Area

Colour: grey-green, weathers dark orange-brown.
Clasts:
- Concentration: usually 1-2%, up to 10% southwest of Vestertana.
- Composition: up to 50% fine-grained greenish sandstone, and dolomite and crystallines.
- Average Diameter: < 5 cm, crystallines tend to be larger.
- Maximum Diameter: about 60 cm.
- Shape: sandstones are tabular, crystallines and dolomite are equant, or slightly elongate. Most clasts show various stages of rounding.

Matrix: fine sand, silt grains in a fine-grained groundmass with some carbonate (Pl. 39c).
Thickness: up to 30 m.
Lower Contact: erosive.
Upper Contact: grades into siltstone, or eroded into by member E tillite, and ?grades into Nyborg Formation.
Structure: massive appearance in inland exposures, but at Auskarnes faint banding, with rare tight folds is prevalent. The bands are lenticular.

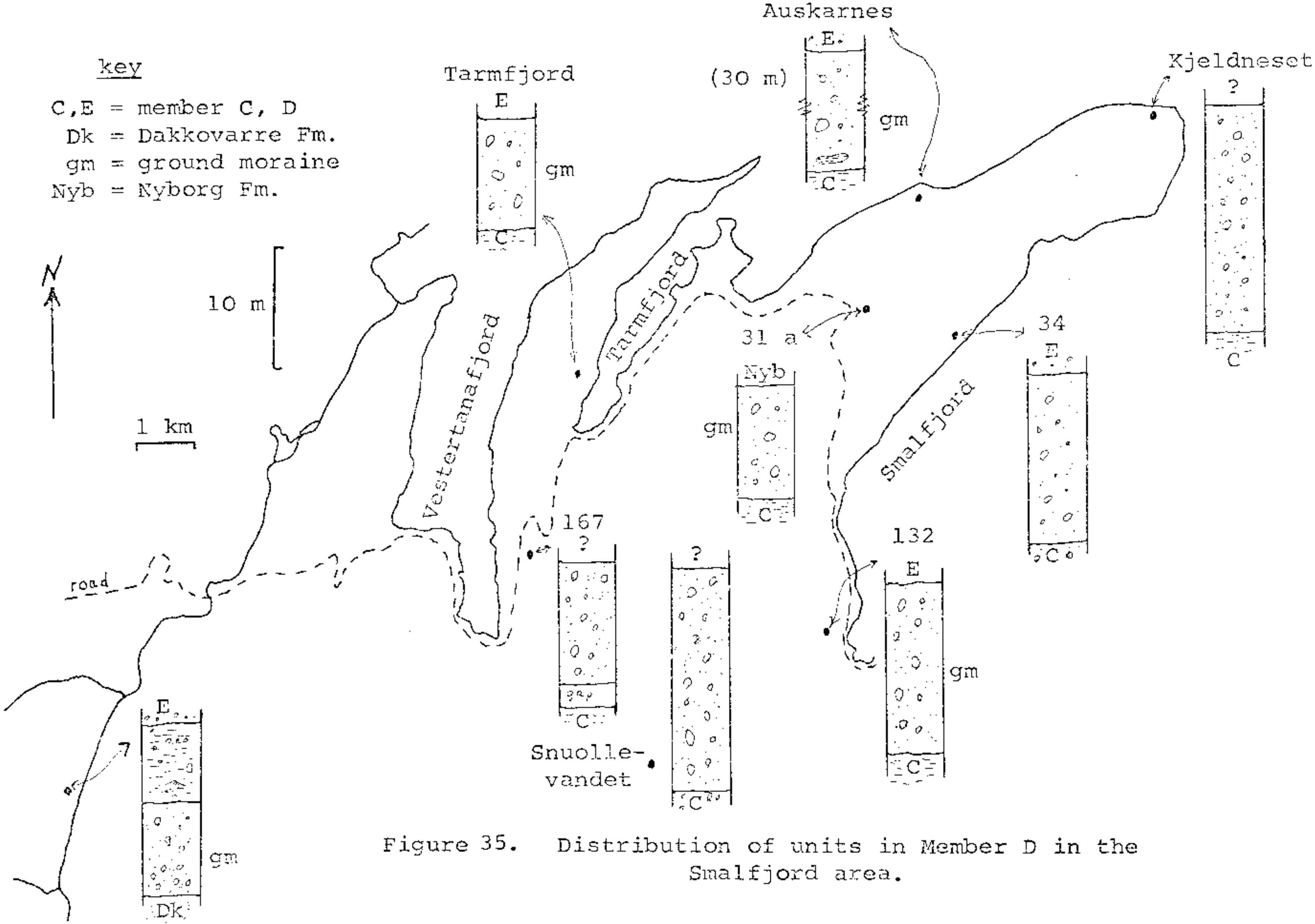


Figure 35. Distribution of units in Member D in the Smalfjord area.

Table 13

Member D Siltstone, Southwest of Vestertana

Colour: mainly grey-green, some purple.
Structure:
    Lamination: finely to coarsely parallel-laminated fine sandstone, siltstone and mudstone (Pl. 35).
    Deformation: plomp-and-drape structure, intense shearing where eroded into by member E tillite.
    Other Features: two graded sandstone beds with parallel-lamination passing up into ripple cross-lamination (Pl. 36). Current direction was to the south.
    Several lenses of dolomite tillite along particular bedding planes. These are clast rich, and the lenses are up to 25 cm wide, and 5 cm high.
Dropstones:
    Distribution: both in rows and dispersed throughout.
    Composition: dolomite and a wide variety of crystalline clasts.
    Concentration: about 5%.
    Size: up to about 30 cm, generally less than 5 cm.
Thickness: up to 6 m.
Lower Contact: gradational.
Upper Contact: erosive.

Over most of the area, the tillite has a massive appearance, but at the coastal exposure at Auskarnes, faint banding is observed. After a brief search, tight isoclinal folding was observed (Pl. 30).

Base of Member D Tillite

At hill 132 (fig. 35) clast-free siltstone (unit C1) from the underlying member C is incorporated into the base of the tillite and is deformed into what may be an overturned fold (Pl. 31). The implied direction of flow was to the north, but this is uncertain.

Near Auskarnes, large blocks 1-2 m high, and at least 5 m long, of the underlying green and purple siltstone of member C occur in the basal parts of the tillite. The blocks are highly deformed by small normal faults and folds (Pl. 32 a and b), and are brecciated. The implied direction of flow was to the south.

At the mouth of Tarmfjord, member D tillite rests erosively on member B siltstone. Siltstone (member B) below the tillite is folded (Pl. 33) and a large amount of siltstone incorporated into the basal part of the tillite is faulted (Pl. 34). The direction of movement was approximately to the southwest.

Where the tillite rests on sandstones of the Dakkovarre Formation southwest of Vestertana, the sand concentration of the matrix is high at the base of the tillite, but decreases upwards. The uppermost layers of the sandstones are occasionally sheared. The sand was apparently derived from the Dakkovarre Formation.

Interpretation of Member D

A ground moraine origin for the tillite of member D is indicated by the strongly erosive base, and the incorporation of underlying sediment. The overlying siltstone may have been of marine origin. Varves are absent, and the interlaminated sand, silt and clay suggests variable currents in an occasionally agitated marine environment. The graded sandstones with the upward change from parallel to cross-lamination representing a waning flow, may have been deposited by turbidity currents. This is consistent with the absence of strong current activity from the surrounding laminated siltstone.

Derivation of Sediment

The abundant sandstone clasts in the tillite, and the fine-grained matrix were probably derived from the fine sandstones and shales of the Vagge Formation. The sandstone fragments are similar to those observed in member C. However, derivation from other parts of the Older Sandstone Series, or from the Barents Sea Group cannot be ruled out.

Derivation from the north is consistant with the geology of the sub-Smalfjord Tillite unconformity, and with the most reliable flow indicators in member D.

5.3.5 Member E

Member E is the highest found in the Smalfjord Tillite in the Smalfjord area. It rests erosively on member D, and is overlain by the Nyborg Formation. The tillite, which makes up most of the member, is distinguished by its sandy matrix, and high dolomite composition in clasts and matrix (Table 14).

Table 14

Member E Tillite, Smalfjord Area

Colour: weathers drab yellow, buff; green-grey when fresh.
Clasts:
- Composition: 5-10%.
- Concentration: mainly dolomite, up to 25% crystallines.
- Average Diameter: about 5 cm.
- Shape: mostly equant, mostly showing some degrees of rounding.

Matrix: sandy with dolomite groundmass (Pl. 39d).
Thickness: up to about 15 m.
Lower Contact: erosive into member D.
Upper Contact: not seen, conglomerate seen above the tillite may represent the top of the tillite.
Structures: massive except for banding at lower contact at hill 132.

Locally, conglomerate occurs at the top of the member at Tarmfjord and southwest of Vestertanafjord, and a thin unit of laminated tillite occurs near Auskarnes (fig. 36).

Base of the Tillite

The contact between the tillites of members D and E is well exposed at hill 132 (fig. 36) where there is a zone of banded tillite about 20 cm thick; the bands are folded, and represent a mixture of the two types of tillite.

Southwest of Vestertanafjord the tillite rests on the

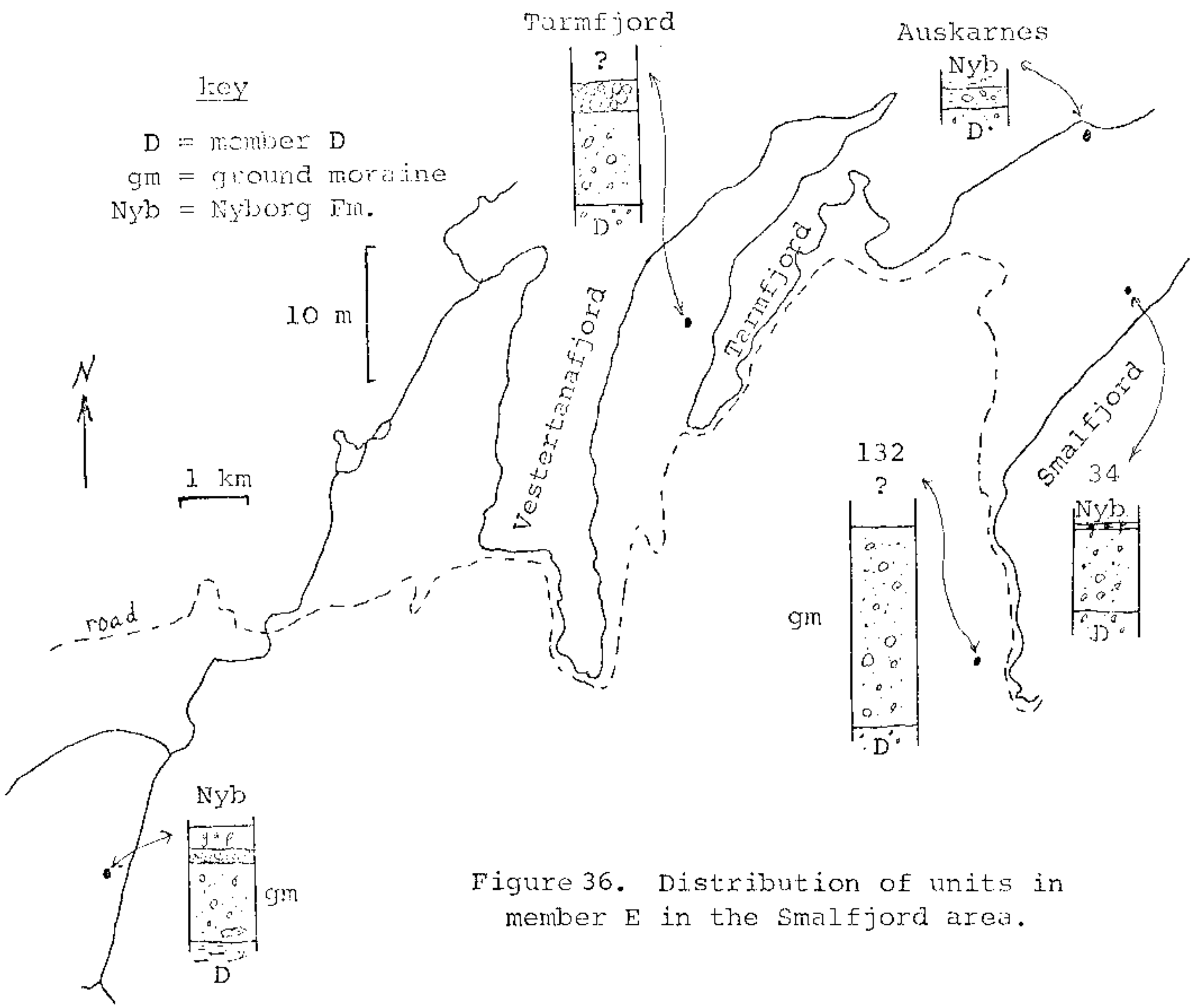


Figure 36. Distribution of units in member E in the Smalfjord area.

siltstone of member D. Up to 1 m of the top of the siltstone is highly sheared and faulted, and the erosion surface cuts into the siltstone to the north. The lower few metres of the tillite contains blocks of sheared siltstone, and the colour is locally purple or green.

Top of the Tillite

At Tarmfjord, and southwest of Vestertanafjord the tillite is overlain by a conglomerate composed largely of rounded dolomite pebbles and cobbles. The unit is up to about 2 m thick.

Auskarnes

At Auskarnes 1 m of brown, sandy tillite occurs at the top of the formation, above member D tillite. About 70 cm of massive brown, dolomitic tillite passes up into 30 cm of parallel-laminated tillite with clasts of tillite and plomp-and-drape structure (Pl. 37). Sharply above is the finely parallel-laminated purple siltstone of the Nyborg Formation which contains dispersed clasts in the lower 10 cm. In polished section, both the laminated tillite and the siltstone are seen to contain numerous shale flakes, which are elongate, and slightly rounded.

Interpretation of Member E

A ground moraine origin for the massive tillite of member E is indicated by the erosive contact with the substrate, and the incorporation of it into the tillite. The conglomerates at the top appear to be erosional lag deposits resulting from the winnowing of the tillite. The laminated tillite at Auskarnes appears to have been deposited subaqueously. The gradation into the Nyborg Formation was accompanied by reworking and erosion, perhaps in shallow water, as suggested by the shale flakes. These do not have the appearance of ice-dropped till, as they are flat in cross section. The internal lamination also suggests a local derivation from the laminated fine-grained tillite.

Derivation of Sediment

The dolomite and sand components of the tillite suggest derivation from the Older Sandstone Series and the Grasdal Formation. The relative scarcity of clasts, especially of sandstone, suggests that it may be, to a large extent, a reworked older till. No observations were made specifying the direction of ice flow, of the location of the source area.

5.3.6 Other Localities

The Smalfjord Tillite was briefly examined at Rødberget, Leirpollen, Trollfjord, West of Njukcagaissa, and South of Laksefjord (fig. 37).

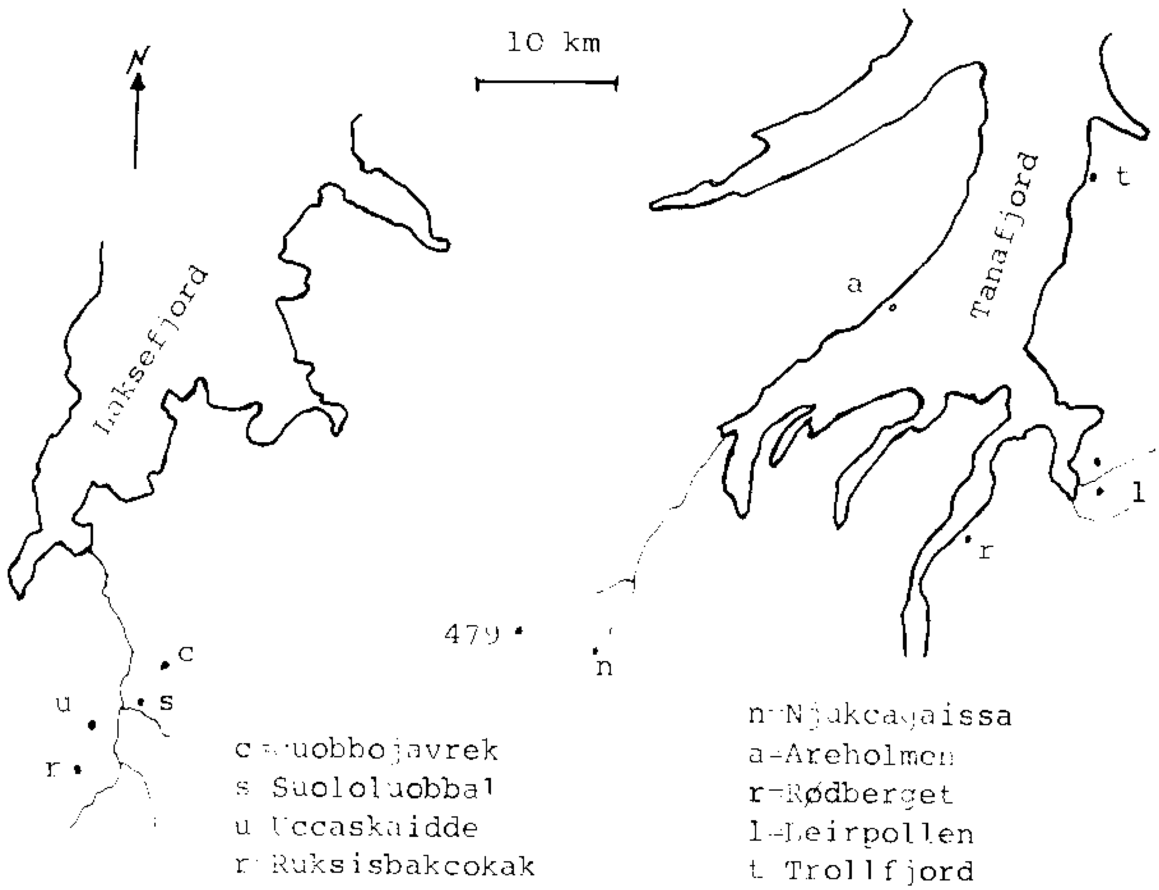


Figure 37. Smalfjord Tillite localities.

Rødberget

At Rødberget, and at a cleft about 1 km to the north the Smalfjord Tillite is well exposed overlying the Gamasfjell Formation. Only a brief reconnaissance could be made due to the interference of diving buzzards. From the base the section is:

1) 18m grey-green massive tillite, with mainly dolomite clasts in a dolomitic matrix. The basal 2 m is very rich in dolomite

and sandstone clasts. This unit may correspond to member B of the Smalfjord area.

2) 12 m brown-grey, parallel-laminated siltstone, with no clasts, sharp base, rare microfaults. May correlate with member C clast-free siltstone.

3) 8 m intercalated pebbly sandstone and tillite, appears to be current deposited due to load structures and irregular lamination. May correspond to pebbly sandstone unit of member C.

4) 10 m grey tillite, scattered sand grains in fine matrix, rare layered structure, rare clasts. May correspond to member D tillite.

5) 20 cm faintly parallel-laminated and thin bedded fine sandstone with copper oxide coatings along joint surfaces.

After a gap this is followed by parallel-laminated siltstone and dolomite of member 1, Nyborg Formation.

Leirpollen

East of Leirpollen, where the lower part of the Vestertana Group is very condensed, the Smalfjord Tillite is 8 m thick and rests on quartzites of the Hanglecerro Formation. The massive tillite is dark grey-brown weathering, dark grey-green when fresh, and contains mostly small dolomite clasts in a silty, muddy matrix with scattered sand grains. At the top, the matrix is very sandy, possibly due to winnowing of the fine fraction. The tillite is overlain by grey-green shales of member 3 of the Nyborg Formation.

West of Njukcagaissa (479)

West of Njukcagaissa near 479, the Smalfjord Tillite is brought up in a small anticline not shown on Føyn's 1937 or 1960 maps. The base of the formation was not observed. Two tillites were seen: one with a very high clast concentration, and composed almost entirely of dolomite and chert clasts (one white granite pebble was found after a diligent search) in a dolomitic matrix, and the second, above, with a variety of clast types and a lower clast concentration. Within the formation is a distinctive varved siltstone. The varves are very well graded, fine sandstone and siltstone, and are well sorted (Pl. 39d) up to a centimetre thick, and disturbed by high angle microfaults. At the top of the formation is a lenticular body of very poorly sorted pebbly sandstone which appears to be filling a 2 m deep channel cut into the underlying tillite. This sandstone may be fluvial in origin. The sandstone and adjacent tillite are sharply overlain by member 1 of the Nyborg Formation. The dolomitic tillite probably corresponds to member B tillite in the Smalfjord area, and further work around Njukcagaissa may help to establish a relationship between these two areas.

Trollfjord

At Trollfjord, the northernmost outcrop of the Vestertana Group, the Smalfjord Tillite rests on the Grasdal Formation. The tillite consists of three units from the base:

1) 6 m banded light buff and dark grey tillite (Pl. 38) with dolomite and sandstone clasts, and silty mudstone matrix. The banding is rarely tightly folded. The unit rests sharply on black shales, which are occasionally highly sheared for about a metre below the contact with the tillite. The lower part of the tillite is rich in black shale flakes, mostly several centimetres long; these decrease upwards, but persist to the top. The banding, and the erosive base suggest that the unit is a ground moraine. Evidence of the flow direction was not seen.

2) 3 m, sharp base on (1), vague beds of dark grey, massive siltstone, up to 30 cm thick, rows of small dolomite pebbles along bedding planes; a few pyrite concretions which formed in place in the siltstone. Inland, weathering brings out crude parallel-lamination in the siltstone. On thin section, siltstone consists of homogeneous , moderately to well sorted,angular

grains of quartz and feldspar with a haematite cement. Mean grain size is 30-50μ, coarse silt, clays and mica are absent, and no trace of sorting or stratification is seen.

3) 50 cm green-grey finely parallel-laminated siltstone with outsize clasts, and rare ripple cross-lamination. Sharp base, top grades over a few cm into the dark buff-brown weathering, parallel-laminated siltstones of the base of the Nyborg Formation.

The upper unit is clearly subaqueous in origin, probably marine as varves are absent, and it grades up into presumably marine shales. The middle unit is difficult to interpret. The lamination and bedding suggest subaqueous deposition, possibly beneath an ice shelf as indicated by the weak stratification and the pyrite nodules due to reducing conditions.

On the other hand, the lamination is poorer than that observed in definite subaqueous deposits, and the bedding is defined by rows of pebbles rather than parting planes of fine-grained sediment. The homogeneous appearance in thin-section is also atypical of subaqueous stratified deposits, as is the well-sorted texture and the scarcity of fine silt and clay grade material. These factors, in combination with the angularity of the grains, suggest that the siltstone is an aeolian subaerial deposit, loess. All of the features described above, except for the composition of the cement, are similar to those of many Pleistocene loess deposits (Richthofen, 1882; Charlesworth, 1957 and Smalley, 1966).

The erosive contact at the base of the formation shows that the regional unconformity extends to Trollfjord as described by Føyn (1937) and Siedlecka and Siedlecki (1971). This appears to contradict the view of Reading and Walker (1966) that the tillite grades up from the black shales of the Grasdal Formation into the tillite, interpreted as an ice rafted deposit. The structure described by Reading and Walker as lamination is glacial shear banding. No correlation with the members of the Smalfjord Tillite at Smalfjord is attempted.

South of Laksefjord

The area around Uccaskaidde and Ruksisbakvarre, south of Laksefjord was studied as part of a stratigraphical investigation carried out by the Oxford University Geological Expedition to Finnmark, 1971 (Edwards et al. in press, N.G.U.). Only the salient features are discussed below. The area has been described by Føyn (1967).

The Smalfjord Tillite rests on the Older Sandstone Series from the Dakkovarre to Hanglecerro Formations. The unconformity dips to the south and east (Chapter 2, fig. 5). Three units are recognised in the tillite:

1) 0-10 m purple parallel-laminated siltstones in the north, and 0-20 m stratified gravel and sandstone to the south. The relation between the two lithologies is unknown, but they are both overlain by unit 2. The latter contains crystalline, chert and reworked ferruginous, nodule-like pebbles, and is very similar to the sandstone unit in member A in the Smalfjord area. At the base of the sandstone are large glacially transported blocks of the Dakkovarre Formation.

2) about 10 m massive tillite with almost entirely dolomite clasts in a dolomitic matrix, and occasional lenses of poorly sorted sandstone. Dolomite clasts are up to about 100 m long. Locally the tillite is overlain by a purple parallel-laminated siltstone up to 4 m thick. The tillite and siltstone may correspond to member B of the Smalfjord area.

3) 5 m dark grey crystalline rich tillite, overlain by up to 20 m of dark grey, brown weathering parallel-laminated siltstone with numerous small outsize clasts. Locally the lamination is absent imparting a massive appearance to the rock. The unit is overlain, sometimes sharply, sometimes gradationally by the basal dolomite bed of member 1 of the Nyborg Formation. The tillite is comparable to member C of the Smalfjord area in that it represents the first important influx of crystalline material into the basin. A similar sequence of units is seen to the east

at Suololuobbal (fig. 37), but north of Cuobbojavrek the tillite is represented by several metres of shale (see Føyn, 1967).

5.4. Discussion

5.4.1 The Origin of Microfaults and Related Structures

An understanding of the relationship between the geometry of certain deformation structures and the stress fields in which they formed is required in order to appreciate their directional significance. Frequently occurring in both the Smalfjord and Mortensnes Tillite Formations is a series of normal faults, most of which dip in one direction, and which occur in a planar, lenticular zone parallel to the bedding.

The development of certain lozenge-shaped boudins in metamorphic rocks has been related to extension and shear. Rast (1956) integrated the ideas of earlier workers and showed that both extension and shear may be represented in a given structure. According to Tchalenko (1968) the resultant of the load and the friction in the direction of shear is the major principle stress direction which may cause a particle orientation, termed a compressive texture, in which the a b plane of the particles is nearly normal to the resultant stress. A vertical compressive stress and a shear stress orientated parallel to the bed may exist at the base of an active ice sheet (fig. 38).

Evidence for an overriding shear associated with the fault zones is provided by occurrence of overthrusts (Pl. 32a). Extension is indicated by the development of normal, as opposed to thrust faults (Pl. 32). The deformation of the faults (see section 7.3.3) may be related to the inequal distribution of stress through the shear zone. The long axis orientation of pebbles in tillite associated with the fault zones (member B, Tarmfjord) indicates a major principle stress direction which agrees with the interpretation of the faults proposed here (Pl. 20).

In all the cases observed (5), the faults dip in a direction

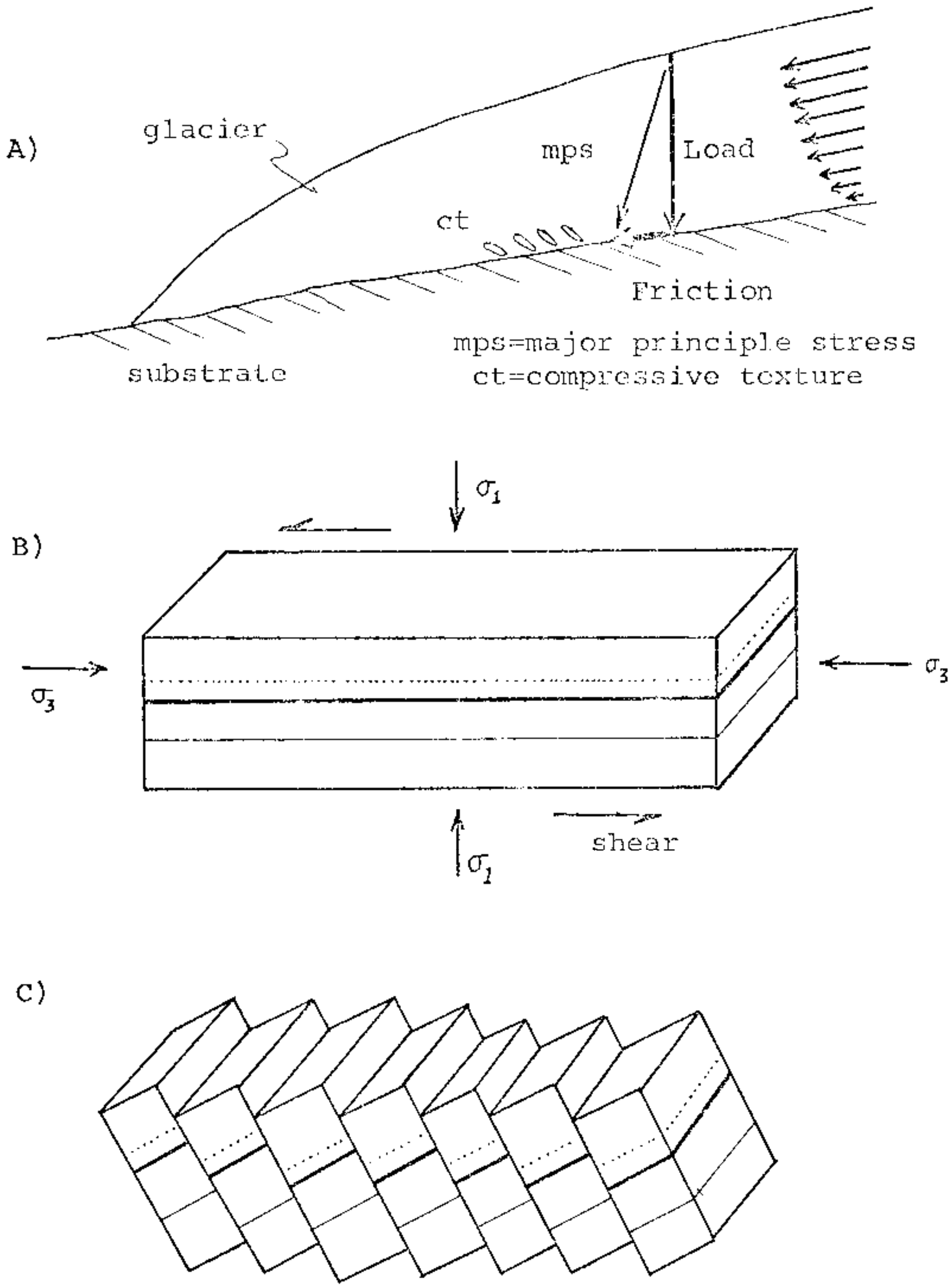


Figure 38. A) Stress conditions at the base of a glacier. B) Undeformed block of siltstone below base of glacier. σ_1 determined by load, shear stress determined by friction. C) Siltstone after brittle deformation, under conditions shown in B.

opposed to the direction of shear, and thus especially when combined with additional structures they are an important and reliable palaeoflow indicator.

5.4.2 Comparison of Facies

Tillite

A comparison of the tillite facies of the different members (Table 15, Pl. 39), reveals the marked difference in properties between the tillites. In general however, the clast concentration, appears to be directly proportional to the amount of dolomite present. This suggests that the dolomite was cohesive, as it formed clasts and was not readily transposed to the matrix of the till, in spite of glacial comminution. An additional factor was probably the ready supply of dolomite from the Grasdal Formation. The lower clast concentration of the higher units may be due to the addition of sand and mud by the breakdown of the clastic sediments of the Older Sandstone Series. This is very likely the case with member D in which sandstone clasts are abundant.

The change in composition from one tillite to the next is probably a function of several factors. The sandstone composition of member A was probably due to the local derivation and short distance of transport. On the other hand, the dolomite composition of the member B tillite indicates a greater distance of transport, but still intrabasinal. The addition of crystalline material in member C indicates derivation outside of, or at the margin of the basin. Primarily, it reflects a greater transport distance, but may also be related to changing ice flow directions, and erosion of the sedimentary cover at the basin margins. The two upper tillites are both dominated by sedimentary material. The dolomite and sandstone composition of the member E tillite is indicative of derivation from the Older Sandstone Series and Gradal Formation, and this suggests that the sandstone of member D tillite is also intrabasinal, although it is impossible to

Member	Colour	Clast		Matrix	Base	Sediment Source	Derived from
		Concentration	Composition				
E	buff-yellow	5-10%	dolomite* & crystalline	sand in carbonate groundmass	Erosive	OSS Grasdal ?older till	???
D	grey-green	1-2%	sandstone* dolomite crystalline	sandy, silty mudstone	Erosive	OSS ?Vagge	?north
C	brown & purple	10-20%	dolomite* crystalline	sand in carbonate groundmass	Erosive	Basement Grasdal	?south, north
B	buff-yellow	25-60%	dolomite	dolomite	Erosive	Grasdal	?north-east
A	purple & green	5-10%	sandstone	sandy siltstone	not seen	OSS ?Dakkovarre	?south

Table 15. Properties of tillite units by member, Smalfjord Area. OSS = Older Sandstone Series

* = most prominent component.

prove. For member D the ice sheet was eroding fine-grained clastic sediment, which may have been the shale formations of the Older Sandstone Series (fig. 4) if intrabasinal, possibly the Vagge Formation. The composition of the matrix appears related to the composition of the clasts.

The direction of ice flow as inferred from source areas and flow indicators (Table 15) particularly. The northerly derivation of members B, D, and possibly C, is unexpected. The traditional picture of a southern, basement source area is supported by the increasing erosion into the Older Sandstone Series to the south (Chapter 2) and the fact that the Fennoscandian Shield is the obvious source of crystalline lithologies (Føyn, 1937; Reading and Walker, 1966) (further discussion in Chapter 9).

Siltstone

Three main kinds of siltstone facies occur in the seven units examined (Table 16). They are distinguished by the presence or absence of varves, parallel-lamination and clasts. The distinction between marine and fresh-water facies is not clear.

The main factors in the formation of the siltstones may have been: 1) a strong seasonal change in sediment input, so that varves could be formed; 2) the presence of currents capable of modifying the sediment to the extent of destroying the varves, and 3) the presence of agents of rafting, by either shore ice, bergs, or an ice shelf. Siltstones with varves probably were deposited in enclosed bodies of water with a range of salinities, while sediments without varves may have been deposited either in bodies of water without glacial influence, or with modifying currents.

Vertically, there is an upward trend from purple to green siltstones but the causes of purple versus green colouration in rocks are obscure. Varves are more prominent towards the base of the formation and there may be a rough correlation between the presence of varves and a purple colour. The reasons described

Member	Colour	Structure		Clasts	
		Varves (Sorting)	Parallel-Lamination	Composition	Distribution
E	yellow-brown	-	+	dolomite crystalline	dispersed
D	green	-	+	dolomite crystalline	dispersed and in rows
C3	green	good	-	-	-
C2	purple & green	(rare)	+	mainly dolomite	in rows
C1	green	-	+	-	-
B	purple	good	+	mainly dolomite	dispersed
A	purple	poor	+	mainly dolomite	dispersed and in rows

Table 16. Properties of siltstones of Smalfjord Tillite, Smalfjord area. Numbers of C siltstone refer to probable stratigraphic order as described in text.

above may have been responsible for the vertical trend.

A noteworthy attribute of the siltstone is the almost complete absence of signs of wave activity, such as oscillation ripple lamination. This may have been due to the damping effect of icebergs. Such an effect has been cited to explain the absence of beaches and wave-cut benches in certain Pleistocene lakes (Hansen, 1956).

Sandstone

Sandstone is an uncommon facies in the Smalfjord Tillite (Table 17). Each of the five examples documented in the preceding descriptions differs from the others in important respects. Two of the sandstone units, those in members A and B both contain cross-stratification and internal scours, and appear to be proglacial outwash. In contrast, the two sandstones in member C appear to have been deposited in a subaqueous environment. The sandstone unit above C1 siltstone contains horizontal stratification and lacks scours and cross-bedding, while the sandstone below C2 siltstone only faintly laminated and occurs with gradational contacts between a ground moraine and subaqueous siltstone. These facies may have been deposited in the zone where an ice sheet begins to float and merges into an ice shelf.

The siltstone at Trollfjord (included here because it is distinct from the siltstone facies in that it lacks a clay fraction) is a unique deposit as it may be an ancient loess. To the author's knowledge, pre-Pleistocene loess has not been recorded (e.g. Pettijohn, 1957).

If the interpretations of the sandstones are correct, then there seems to be an upward trend from fluvial to marine conditions from members A and B to C. The palaeo loess siltstone and the laminated siltstone at Trollfjord indicate that following the retreat of the ice, subaerial, and then subaqueous conditions prevailed.

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	tillite (ground moraine) below, siltstone (subaqueous) above	loess
C, below C2 siltstone	poorly-sorted sandstone with few pebbles	massive, faintly parallel-lam	as above	subaqueous, proglacial
C, pebbly sandstone above C1 siltstone	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 stratified tillite (supraglacial)	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 siltstone, rests on regional unconformity	fluvio-glacial outwash

Table 17. Sandstones and pebbly sandstones in the Smalfjord Tillite at Tanafjord and Laksefjord.

5.4.3 Lateral Variation in the Smalfjord Tillite

Shape of Units

Most tillite and siltstone units are highly variable in thickness, sometimes over short lateral distances. Changes of 10 m over several hundred metres are not uncommon. The erosive nature of the base of each member is probably the greatest cause of the lenticularity, but it may also be related to primary sedimentation, for example where an end moraine was deposited. The same may also apply to siltstones, which may have been deposited in depressions, and wedged out laterally towards high ground. Examples of this cannot be demonstrated for the Smalfjord Tillite.

Properties of Units

Detailed quantitative information concerning the properties of the tillites or siltstones was not collected from the Smalfjord Tillite. However information of a semi-quantitative nature is interesting. Although the clast concentration of member B tillite is high (Table 15), there is considerable variation from place to place as shown by the range in percentage (Table 5). A similar range in clast concentration is seen in tillite of member D which is extremely low in the east, but increases up to 5%, and even 10% southwest of Vestertana. The increase in clasts is related to a greater proportion of crystalline clasts to the southwest. The causes of such trends are uncertain.

Continuity of Members

The probable correlation of members between Laksefjord and Tanafjord suggests that the events which formed the members were large-scale advances and retreats of an ice sheet, rather than local events. This agrees with the changes in composition between successive tillite units. The presence of such large-scale events suggests that eventual correlation with Varangerfjord may be possible.

Thickness of the Smalfjord Tillite Formation

As pointed out by Føyn (1937), the Smalfjord Tillite is highly variable in thickness (fig. 5), especially compared to the Mortensnes Tillite. The causes of such variation might have been: 1) irregularities on the sub-Smalfjord Tillite unconformity; 2) vagaries of glacial erosion and deposition 3) irregular subsidence during the deposition of the Smalfjord Tillite, and 4) postglacial erosion preceding and ?accompanying the Nyborg Formation transgression.

Relationships at Laksefjord show that there are great changes in thickness of the Smalfjord Tillite with little erosion of the underlying Hanglecerro Formation. It seems unlikely that (1) is an important cause of thickness variations.

Irregular subsidence of the substrata (3) during deposition would involve areas smaller than that of the main basin, on the order of 20-50 km. Such basins were not developed in the non-glacial shallow marine sediments of the Older Sandstone Series (Edwards et al. in preparation) or the postglacial sediments (Banks et al. 1971, Føyn, 1967). It is therefore considered unlikely.

Erosion occurring prior to, and/or during the Nyborg transgression (4) is seemingly demonstrated by the lateral impersistance of member E and the overlying lag conglomerate. Part of this impersistance in member E is probably due to glacial deposition erosion, as seen also in members A-D. The presence of the upper members D and E preserved over the Smalfjord area suggests that there was no significant erosion of the tillite. The thickest lag conglomerates of 2 m may represent erosion of no more than about 10 m of tillite. In most localities such a lag does not separate the Smalfjord Tillite and Nyborg Formations, and often this contact appears gradational (e.g. Trollfjord). It is thus considered unlikely that postglacial erosion determined the present thickness variation in the Smalfjord Tillite, although it may have had some influence.

It would thus appear that the main course of local thickness changes on a formation and member scale was glacial erosion and deposition. Combined with factors (1) and (4), and other unknown causes, this may have led to the irregular thickness trends in the Smalfjord Tillite Formation.

5.4.4 Further Remarks on the Glacial Advance-Retreat Model

To the four groups of observations presented at the opening of this chapter we may make several additions:

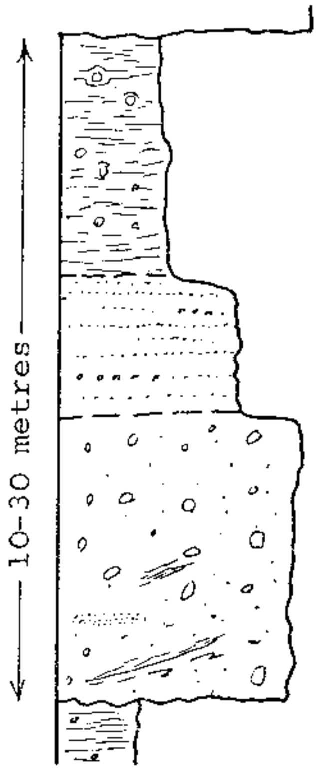
1) The erosive base of the tillite units is associated with the deformation and incorporation of the underlying sediment.

2) Most tillites are massive, but some are banded and contain deformation structures attributed to internal shearing and flowing within an active ice sheet.

3) Supraglacial and proglacial subaqueous and subaerial deposits are relatively scarce in the Smalfjord Tillite.

4) Siltstones were deposited in relatively quiet water areas in which ice rafted stones were occasionally dropped. Siltstone is the characteristic proglacial deposit in the Smalfjord Tillite.

The features of (1) and (2) are those of subglacial ground moraines, with retention of some features of englacial processes. They suggest, in addition to (3), that this was the prime mode of sedimentation for tillite in the Smalfjord Tillite Formation. Thus tillite units represent lenticular, continuous and discontinuous ground moraines rather than sporadic end moraines (fig. 39). This conclusion is opposed to that of Reading and Walker (1966) who interpreted the tillite facies of the Smalfjord Tillite in this area as essentially subaqueous marine deposits (pp. 186, 200, 204). Glacial marine sediments of the type envisaged for the Smalfjord Tillite by Reading and Walker (till formed from grounded and floating ice shelves and icebergs) appear to be very rare in the Smalfjord Tillite according to



LITHOLOGY	INTERPRETATION
Siltstone, laminated, varved, with or without dropstones.	Deposition of siltstone largely from suspension in quiet water, fresh or marine; dropstones supplied from ice shelf or ice-bergs.
Crudely horizontally laminated and bedded poorly sorted sandstone with pebbles and silt.	Subaqueous, proglacial deposits formed at lifting zone of ice shelf, or in front of ice sheet grounded in water.
Tillite, mainly massive, also banded and with rare stratified sands.	Subglacial deposits of dry-based ice sheet, composed of exotic and locally derived materials, often mixed together.
Erosion surface	Subglacial erosion, incorporation of substrate into ice sheet.

Figure 39. The tillite to siltstone succession which composes most of the Smalfjord Tillite at Smalfjord. Proglacial outwash sands are scarce, and occur in association with supraglacial tillite. The subaqueous, proglacial sandstone, shown above, is also an infrequent deposit. Possible causes of the sequence are discussed in the text.

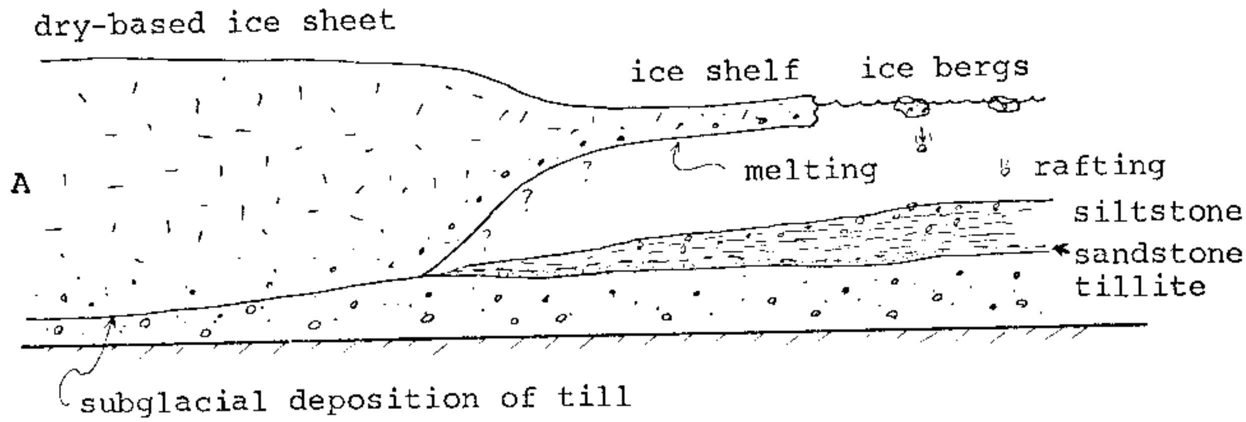
the present study.* The siltstones and some of the sandstone may have formed partially beneath an ice shelf (fig. 40).

A topography with relatively low relief, and numerous shallow, closed depression might explain (3) and (4) above. This would cause the formation of large lakes, and brackish or marine areas if connected to the sea. Ice margins may have terminated in such shallow water bodies, forming siltstones with varves and dropstones, rather than either on land where they would have formed fluvial outwash (as in unit 2, member B at Auskarnes) and extensive supraglacial deposits, or in deep water where ice shelves would have formed their characteristic sediments (possibly the pebbly sandstone unit of member C). In any case, the absence of thick accumulations of stratified sands and gravels from the Smalfjord Tillite suggests that glacial retreat was relatively rapid.

Pleistocene deposits, similar in terms of till body shape, and interstratification of subaqueous deposits, occur in the Hudson Lowlands (McDonald, 1968), and are typical of areas of low to moderate relief that have been overridden by an ice sheet, but not subjected to appreciable subaerial ice margin conditions.

---

* Reading and Walker distinguished terrestrial from grounded shelf ice. This distinction seems academic to the present author who has encountered no critical evidence to distinguish the deposits of the two, except by association with other facies. In the Smalfjord Tillite the absence of interfingering between the massive subglacial tillite, and laminated subaqueous siltstone (Reading and Walker's stratified tillite?) argues against a grounded shelf origin for the tillites. Where describing the origin for the Smalfjord Tillite, Reading and Walker state (p.200) "The Lower Tillite Formation, with good stratification, would be formed by wet based floating shelf ice and icebergs, with melt water currents locally important in the south", and (p.204) "The Lower Tillite Formation with well-developed stratification ...(formed by) ... deposition from icebergs over most of the Tanafjord area. Subglacial streams were probably locally important in the south". It seems apparent to the present author that Reading and Walker thought deposition of the tillite to have been mainly by <u>floating</u> ice, and not <u>grounded</u> ice.



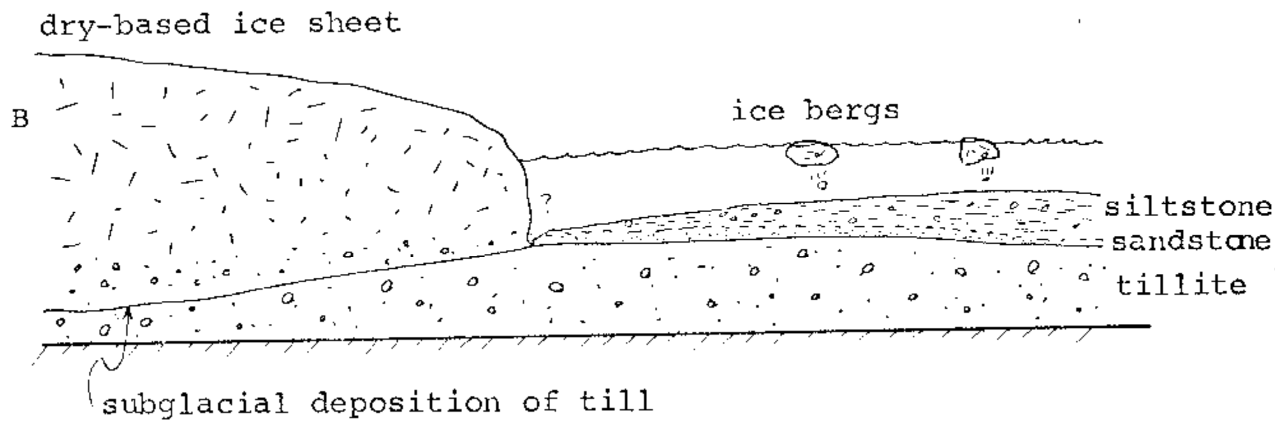


Figure 40. Two alternative models to explain the development of tillite to siltstone sequences in the Smalfjord Tillite around Smalfjord: deposition subglacially and subaqueously in proglacial zone. A) with ice shelf , B) without ice shelf. Ice shelf deposits as predicted by Carey and Ahmed (1961) are only rarely encountered according to the present interpretation.

Probably influencing the development of facies were eustatic changes in sea-level and isostatic adjustments of the crust particularly during the retreat phase. A rise in sea-level would be simultaneous with glacier retreat, but the degree of relief would determine whether or not a higher sea-level could inundate the area of sedimentation, and possibly raise the ice sheet up into an ice shelf, hastening the rate of ablation and retreat. The presence of subaerial facies such as fluvial outwash and loess indicate that marine conditions did not always overlap with deglaciation, but followed the retreat of the ice.

Isostatic adjustments would become important after eustatic changes. The effect might be to maintain shallow conditions in the area of sedimentation. No evidence for rising of the crust was observed within the Smalfjord Tillite.

The glacial influence manifest in the siltstone suggest that deglaciation was not complete during the retreat phases. For this reason the extent of eustasy and isostasy directly related to glacial retreat might be limited, and their sedimentological significance reduced.

5.4.5 Resume of the Glacial History of the Smalfjord Tillite

The history of formation of the Smalfjord Tillite can be divided into two main phases: an earlier one of erosion, and a later one of deposition. The occurrence of member B over much of the area suggests that significant erosion did not occur in the area following the deposition of member B. Member A is not as widespread as member B, but its occurrence at Laksefjord and Tanafjord also suggests that significant erosion did not occur after its deposition. Thus, it appears that the unconformity reached a rough approximation of its final form prior to the deposition of at least members B to E. It is uncertain what the agent or agents of erosion were in this early phase.

Following the erosive phase, five major advances and retreats are documented in the Smalfjord Tillite at Smalfjord:

Member A: advance of the ice sheet, possibly from the south, which during retreat deposited mainly outwash and silts, with possibly a thin basal till.

Member B: readvance of the ice sheet, possibly from the north or northeast. It eroded into underlying sediments and deposited primarily ground moraine with end moraine and proglacial outwash at Auskarnes. The dolomitic composition suggests continued erosion of the Grasdal Formation. Silts were deposited during the retreat stage.

Member C: readvance of an ice sheet, direction of flow uncertain, possibly from the north, bringing in the first important quantities of extrabasinal, basement material into the basin. The tillite is predominantly ground moraine, with two horizons of submarine proglacial deposits and several horizons of siltstone which suggest local retreats and advances.

Member D: readvance of an ice sheet possibly from the north, dominated in composition by intrabasinal clastic material, green sandstone perhaps from the Vagge Formation of the Older Sandstone Series. The tillite is a ground moraine, relatively continuous, and eroding into to the underlying deposits. During the retreat phase silts were deposited.

Member E: the final recorded ice advance appears to consist of intrabasinal material, possibly older moraine. The direction of ice movement is unknown. The tillite is largely a ground moraine.

Erosion: a minor period of erosion preceding or accompanying the deposition of member 1 of the Nyborg Formation is marked by lag conglomerates and the lenticularity of Member E. Fluvial activity was locally present at this time.