CHAPTER 7

MORTENSNES TILLITE FORMATION

7.1 Introduction

Based on intensive work around Vestertana in the centre of the study area, the Mortensnes Tillite is subdivided into three informal members on the basis of composition, primary structures, and stratigraphical position (fig. 62). The ensuing descriptions and interpretations are by member, and in each case cover first the Vestertana area, and then the surrounding localities. Interpretations are based largely on the account of glacial processes and products in Chapter 3.

7.2 Lower Member

7.2.1 Introduction

The lower member is a northward thinning wedge of tillite (fig. 63), largely massive, which rests on a regional unconformity cutting into the Nyborg Formation, Smalfjord Tillite, and Older Sandstone Series (see Chapter 2, fig. 6). It is followed by the middle member at all but the southernmost localities where the top is not seen.

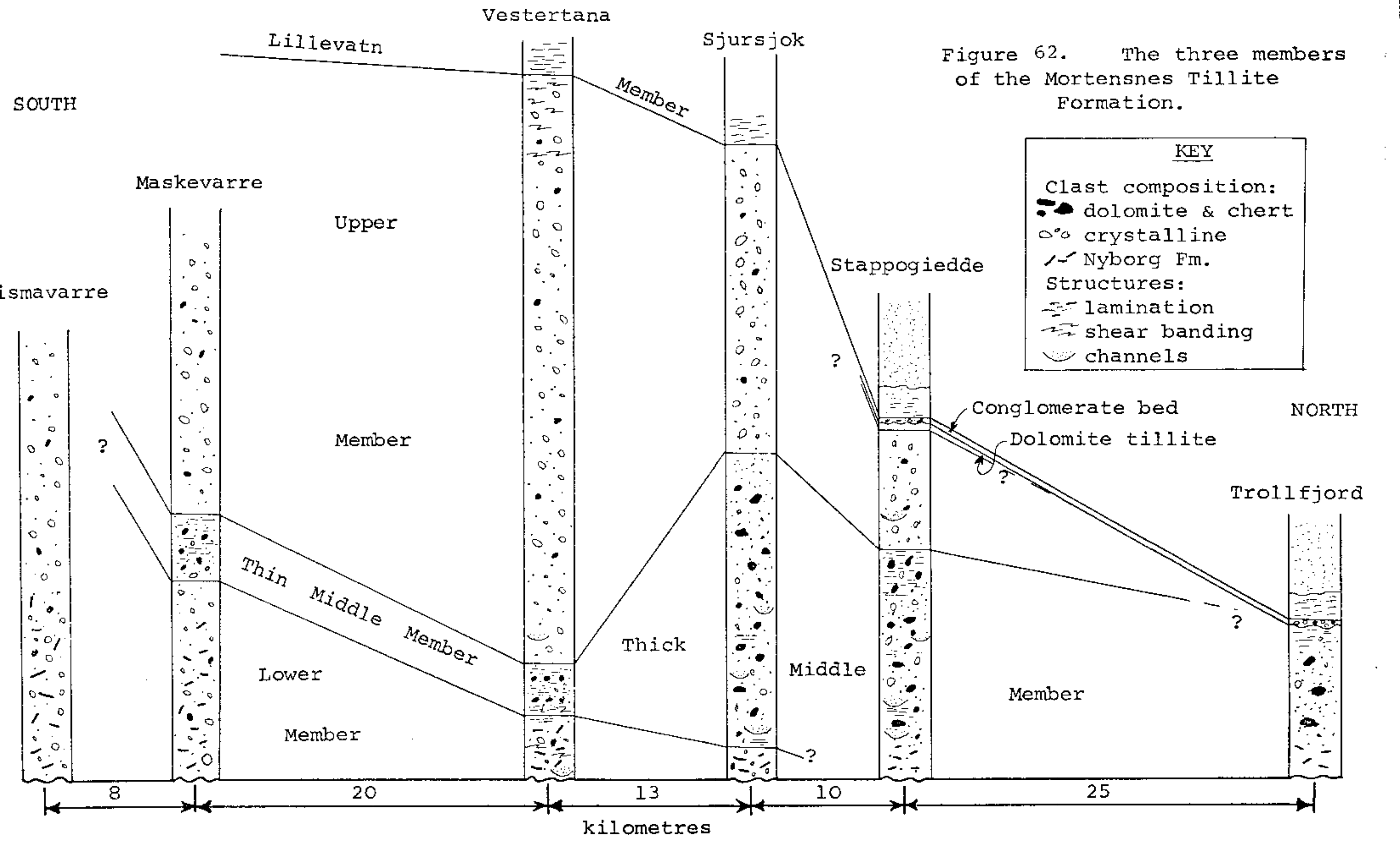
The colour of the tillite, generally dark green-grey or purple, reflects the colour of the Nyborg sediment from which the tillite was formed; locally derived Nyborg sediment is often an important constituent of the clasts and matrix of the tillite. Of the extrabasinal clasts, crystallines dominate over dolomite and chert.

7.2.2 Description

Vestertana

In the Vestertana area (fig. 64) the lower member forms

Figure 62. The three members of the Mortensnes Tillite Formation.



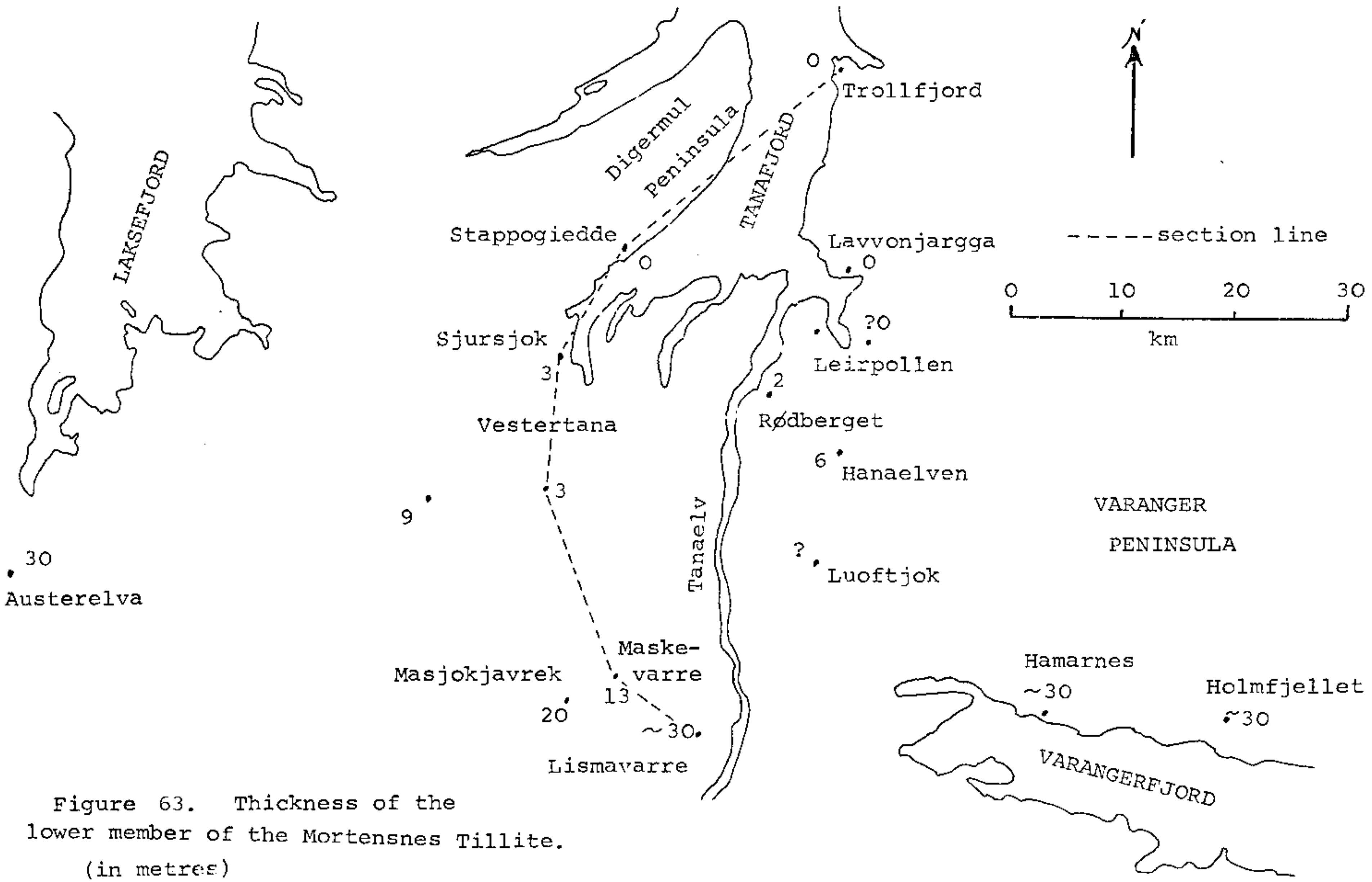


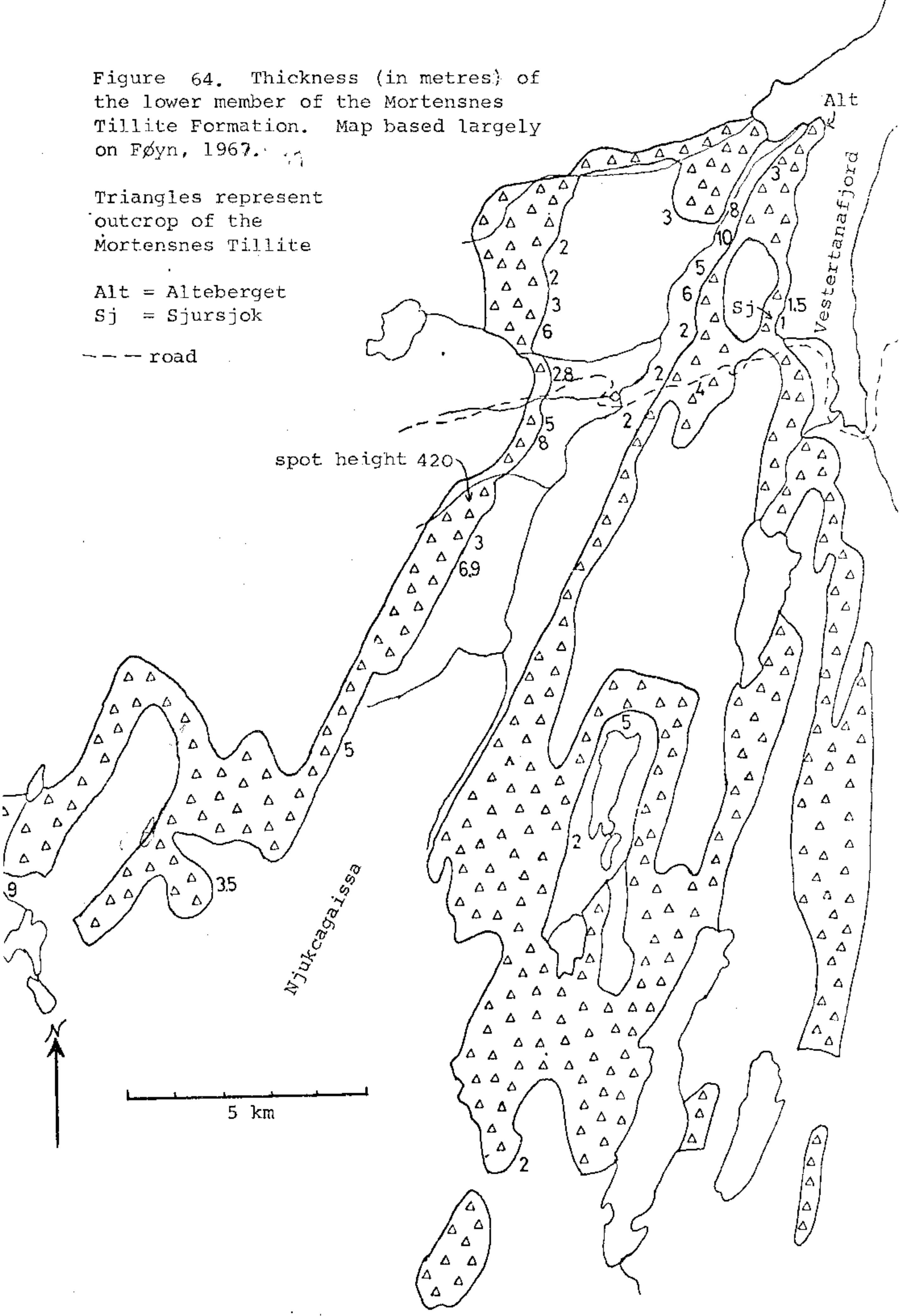
Figure 63. Thickness of the lower member of the Mortensnes Tillite. (in metres)

Figure 64. Thickness (in metres) of the lower member of the Mortensnes Tillite Formation. Map based largely on Føyn, 1967.

Triangles represent outcrop of the Mortensnes Tillite

Alt = Alteberget
Sj = Sjursjok

- - - road



a blanket of tillite 1-10 m thick over the deeply eroded Nyborg Formation (Table 22). In the northern part of the area the member is difficult to trace because the bases of both it and of the thick middle member (where the latter comes to rest directly on the Nyborg Formation) are dominated by Nyborg-derived sediment and have a similar appearance.

Erosion of the Nyborg Formation is seldom visible, only rarely can the cutting out of beds be observed (Pl.77); the same bed can usually be traced beneath the tillite for the length of the exposure (Pl. 78). Thickness variation in member 3 of the Nyborg Formation (fig. 65) shows thinning to the south, apparently due to greater erosion, in agreement with the regional distribution of members in the Nyborg Formation beneath the unconformity (see Chapter 2, fig.6).

The composition of both clasts and matrix in the lower member is highly variable and consists of two important groups of materials: 1) exotic extrabasinal, predominantly crystalline, with minor amounts of dolomite and chert, and 2) locally derived Nyborg sediment. These are rarely seen unmixed with each other; the "average" tillite in the lower member contains about 5% extrabasinal clasts and about 5% Nyborg clasts scattered in a fine-grained and even-textured matrix apparently derived, in most part, from the comparatively well sorted Nyborg sandstones and mudstones (Pl. 79, 80). Relatively pure extrabasinal tillite is seen as lenses with a high (20-60%) clast content and a matrix of unsorted micaceous silt with angular grains of quartz and feldspar.

A layer of almost purely locally derived sediment up to 1 m thick is often seen at the base of the lower member (Pl. 79). It contains about 5-10%, sometimes more, clasts of Nyborg sediment (Pl. 81) usually less than 3-4 cm long, angular and tabular, in a fine-grained matrix of well-mixed Nyborg sediment. Imbrication of the clasts is occasionally developed (Pl. 82). The basal layer passes sharply or gradually up into the normal tillite.

Figure 65. Thickness (in metres) of member 3 of the Nyborg Formation, and the colour of Nyborg-derived sediment in the overlying lower member of the Mortensnes Tillite. Map based largely on Føyn, 1967.

Triangles represent outcrop of the Mortensnes Tillite

Alt = Alteberget
Sj = Sjursjok

Colour in lower member:
gn = green
ppl = purple

– – – road

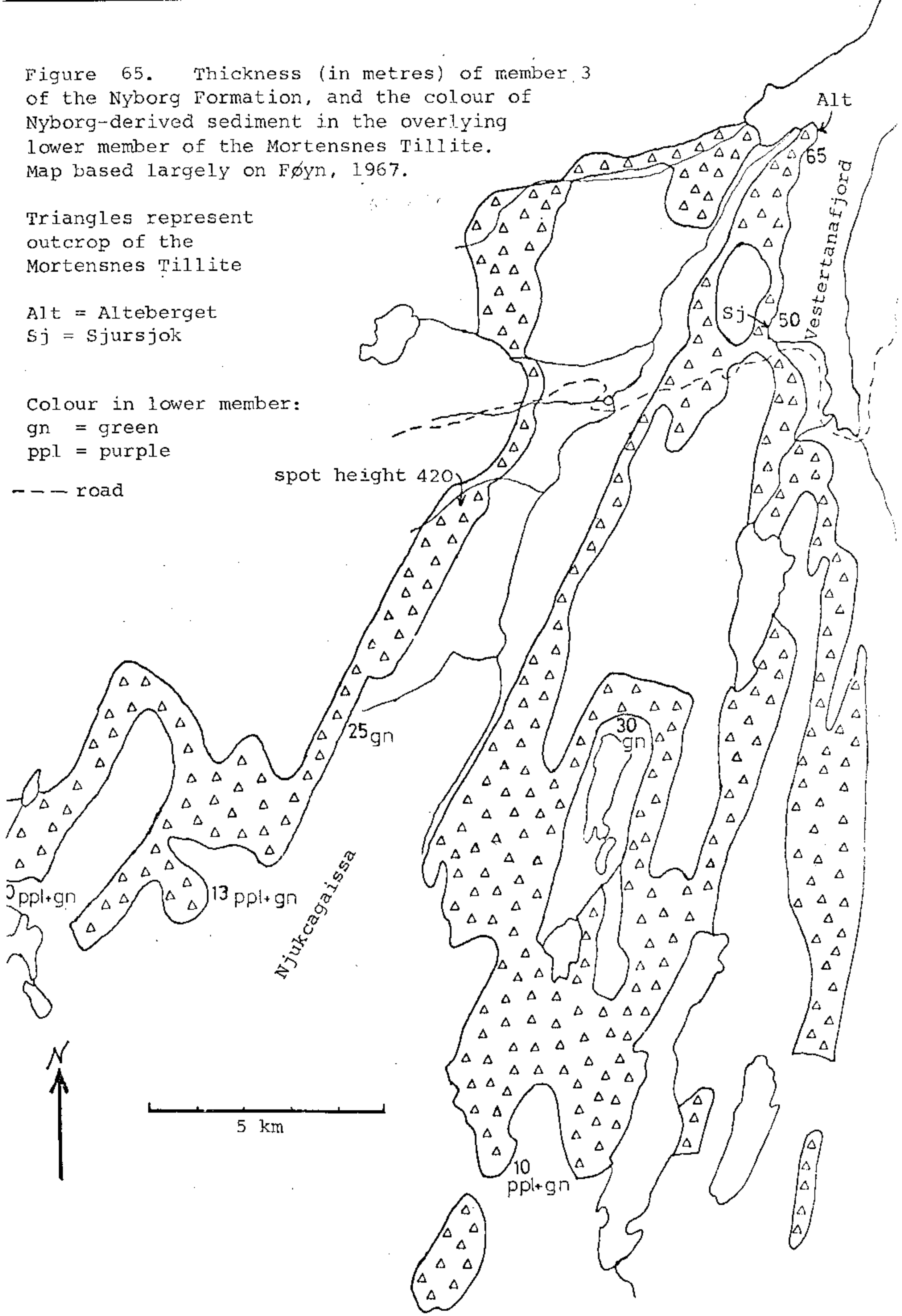


Table 22

Characteristics of Lower Member Tillite, Vestertana.

Colour: mostly dark green-grey, purple in the south.
Clasts:
- Concentration: usually 5-10%
- Composition: Nyborg is dominant; crystallines include light coloured gneiss and granite, dolomite and chert scarce.
- Average Diameter: 5-10 cm.
- Shape: Nyborg clasts are angular, crystalline clasts are rounded.

Matrix: massive, sandy, silty mudstone.
Thickness: 1-10 m, averages around 3-5 m.
Lower Contact: sharp and erosive, may appear gradational.
Upper Contact: appears to grade into the middle member.
Structures: incorporated blocks of Nyborg sediment, occasionally deformed, lenses of stratified sandstone and conglomerate, rare lamination in the upper part.

Along this junction may occur large tabular blocks of Nyborg sediment, largely undeformed, aligned parallel to the regional bedding. Near Sjursjok a 20 x 1 m block (Pl. 83) was observed. Deformation is only rarely seen (Pl. 84).

The lower member is dark green-grey, or dark purple. The former is typical except for the southern part of the area where the two colours occur mixed together (fig. 65). Sometimes clasts of purple Nyborg occur in a green-grey matrix.

Structures in the tillite are scarce. Inland exposure hampers the recognition of structures which might be visible in coastal outcrops, and which can be detected in polished specimens (Pl. 85). The alternating layers visible are 1 mm to several centimetres thick, and vary from dark layers rich in extrabasinal clasts with a poorly-sorted sandy, muddy matrix, to light-coloured, finer-grained layers composed mainly of Nyborg grains and matrix. There is no indication of current sorting, nor are sedimentary, or deformational structures observed.

The bodies of extrabasinal tillite mentioned earlier form discontinuous layers up to 2 m long and 30 cm thick. A bedding plane surface of such a layer is shown in Plate 86. Clasts in the layers are mostly rounded, also sub-angular, and are up to 40 cm across.

Although sedimentary structures are rare in the lower member, three kinds of structures were observed. At one locality, faint, fine parallel-lamination was observed near the top of the lower member. The zone of lamination is about 80 cm thick and has an isolated cross set at the top (Pl.87) which shows that the current flowed approximately to the south.

The second structure, seen at three localities, consists of repeated graded laminae forming units up to 1 m thick and traceable laterally over several metres (Pl.88a). The laminae consist of coarse sand to silt, are from several millimetres to several centimetres thick, and the quality of grading varies from excellent to poor (Pl.88b). The top of each lamina is poorly sorted siltstone. No mud layers are present between the laminae, and no other sedimentary structures were observed.

The third structure includes three channels filled with poorly bedded gravels seen west of Vestertana. The gravels rest either on Nyborg Formation (Pl.89) or lower member tillite, and are overlain by lower member tillite. The gravels are up to 4 m thick, poorly sorted, and with an average pebble size of about 3 cm, composed of rounded crystalline and dolomite pebbles. The gravel in the northern exposure has a boulder lens to one side (Pl.90), and the gravel in the southern exposure has a soft-sediment deformed upper margin shown by vertical loading of gravel and tillite.

The upper contact of the lower member varies from gradational to sharp. It is frequently marked by the gradual increase in dolomite content in clasts and matrix, slow appearance of lamination, and the change to a brownish weathering colour (Pl.91).

Maskevarre and Masjokjavrek

These two neighbouring localities (fig. 63) are an important link in correlating the Vestertana and Varangerfjord tillites. They are situated about 20 km SSW of the Vestertana area, and are about 5 km north of the crystalline shield.

On the western slope of Maskevarre, the lower and middle members outcrop as the downfolded cores of synclines surrounded by the Nyborg Formation (Føyn, 1937, p.119). Although the contact is not exposed, the lower member appears to rest on interbedded purple sandstones and mudstones of member 2 of the Nyborg Formation. It consists of 10 m of purple tillite with purple shale clasts and crystalline clasts. This is followed by about 3 m of grey-green tillite which shows increasing content of dolomite in clasts and matrix, and of sand grains upwards, as shale clasts die out. This grades up into the middle member of the Mortensnes Tillite.

About 1½ km west of the south end of Masjokjavrek severely cleaved Mortensnes Tillite occurs in the overturned western limb of a major anticline. The lower member consists of about 20 m of purple tillite with purple shale clasts and crystalline clasts. It may be considerably tectonically thinned. It rests on member 2 of the Nyborg Formation and is apparently overlain by the upper member of the tillite. The middle member may have been sheared out by the deformation.

Lismavarre and Varangerfjord

The three localities described here, Lismavarre, Hamarnes and Holmfjellet (fig. 63), represent a stretch of about 50 km of Mortensnes Tillite along the south margin of its outcrop, and at some points adjacent to the crystalline rocks of the shield. The Mortensnes Tillite has been reported a further 35 km to the northwest of Holmfjellet (Siedlecka and Siedlecki, 1968 in Røe, 1970) in outcrops not examined by the author. In the area visited by the author the top of the lower member was not seen; just shales of the lower submember of the Lillevatn Member. Thus, it is not known if the middle or upper members occur here.

At Lismavarre the massive tillite of the lower member rests sharply on undeformed, member 2 interbedded purple sandstones and mudstones of the Nyborg Formation. The 25 m of purple tillite contains abundant purple Nyborg clasts and crystalline clasts, predominantly of grey gneiss, and red granite, both rounded and angular. The matrix is poorly sorted and contains scattered sand and silt grains. A few patches of green tillite occur near the top of the section.

The basal contact and about 20 m of lower member are exposed in road and coastal exposures around Hamarnes. These have been described previously by Reusch (1891), Holtedahl (1918), Rosendahl (1931) and Føyn (1960). The contact is sharp with no obvious cutting down into the underlying member 2 purple sandstones and mudstones of the Nyborg Formation. However, at the west end of the coastal exposure the Nyborg sandstone is brecciated (Pl.92) and blocks of similar sandstone occur in the immediately overlying tillite.

The tillite is almost entirely massive and purple throughout. Green tillite occurs as lenses up to several metres long. No other differences aside from colour were noted between green and purple tillite. Several kilometres east of Hamarnes the upper part of the tillite is often green. A wide variety of crystalline clasts, including grey gneiss, red granite and dark, fine-grained basic rocks are dominant over dolomite clasts. These are up to 1½ m across, the largest seen in the lower member in the study area, (Pl.93), and are both rounded and angular (Pl.94).

At the base of the tillite, Nyborg fragments are extremely abundant, as noted by Rosendahl (1931), but they decrease upwards. In the basal 2 m several beds of Nyborg Formation can be seen, along with layers of brecciated Nyborg sediment. Both beds and layers have been folded (Pl.95, 96, 97), and indicate that movement was directed to 270° and 250°. Nyborg fragments are mostly 1 cm across and are angular. Several striated clasts and one excellent striated and facetted clast composed of altered diorite were found (Pl.98). Reusch (1891) also found striated clasts at this locality. The long axis orientation of 43 clasts shows a preferred NNE-SSW trend (fig. 66a).

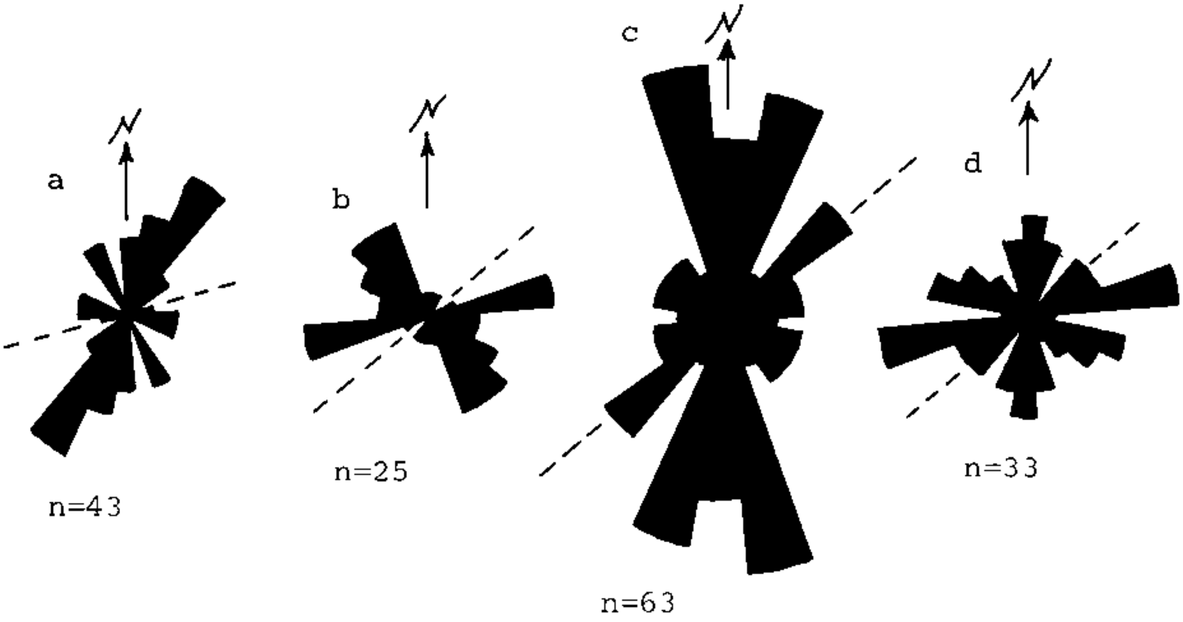


Figure 66. Long-axis orientation of clasts in the Mortensnes Tillite Formation. a) lower member, Hamarnes; b) contact between unit 4 thick middle member and upper member tillites, locality L-24, Digermul Peninsula; c) upper member tillite, locality S-21, Digermul Peninsula; d) conglomerate bed in upper member, S-21. n=number of clasts measured, dashed line is local cleavage orientation.

The matrix of the tillite consists of sand and silt grains scattered in a fine-grained, haematite stained groundmass. One clast of dolomite pebble conglomerate, identical to that observed in the nearby Smalfjord Tillite, was observed (see also Føyn, 1937).

Two stratified lenses within the tillite appear to have formed in place. A tectonically deformed lens near the base massive sandstone at the base passing up gradually into parallel-laminated shale with sandstone laminae. The shale contains outsize clasts up to 15 cm across, and is rich in pyrite. The lens is overlain sharply by tillite. A second lens, 3 m wide and 40 cm high, (Pl.99) is laminated sandstone with a pebble lag at the base. The top interfingers with tillite. It is at least 5 m from the base of the lower member. Two other structures observed here include thinly banded tillite, and a thin, discontinuous layer of crystalline clast-rich tillite, similar to a structure described in the Vestertana area.

At Holmfjellet 30 m of predominantly massive tillite rest on grey-green sandy siltstone of the Upper Siltstone of the Older Sandstone Series (see Chapter 2). The tillite is grey-green and sandy with large-scale spheroidal weathering. Quartz sand grains, many of which are well rounded, compose about 50-60% of the matrix, the rest a fine-grained muddy groundmass. The clasts, which compose about 10% of the tillite are mainly of Upper Siltstone fragments near the base, decreasing upwards as crystalline clasts and scarce dolomite clasts increase in frequency. Several thin, lenticular sandstone beds, deformed and undeformed, are seen. About 10 m from the base is a 20 cm thick bed of crystalline rich tillite which can be traced laterally for about 20 m the width of the exposure. Its matrix differs from that of the normal tillite by being composed of angular sand and silt grains in a fine-grained groundmass. Sand grains make up about 20-30% of the matrix, and plagioclase and microcline are abundant.

Austerelva

Along the west slope of Stuoraskaidde, two small tributaries to the Austerelva provide complete sections though the Mortensnes Tillite. The lower member consists of 30 m of massive grey-green and purple tillite. It rests on what appears ~~to be the lower~~

to be the lower part of member 2 of the Nyborg Formation, intercalated fine sandstones and mudstones, mainly purple, but in part grey-green. The contact between the Nyborg and Mortensnes Tillite Formations is diffuse, the Nyborg is highly deformed, and crystalline clasts appear slowly upwards in the tillite.

The tillite contains a variety of crystalline clasts with a few dolomite clasts. Nyborg clasts (Pl.189a) in general decrease upwards from the base, but large blocks, highly brecciated are present 10 m from the base. Near the base is a layer of clast-rich tillite with angular and subangular crystalline clasts (Pl.100). No sedimentary or deformational structures were observed in the lower member. It grades up into the middle member.

7.2.3 Interpretation

The lower member of the Mortensnes Tillite is interpreted as the ground moraine of a continental ice sheet because:
1) its occurrence over a large area, about 100 x 40 km, with a low-angle wedge-shape is typical of ground moraine deposits of continental areas of low relief, and appears to rule out alluvial fan or slump origins which would be associated with pronounced thinning in one direction.
2) The locally derived sediment, brecciated and comminuted, and intermixed with exotic clasts (transported a minimum of 40 km) suggests the erosion and crushing abilities of grounded ice.
3) The presence of isolated, stratified, and in situ sandstone lenses and beds appears to rule out a subaqueous origin, such as by rafting from icebergs or a floating ice shelf.
4) The scarcity of stratification, and of current-sorted sediments appears to rule out supraglacial deposition.

In addition, a ground moraine origin is entirely consistent with the regional unconformity at the base of the Mortensnes

Tillite, and with the fact that there is no evidence for contemporaneous tectonic activity in the south (see Chapters 2 and 4). A ground moraine origin is a suitable starting point from which to consider the origin of the structures and other features of the lower member.

Basal Contact

The basal contact of the lower member is invariably planar, either parallel, or at a slight angle to the bedding. The presence of Nyborg clasts in the lower member, and the fact that the gravel-filled channels do not scour into the underlying Nyborg sandstones and mudstones suggests that the Nyborg Formation was at least partially consolidated at the time of erosion. The planar aspect of the unconformity is consistent with glacial erosion, whereas fluvial or marine erosion might have formed a more irregular surface, influenced by the contrast in strengths of the materials being eroded. This agrees with observations made on the Smalfjord Tillite around Varangerfjord (Chapter 4).

Composition

Within the lower member there is a vertical change in composition from mainly locally derived material at the base, to increasing amounts of exotic material upwards. In addition, the size of the clasts, both of local and exotic materials decreases upwards, away from the basal contact. The mixing together of local and exotic material suggests that vertical transfer of material took place in the ice sheet prior to deposition. This may have been caused by diffusion (Weertman, 1968), irregular internal flow, or internal thrusting. The absence of any appreciable-sized deposits of uniquely locally derived tillite suggests that movement of debris was mainly forward, parallel to the base of the ice sheet, rather than directed upwards. The mechanism is similar to a conveyor belt, with relatively little exchange between the higher pure part of the ice sheet, and the basal debris-laden zone. In this situation the principal cause of erosion is the continuous supply of fresh ice, and the forward movement of the ice sheet. Extensive mixing would take place in the basal, debris-rich zone of the ice sheet.

Nyborg blocks at the base of the lower member suggest that block freezing (Boulton, 1970a) of material onto the base of the ice sheet was an important mechanism of erosion.

Sedimentary Structures

The very scarcity of stratified deposits in the lower member suggests that there was little free water at the base of the ice sheet during the depositional phase. The amount of melted ice required to produce 2-4 m of till is related to the concentration of debris in the ice. This, of course, could vary immensely, and there is no reason why the low concentrations found in most present-day glaciers should be taken as typical of glacier ice in general. In addition the rate of melting would also help to determine the capacity of the meltwater to form flows capable of producing stratification. Thus, a high initial concentration of debris in the ice, plus low rates of basal melting might form a massive ground moraine.

Most sedimentary structures in the lower member were formed by the channelised flow of water; one, with fine parallel lamination, may have formed by sheet flow. The gravel lag in one channel, and the conglomerate fill in the others indicate the erosive nature of the currents. As the tillite is interpreted as a ground moraine the channels must have been subglacial, formed at the ice-till interface. As none of the channels show glacially induced deformation (one may be tectonically deformed) the subglacial till apparently did not undergo deformation after deposition, but was essentially stable. This is supported especially by the graded sandstone lenses in the Vestertana area. The absence of any parallel-lamination or inverse grading suggests deposition by the fall-out of debris in standing water, rather than by waning currents (see Fisher and Mattinson, 1968). These may represent subglacial channels cut off from a subglacial stream net (Lliboutry, 1968). The dominance of massive tillite with rare current formed channels indicates that free water was confined to channels, rather than flowing freely as a sheet at the base of the ice sheet.

Deformation Structures

Shear banding described from the lower member was clearly formed by the intermixing of local, underlying Nyborg Formation, and exotic crystalline rocks, derived possibly from the shield to the south. Shear bands may have several origins (Chapter 3) but in this case they probably formed in the basal zone of the ice sheet where plastic deformation is particularly intense. Presumably, after sufficient time, the component materials would be homogenised within the ice. Bodies of crystalline-rich tillite may represent primary till, unmixed with Nyborg sediment. The formation of the banding by basal regelation is not consistent with the two-component composition of the banded tillite.

The brecciated appearance of Nyborg fragments within the basal part of the lower member is a clear indication of brittle deformation, which was probably caused by the fact that, at the time of erosion, the Nyborg Formation was more coherent than the surrounding plastic ice, causing the sediment to tear apart, in the same way that boudins may form in certain metamorphic rocks (Rast, 1956). Occasional fold structures attest to non-brittle deformation. It is not known to the author why brecciated material tends to break into certain sizes.

Local imbrication of clasts is also related to a deforming stress field (Chapter 3, Chapter 5, fig. 38), as is a preferred long axis orientation of clasts (Chapter 3).

Upper Contact

The significance of the upper contact, which appears to be gradational, is more appropriately discussed after considering the nature of the middle member. We note here that it was associated with a change in the conditions of deposition, as well as in the composition.

Geometry

The northward thinning of the lower member may reflect either the northward flow of the ice sheet (see below), or a decrease in slope as the ice moved from the basement onto the more easily eroded basinal sediments. The decrease in slope would cause deposition, which would taper off downflow from the change in slope. Subsequent erosion was probably not important as suggested by the upper gradational contact.

Palaeoflow

Structures, tillite composition, and clast size help to determine the direction in which the ancient ice sheet flowed, and where the debris was derived from. Clast imbrication of Nyborg fragments at the very base of the lower member in the Vestertana area show directions of flow to both the east and west. Clast long axis orientation at Hamarnes (fig.66a) indicates north or south flow if the fabric was longitudinal to the ice motion. However, fold axes at the same locality indicate a westward flow, suggesting that the fabric was transverse. One example of cross-stratification shows a current flow to the south.

The composition of the tillite also indicates flow directions. Red granite and gneiss clasts in the lower member, and which are largest at Hamarnes, are very similar to lithologies noted in the basement to the south (Føyn, 1937, pp. 129-130, and personal observations). This suggests at least some northward component to the flow. The distribution of purple and green Nyborg clasts in the lower member and the subjacent Nyborg Formation also indicate a northward component to the flow as purple fragments occur in the lower member north of where purple Nyborg, member 2, is truncated by the unconformity with the tillite.

A decrease in maximum clast size of the red gneiss and granite from Hamarnes to the Vestertana localities also suggests a northward flow.

7.2.4 Conclusions

1) The lower member was deposited by a continental ice sheet.

2) The final moulding of the unconformity was glacial.

3) The tillite is composed of local (Nyborg) and exotic (crystalline and dolomite) components which occur together as a) massive, homogenised tillite, and b) poorly mixed banded tillite.

4) Erosion was, at least in part, by basal freezing.

5) During the depositional phase, little free water was present at any given time, and this flowed in discrete channels.

6) Nyborg clasts formed by brittle deformation of partially lithified Nyborg Formation.

7) The ice sheet had an important component of flow to the north, but deviations to the east and west occurred.

7.3 Middle Member

7.3.1 Introduction

The middle member is the most widespread of the Mortensnes Tillite divisions, being observed at all but the exposures in the southernmost part of the area. The predominance of dolomite and associated chert clasts over crystalline clasts, and the sandy matrix with a dolomite groundmass, distinguishes clearly the middle member from the lower and upper members, and imparts a characteristic buff-brown weathering colour to the middle member. Also, the abundant sedimentary structures contrast with the relatively massive tillite of the other members (fig. 62) (Table 23).

Where the lower member gradually thins to the north, and wedges out west of Alteberget (fig. 63), the middle member comes to rest on the Nyborg Formation and it locally contains large quantities of Nyborg sediment. This sediment imparts a grey-green colour to the tillite, similar in appearance to the lower member just to the south. The distinction between the two members in this area must be based on the relative amounts of dolomite and crystalline clasts.

The thickness of the middle member is a characteristic which divides it into two main divisions, each occurring in different areas (fig. 67). The change in thickness is rapid, and occurs just to the north of Sjursjok. Each division also has distinctive sedimentary structures. The thin middle member, 0-6 m thick occurs in the south, while the thick middle member, 10-30 m thick occurs in the north. To the west, south of Laksefjord, the middle member is distinct from the lower and upper members, as described above, but is also different from the development of the middle member in the Tanafjord area.

Table 23

Characteristics of the Middle Member Tillite, Vestertana.

Colour: buff-grey fresh, weathers buff-brown.
Clasts:
 <u>Concentration:</u> 5-10%
 <u>Composition:</u> >90% dolomite and chert, others include grey granite, gneiss and diorite.
 <u>Average Diameter</u>: about 5-10 cm, grey granite clasts are often >30 cm in diameter.
 <u>Maximum Diameter</u>: dolomite rarely over 30 cm, few grey granite clasts up to 80 cm.
 <u>Shape</u>: mostly equant, tabular, showing signs of rounding; one striated clast of diorite (Pl.115).
Matrix:
 Coarse silt to fine sand, about 40-50% in fine-grained dolomite groundmass. Many sand grains are in contact, sorting is very variable. Sand grains are mainly of monocrystalline quartz, subangular to rounded (Pl.189c).

Thin Middle Member

Thickness: 0-6 m.
Lower Contact: gradational, or sharp on lower member.
Upper Contact: grades up into laminated tillite of middle member, sharp or erosive into upper member tillite.
Structures: stratification is abundant, and often deformed.

Thick Middle Member

Thickness: 10-30 m.
Lower Contact: erodes into member 3, Nyborg Formation, may erode into lower member tillite.
Upper Contact: grades into laminated tillite, or overlain sharply by upper member tillite.
Structures: lenses and beds of sandstone, laminated tillite bodies, deformation is common.

7.3.2 Thin Middle Member

Description

<u>Vestertana</u>

The thin middle member forms an almost continuous blanket of tillite, usually 2-4 m thick, from the southernmost part

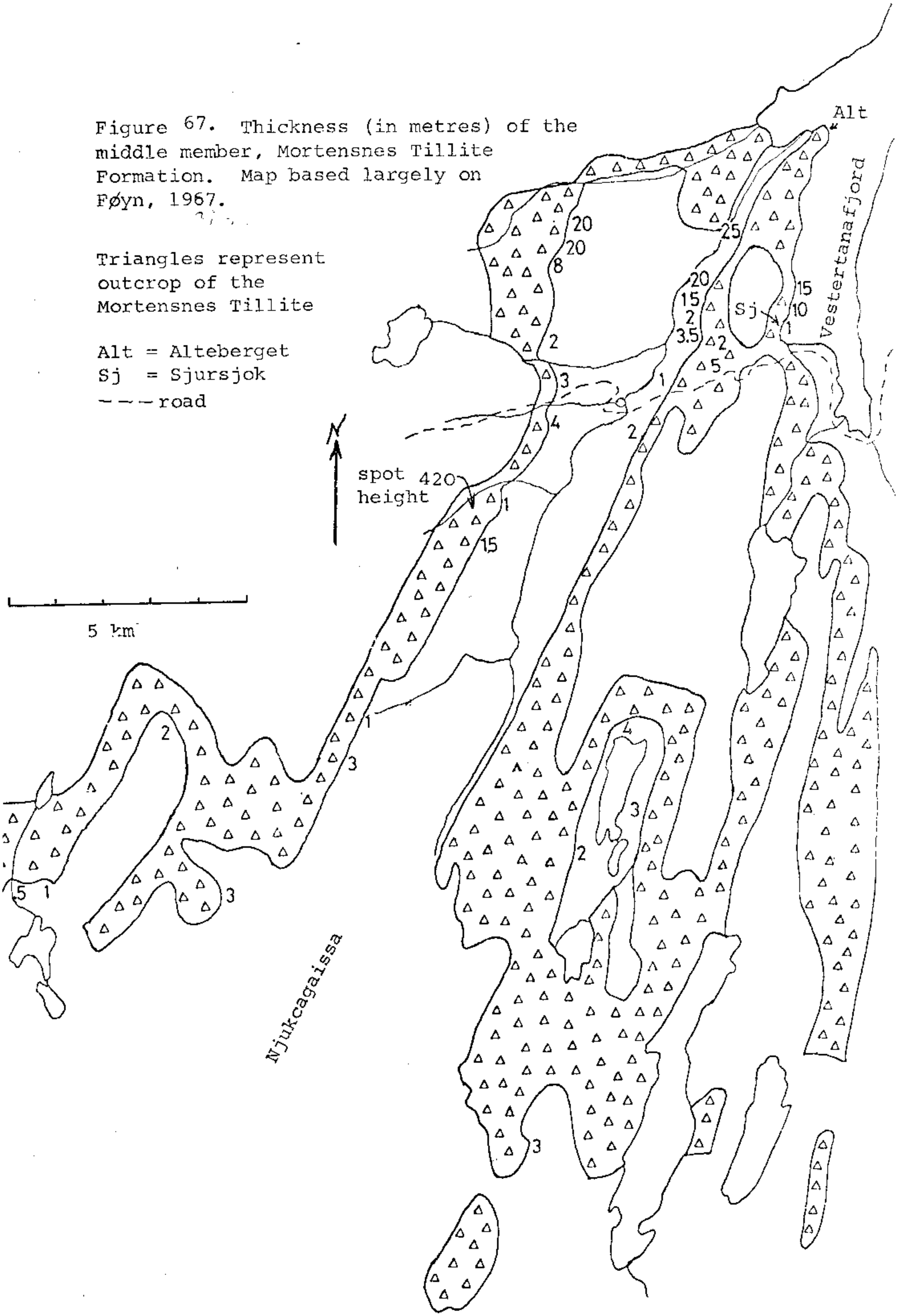


Figure 67. Thickness (in metres) of the middle member, Mortensnes Tillite Formation. Map based largely on Føyn, 1967.

Triangles represent outcrop of the Mortensnes Tillite

Alt = Alteberget
Sj = Sjursjok
- - - road

of the area, to Sjursjok in the north (fig. 67), a distance of about 17 km. The appearance of the lower contact is variable even between nearby exposures; gradational in composition, colour, and the development of lamination is typical, but a sharp contact is occasionally seen. At a few outcrops deformed lamination was observed at the contact (Pl. 101). Lamination may come in before the dolomite, or the reverse may occur. A recurring structure is broad, parallel layering, the alternate layers being grey-green and fine grained, and buff-brown and sandy, and about 1-3 cm thick. The layers pass laterally into massive tillite.

Two other types of tillite, both observed only once, were seen in the thin middle member. One, (Pl.102) is highly dolomitic and has a low sand content. The contact with the normal sandy, dolomitic tillite below is sharp and shows soft-sediment deformation. The tillite below appears to have extended upwards, almost like a diapir into the overlying dolomitic tillite.

The second tillite (Pl.103) is dark grey and is composed of angular crystalline clasts and silt to sand sized grains in a dark, micaceous, low-carbonate groundmass (Pl.189b). The clasts are predominantly gneissic, one clast of coarse-grained marble was seen. Along the contact with the adjacent normal tillite, the two tillites are mixed together into highly deformed, horizontally elongated pods and bands (Pl.103).

Parallel stratification is characteristic. It grades from lamination to bedding as the thickness varies from a few millimetres to several centimetres (Pl.104) and is laterally continuous. Associated rare cross-bedding and ripple cross-lamination demonstrate the current origin of the structures (Pl.105). Rare scours are observed (Pl.106). The outsize clasts are associated with a variety of plomp-and-drape structures. In sandy tillite, lamination is often relatively undeformed around the clasts, (Pl.105, 107), but may be deformed with fine-grained tillite (Pl.108). A distinctive, common clast type is buff-brown tillite, similar to the middle member tillite, but massive. These are mostly smaller than 10 cm, but are up to 5 m long (Pl.105, 109).

Deformation within the thin middle member is common and varied. Most abundant is the folding of the lamination on both a large (Pl.110) and small (Pl.111) scale. The chaotic nature and the extent of the deformation in many cases precluded determining the orientation of the associated stress-field. Deformation occasionally occurs within beds of tillite, imparting a slumped appearance to the beds (Pl.112). Axial planes of folds are not usually horizontal, and may have moderate to steep dips (e.g. Pl.110). Several examples of steeply inclined faults were seen (Pl.113). An unusual type of deformation (Pl.114) is the occurrence of smeared tillite above undeformed stratified tillite, the two separated by a curved, gently inclined surface dipping towards the south. Locally the thin middle member dies out for up to 20-30 m, and the member is often highly deformed adjacent to these localities.

The sandy tillite, where not followed directly by the upper member, grades up into finely parallel-laminated silty mudstone with sandy laminae and beds, and outsize clasts (Pls.116, 117). This lithology is up to 1 m thick, is occasionally folded and sheared (Pl.118), and is overlain sharply by the upper member. If the unit is not present, the sandy tillite is overlain sharply by the upper member, sometimes with deformation (Pl.119).

Just north of Sjursjok, near the contact between the thin and thick middle members, the middle member is locally about ½ m thick, and is highly folded. It also occurs as bands alternating with the darker bands of the lower and upper member tillites (Pl.120).

Maskevarre

At Maskevarre (fig.63) the lower member - thin middle member contact is gradational over about 3 m. Across this contact Nyborg clasts die out, the dolomite clasts become more numerous, and the colour changes from grey-green to brown, reflecting increasing amounts of dolomite in the matrix.

Overlying the massive, dolomitic, sandy tillite is 4 m of laminated, brown-weathering tillite consisting of parallel, graded units with outsize clasts (Pl.121). The units average 3-4 mm thick, are faintly and finely parallel-laminated, and the grading is of the continuous, poorly-sorted, symmict variety (Sauramo, 1923). The top of the member is not exposed.

7.3.3 Interpretation

The thin middle member shows an influx of new exotic material, dolomite and sand, as opposed to the crystalline rocks of the lower member. There is a coeval change in environment as shown by:

1) deposition of the thin middle member, primarily by currents, over an area of about 25 x 40 km.

2) presence of outsized clasts in laminated sandy tillite and laminated silty tillite, which occasionally deform and tear the underlying lamination, but are covered by a draping lamination.

These features, and the widespread, continuous nature of the lamination in the sandy tillite rule out a ground moraine origin, while the presence of dropped in clasts rules out a supraglacial origin. A subaqueous origin for the thin submember is very probable, and below, the features of the member are interpreted on this basis.

Lower Contact

The appearance of dolomite before stratification, and stratification before dolomite (also in the top of the lower member) at some localities indicates that the incoming of exotic material and the change in environment did not occur exactly at the same time everywhere. The interlayering of green and brown tillite at the base of the middle member may be banding structure developed where the mixing of lower and middle member tills occurred while still in a subglacial environment. The change from ground moraine to subaqueous conditions suggests that the contact represents the lifting up of an ice sheet to form an ice shelf, or the retreat of the ice sheet from a large body of water, with iceberg rafting of outsize clasts.

Sedimentary Structures

The relatively poor sorting and stratification of the sandy tillite of the thin middle member suggests that current activity was important but not strong or continuous enough to sort the sediment, which settled through water, after having been released by melting ice above. The stratification may have formed by fluctuations in current strength, which imparted a different degree of sorting to the adjacent laminae. Rare cross-stratification and well-sorted sandstone are supporting comparisons, having formed by stronger, and more continuous currents.

The sandy stratified tillite has no similar counterpart either in the lower or upper members of the Mortensnes Tillite, or in the Smalfjord Tillite.

The laminated siltstone at the top of the thin middle member, similar to siltstones in the Smalfjord Tillite, is very fine-grained and contains small outsize clasts. It marks a decrease in current activity, and perhaps less intensive rafting.

The symmict varved siltstone at Maskevarre suggests deposition in saline, probably marine conditions.

Deformation Structures

Deformation structures are largely restricted to beds or zones within the middle member; only when the middle member is temporarily missing is the deformation pervasive. While the deformation which occurs within discrete beds is apparently due to slumping, most of the deformation affects only a certain area, it dies away laterally. In addition, the form of most of the folds is not reminiscent of folds formed by overriding. Directions of an overriding stress could not be obtained from many folds observed. An alternative mechanism, capable of producing local, irregular deformation in a subaqueous environment, is the grounding of icebergs, or of an ice shelf.

Pervasive deformation of the thin middle member, and deformation along the upper part of the member, particularly tight, sheared-out folds in the laminated siltstone were likely to have occurred after deposition of the middle member, possibly related to the genesis of the upper member.

Composition

The dolomite and sand component in the thin middle member indicate a change in source area, or a change to a more erosive regime in those parts of the ice sheet which rested on the Porsanger Dolomite and Older Sandstone Series. The presence of large granite, or quartz diorite boulders in the middle member, but not in the lower member suggests a major change in the source of the ice.

Upper Contact

The upper contact appears undeformed and gradational at many exposures. However, the occasional deformation structures, and the local absence of the upper siltstone, or even the entire middle member suggests that the contact is erosive. This is further considered in relation to the upper member.

7.3.4 Conclusions: Thin Middle Member

1) The thin middle member was deposited in a subaqueous environment with rafting of much of the sediment from icebergs, or an ice shelf.

2) The compositional change from the lower member to the middle member probably represents a major change in the source area of the ice.

3) The change from subglacial deposition in the lower member to subaqueous deposition in the thin middle member is a glacial retreat sequence similar in some respects to those described from the Smalfjord Tillite Formation.

7.3.5 Thick Middle Member, Description

Vestertana

The thick middle member which develops north of Sjursjok (figs. 63, 67) has an average thickness of about 25 m, and is the same composition as the thin middle member (Table 23). In inland exposures the bulk of the tillite appears massive (though discrete structures are quite common), but west of Alteberget (fig. 67) in the only coastal exposure, the tillite contains irregular, discontinuous patches of a lighter tillite in a darker one (Pl.122) similar to ghost structure (Chapter 3).

A variety of distinctive clasts are found in this member. Near Alteberget is a 10 x 3 m block of well-bedded, undeformed dolomite (Pl.123), which is slightly sandy, and laminated internally. Contacts with the surrounding tillite are sharp, and the bedding of the block dips about 30° to the bedding in the tillite. Very common are widely scattered dolomite breccia bodies, mostly up to 1 m long, and generally tabular, but occasionally equant (Pl.124) in shape. These consist of mainly angular dolomite and chert clasts, with some sandy patches in a dolomite matrix. These bodies of breccia usually have sharp contacts with the surrounding tillite.

Sedimentary structures occur as bodies and channels up to 7 m long of moderately sorted, medium grained white sandstone lacking conglomerate. Only rarely is a well developed channel shape observed (Pl.125). Usually the bodies are oval or elongate and have sharp contacts with the surrounding tillite. The sandstone is frequently laminated or bedded, and sometimes is massive. At one locality south of Alteberget four well-bedded sandstone bodies, each roughly 2 x 1 m were observed in a row (Pls. 126, 127).

Many sandstone and other bodies show soft-sediment deformation either at the margins, (Pl.128) or of the entire body (Pl.129). Lenses of laminated tillite that occur in the member are frequently deformed into chaotic folds (Pl.130, 131). One unusually large block 6 m long, of stratified dolomitic tillite is sharply over-folded at its southern margin (Pl.132). This tight fold has apparently developed an axial plane cleavage (Pl.133).

The upper contact of the member is sharp, or is a rapid transition from brown, sandy dolomitic tillite to grey tillite of the upper member. No distinctive features were observed at this contact.

Digermul Peninsula

The middle member of the Mortensnes Tillite on the Digermul Peninsula has been subdivided into informal units defined on the basis of composition, structure and stratigraphic position, and not intended for correlation with other areas. A summary of the units is outlined diagrammatically in figure 68.

Unit 1

Unit 1 forms a nearly continuous blanket of tillite over the unconformity (fig. 68). The tillite is purple and grey-green, unstratified, and contains less than 5% clasts mostly

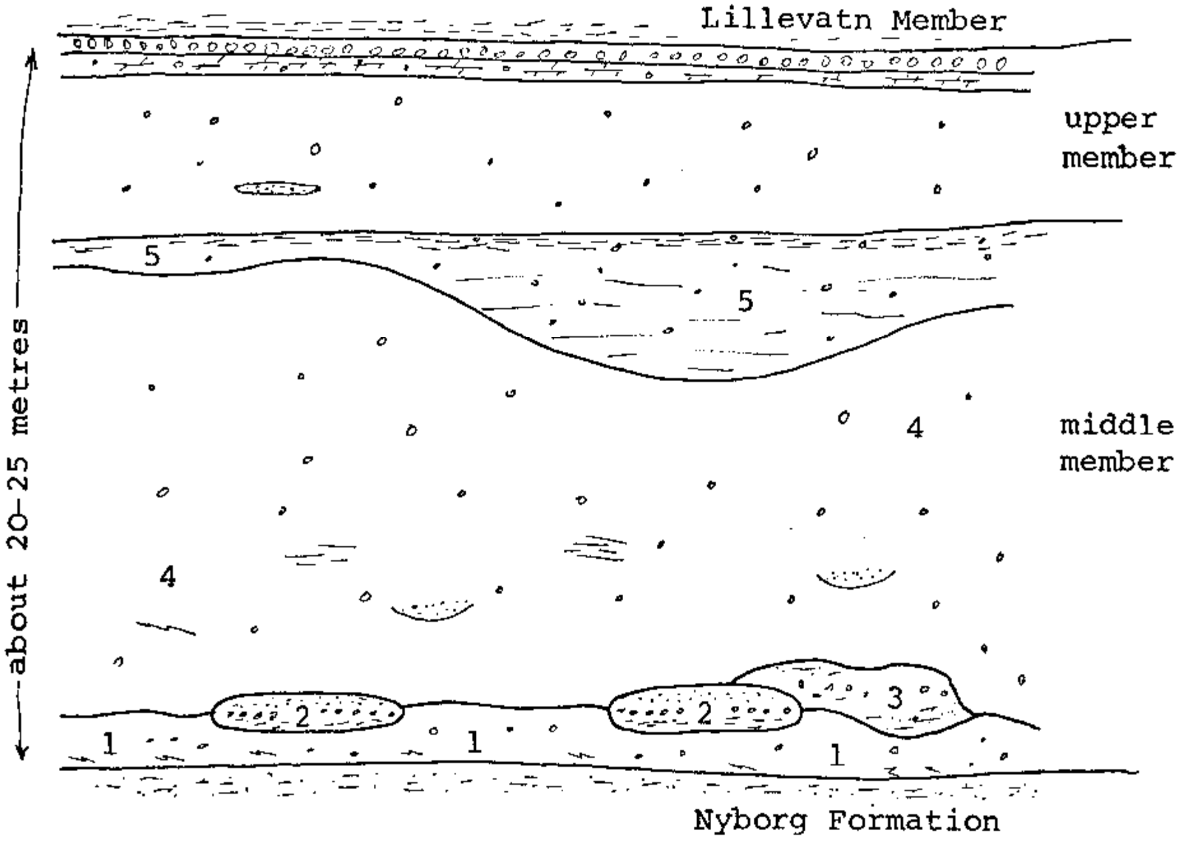


Figure 68. Diagrammatic sketch of relationships between the units in the thick middle member, Mortensnes Tillite, Digermul Peninsula.

of fine-grained sandstone, siltstone and mudstone; dolomite and crystalline clasts are scarce. The matrix consists of poorly to well-mixed sand, silt and clay grade material. Sedimentary clasts up to 6 m long at locality L-24 (fig. 69) have been derived locally from recognizable lithologies in member 4 of the underlying Nyborg Formation (fig. 70). Some clasts have undergone considerable deformation; brecciation the most often (Pls. 134, 135) but also folding and faulting (Pls. 136, 137, 138, 140). Imbricated clasts were observed once (Pl.139). Loaded bedding (Pl.141) occurs just beneath unit 1 at locality S-17 (fig. 69), but this is best considered as part of the Nyborg Formation.

Only one structure was observed in the Nyborg Formation which may have formed in relation to the overlying tillite. This is a low angle thrust fault which dips to the northeast,

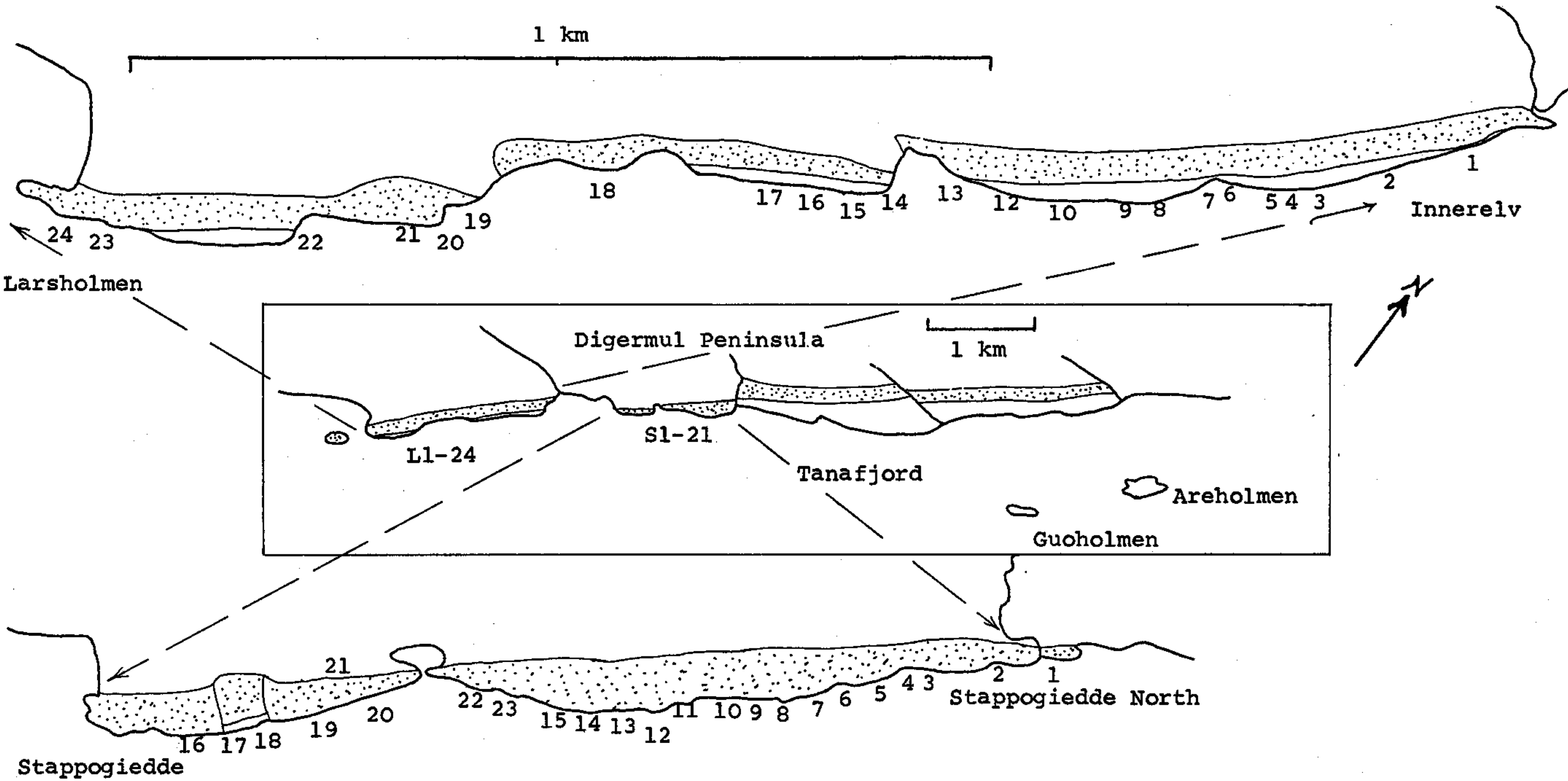


Figure. 69. Localities in the Mortensnes Tillite (dotted) along the southeast coast of the Digermul Peninsula.

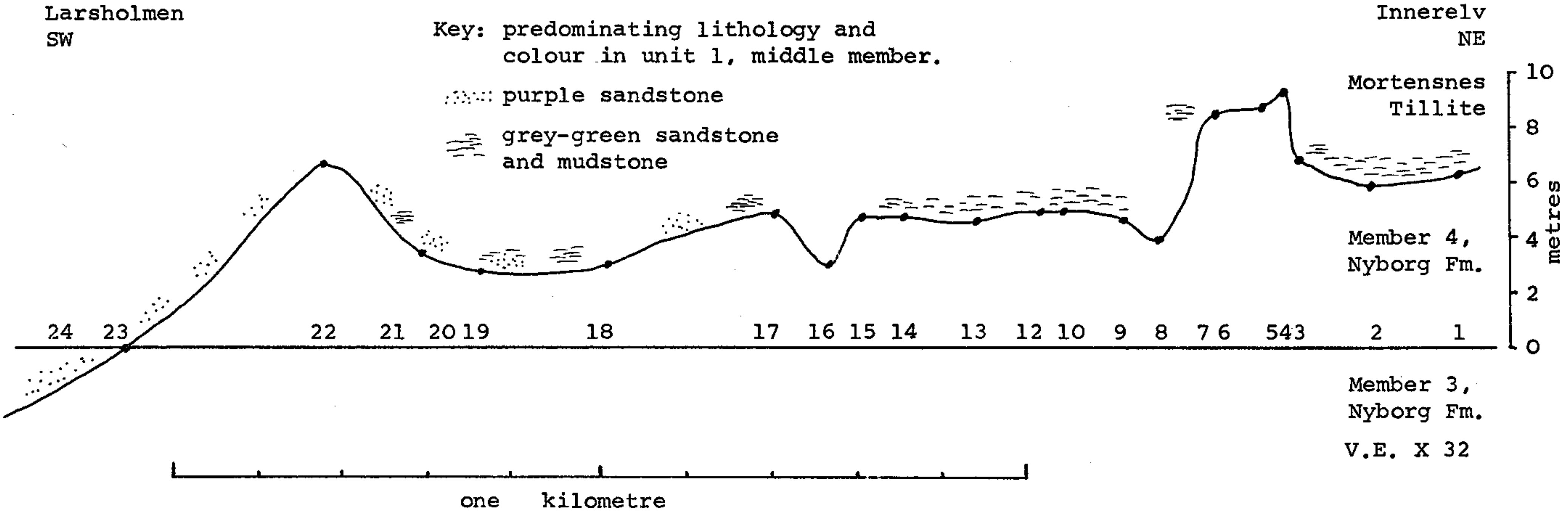


Figure 70. Sketch of Nyborg Formation - Mortensnes Tillite unconformity, Larsholmen to Innerelv, Digermul Peninsula, showing colour and lithology of Nyborg-derived sediment predominant in unit 1 of the middle member.

seen about 2 m below the unconformity.

Unit 2

Unit 2 comprises large, horizontal tabular blocks near the base of the middle member, many of which include three lithologies: Nyborg sediment, tillite, and white sandstone, usually seen in that sequence from the base up (Pl.142). In some instances only one or two of the lithologies are present. The distribution of the three lithologies in the middle member as seen, particularly between Larsholmen and Innerelv, demonstrates that they are related to each other (fig. 71). The blocks may appear to die out laterally into tillite, or may end abruptly against tillite (Pl.143).

Nyborg Sediment

Nyborg sediment in the lower part of the blocks of unit 2 consists of up to 6 m of intercalated thin to medium bedded grey-green fine sandstone and mudstone. Sandstone lenses in mudstones are loaded, and the medium sandstones show ball-and-pillow structure. The two possible sources of this sediment are member 3 and member 4 of the Nyborg Formation. The association of rippled sandstone, soft-sediment deformation, and mudstone interbeds and partings is very similar to an horizon in the upper part of member 4 between Guaholmen and Areholmen.

Unit 2 blocks rest sharply or gradationally on unit 1 tillite which locally approaches in composition a breccia of Nyborg sediment. Rarely, a breccia, or tillite of Nyborg sediment occurs at the top of the Nyborg sediment in unit 2 (Pl.144).

Tillite

Sandy brown tillite, 20 cm to 2 m thick usually rests

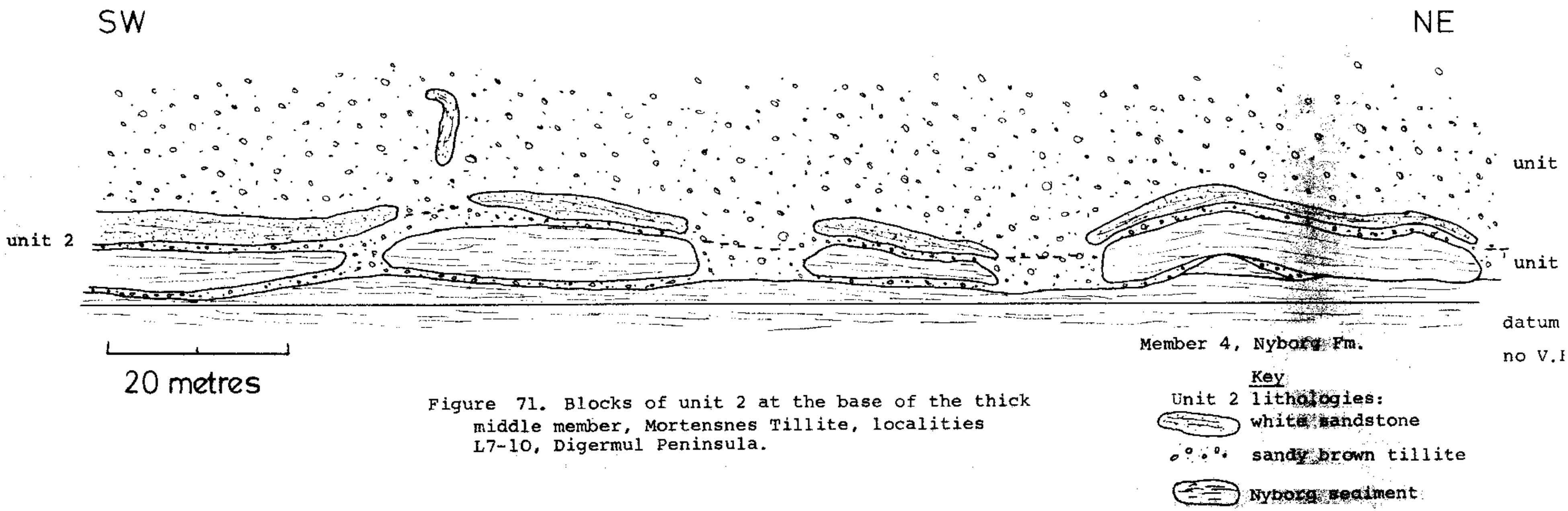


Figure 71. Blocks of unit 2 at the base of the thick middle member, Mortensnes Tillite, localities L7-10, Digermul Peninsula.

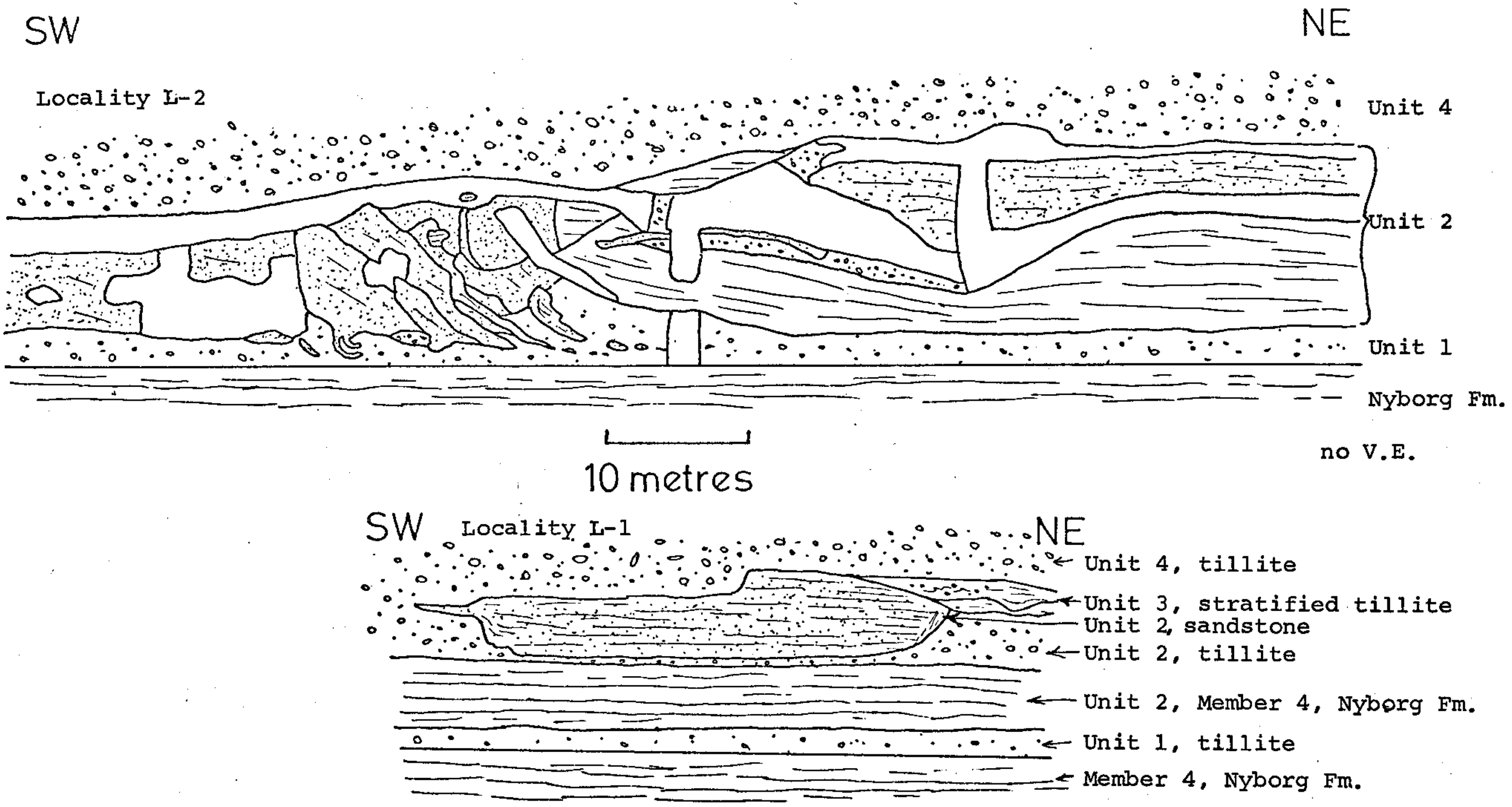


Figure 72. Units 1-4, middle member, Mortensnes Tillite, Digermul Peninsula

sharply upon Nyborg sediment (Pl.145), or upon a Nyborg breccia (Pl.144), and is overlain by white sandstone. Clasts, mostly of dolomite make up about 5% of the tillite. The matrix is mostly poorly sorted sand with a dolomite groundmass. Except for a few sandstone lenses, the tillite is massive. Nyborg sediment was never observed in this tillite.

White Sandstone

White sandstone, medium grained and moderately sorted, occurs as lenses and sheets up to 4 m thick usually eroding into the underlying tillite of unit 2. It also occurs as isolated blocks, often highly deformed, scattered about in various orientations in unit 4 (fig. 71). The sandstone in unit 2 scours up to 2 m into the tillite, sometimes in steep-sided channels (fig. 72) (Pl.147). The sandstone is generally thin bedded, and has a faint parallel lamination. On one surface, flat sinuous, symmetrical ripple marks were observed. One unusual channel has a convex downwards base and is filled by curved drapes of laminated sandstone (Pl.146). The sandstone is overlain sharply or erosively by units 3 and 4.

Developing south of unit 2 near Innerelv (fig. 73) are several unique lithologies. These include a lag conglomerate and sandstone (Pl.148), a slumped sandy tillite bed, and a slightly deformed parallel-laminated fine sandstone with a few outsize pebbles (Pl.149).

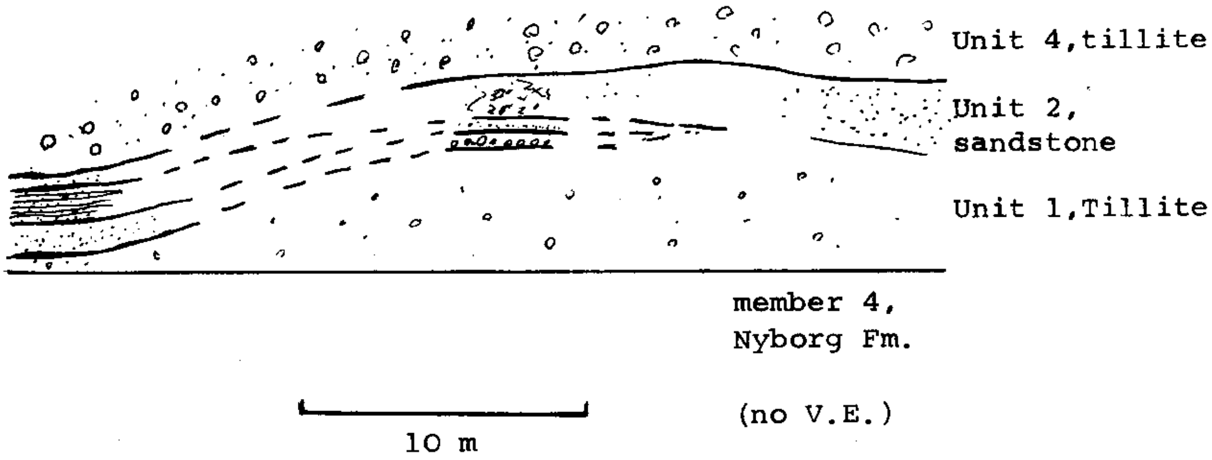


Figure 73. Lithologies developed south of locality L-2, laterally from unit 2, middle member, Mortensnes Tillite, Digermul Peninsula. (see text)

Unit 3

Unit 3 includes stratified, dolomitic tillite and sandstone observed at two localities between Stappogiedde and Stappogiedde North (fig. 69) and possibly south of Innerelv. The tillite contains about 10-30% clasts, almost entirely of dolomite and chert, set in a fine grained dolomitic groundmass with scattered sand grains. The unit rests on units 1 and 2, and is invariably overlain by unit 4 (fig. 68).

At locality S-17 (fig. 74) up to 2 m of bedded tillite rests on unit 2 grey-green Nyborg sediment which is highly sheared in places. The tillite consists of alternating sandy tillite and poorly sorted conglomerate with small, angular dolomite clasts; some beds contain shale flakes. Tillite between the two prominent clasts of Nyborg sediment (unit 2) is faintly laminated, and appears to have been weathered shortly after deposition. At locality S-16 (fig. 75), unit 3 rests on Nyborg rich tillite of unit 1, which also contains sandy layers and many sandstone fragments towards the top, and a tight isoclinal fold with a horizontal axial plane, and closure to the north. Below this tillite is about 1 m of grey-green fine sandstones and shales, similar to those observed in unit 2. These sandstones are also part of unit 2 as the autochthonous Nyborg Formation is predominantly purple sandstone here. The base of the sandstone is below low sea-level.

Unit 3 includes here a basal stratified channel fill, massive tillite, and stratified sandstone at the top (fig. 75). The channel cuts about 2 m into the Nyborg Tillite (Pl.150); its fill is mainly sandstone in graded units with some pebbly bases and layers. The units erode into each other, die out laterally and drape up onto the margin of the channel (Pl.150). Some are inversely graded at the base, and some parallel-laminated in the upper, finer part (Pl.151). Pebbles are mostly less than 1-2 cm in diameter, but outsize clasts up to 20 cm across occur (Pl.152). At the southwest end of the base

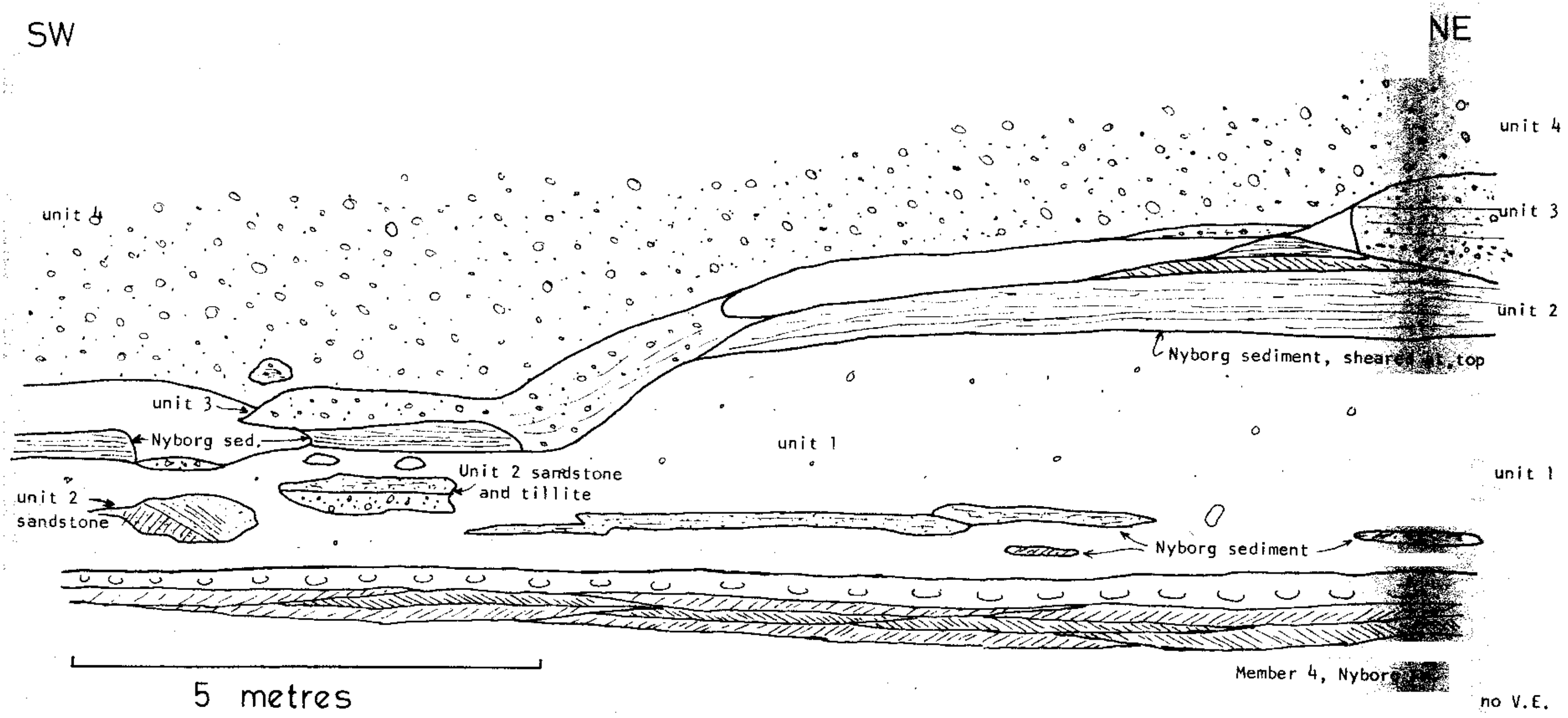


Figure 74. Units 1-4, thick middle member, Mortensnes Tillite, locality S-17, Digermul Peninsula. (Description of units in text).

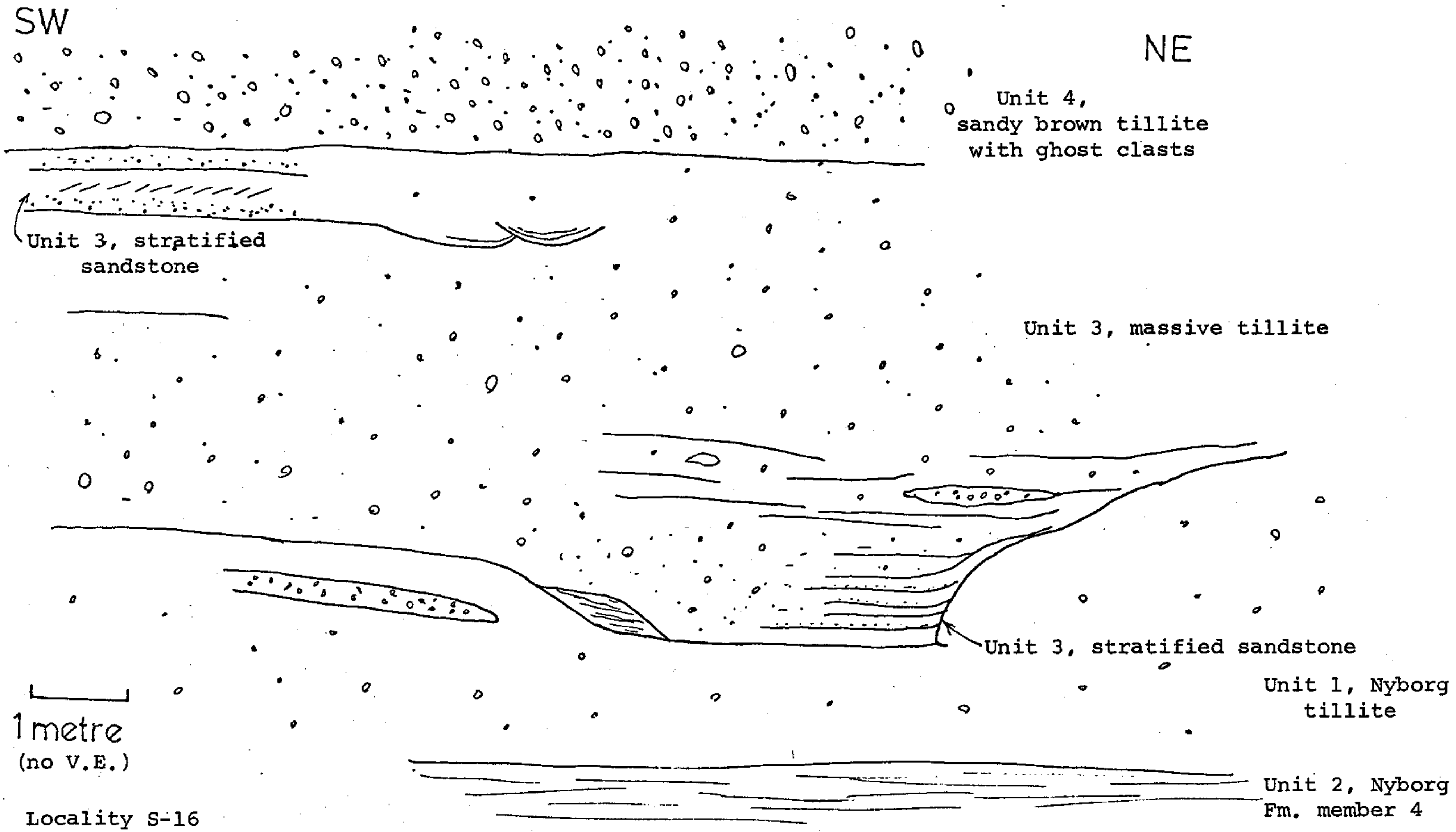


Figure 75. Units 1-4, thick middle member, Mortensnes Tillite, Digermul Peninsula.

of the channel, the laminae have apparently been deformed by slumping. Near the top of the fill is a layer of clast-rich tillite composed almost entirely of dolomite clasts. The laminated channel fill grades up into 3-4 m of massive tillite which contains 20-25% clasts, mostly of dolomite. The tillite thins to the southwest. Above the tillite are small scours and a few graded pebbly sandstones which pass laterally into laminated sandstones with occasional outsize clasts (Pl.153). Some of the laminae are graded from medium and coarse sand up into fine sand and silt. These laminae have been intensely cut by small-scale normal faults which are apparently of glacial tectonic origin (Pls. 153, 154) and indicate shear to the south (fig. 38). At the top of the fault zone the sandstone is brecciated and contains overthrust structures. Sharply above is unit 4 tillite.

Just south of Innerelv at locality L-1, above white sandstone at the top of a unit 2 block, and overlain by unit 4 tillite is almost 1 m of massive and stratified tillite, and pebbly sandstone with channels and deformation structures (Pl.155). The clasts are mainly dolomite. The sediment is tentatively assigned to unit 3.

Unit 4

Unit 4 is distinguished by its sandy matrix, the predominance of dolomite clasts, and the abundance of sedimentary and deformational structures, particularly ghost structure (Pl.156) (see Chapter 3). The thickness varies from 8-20 m, generally thinning towards the northeast. North of Stappogiedde North units 2 and 3 were not observed; the lower 1-2 m of unit 4 often contains Nyborg sediment and rests directly on the Nyborg Formation. Concomitant with the upward dying out of Nyborg sediment is a change in colour from greenish-grey to buff-brown. Between Innerelv and Larsholmen, where unit 1 is developed, unit 4 grades up from unit 1, or rests sharply, or erosively on unit 2. Between Stappogiedde and Stappogiedde North, unit 4 rests erosively on units 2 and 3 (figs. 68, 69). Unit 4 is overlain by units 5 and 6.

Subordinate to chert are a variety of crystalline clasts which account for about 15% of the clasts. Most clasts are smaller than about 10 cm, but the largest clast observed was about 1 m across, and consisted of grey granite. Clasts are rounded to sub-angular, no striated clasts were observed; flat surfaces on crystalline clasts may represent joints as well as glacially formed facets.

The matrix of unit 4 is dominantly very fine to very coarse sand in a fine-grained dolomite groundmass. The sand is composed largely of monocrystalline un- or slightly strained quartz with some polycrystalline and highly strained quartz; plagioclase and micrcline are subordinate. The grains are angular to well-rounded and are corroded by the dolomite groundmass.

The wide variety of sedimentary structures in unit 4 are classified into three groups: ghost structure, stratified till and channels. Ghost clasts, mostly 5-10 cm long, are aligned parallel to the regional bedding, have weathered a lighter colour than the surrounding tillite and occur throughout unit 4 (Pl.156). Most are rounded and massive, some are angular, and a few are laminated. They are occasionally deformed. Stratified tillite occurs as wisps, lenses, and lenticular beds particularly near the base of unit 4. They are better sorted than the surrounding tillite, but have pebbles scattered through them (Pl. 157). Stratified tillite can usually be traced several metres; beds are generally thinner than about 30 cm. Though most units have gradational margins, a few lenses of stratified tillite have sharp margins. Channels filled mostly with parallel-laminated or massive sandstone, sometimes with tillite, occur in the basal part of unit 4. Most channels are 1-2 m high, and up to about 10 m long. One channel at station S-16 is filled with alternating layers of sandstone and tillite (Pl.158). Other channels are filled with laminated, poorly sorted sandstone (Pls. 159, 160). Conglomerate was never observed in the channels. A large massive sandstone body north of Stappogiedde North appears to have formed in place, within a channel (Pl.161). Some of the sandstone fills are quite similar in appearance to the white sandstone of unit 2. Most channels are orientated within 45° of north (fig. 76a).

Deformed sedimentary structures and clasts are common in unit 4. Folded lamination with overfolding to the south is abundant (fig. 76b) (Pl.162). At one locality ghost clasts are cut by southward dipping faults (Pl.163). The deformation of sandstone laminae in one case formed a boudinage-like structure (Pl.164). Deformed clasts of unit 2 sandstone occur in the basal part of unit 4 south of Stappogiedde North (Pl.165). A large dolomite and chert block is internally brecciated and intermixed with tillite, and is deformed into a large overfold, the axis orientated at 175°-355°, and the apparent direction of stress to 85° (Pls. 166, 167). Several blocks of brecciated sandstone and of dolomite occur between Stappogiedde and Stappogiedde North. These are up to about 3 x 2 m, and contain either lithology as both clasts and matrix. At localities S-3 and S-6 layers of sheared green Nyborg sediment occur at least 5 m from the base of unit 4, these can be traced for about 4 m, and are up to 40 cm thick. A particularly interesting case is the development of mullion structure at locality L-13 (fig. 76b). The sandstone splits along parallel columns of sandstone which are partially circular in cross-section, and which show striations and grooves lengthwise (Pls. 168, 169). Similar structures have been described from Moinian rocks where they were considered to be accommodation structures in the cores of folds (Wilson, 1953). They were found to be orientated parallel to the regional fold axes, and perpendicular to the transport direction.

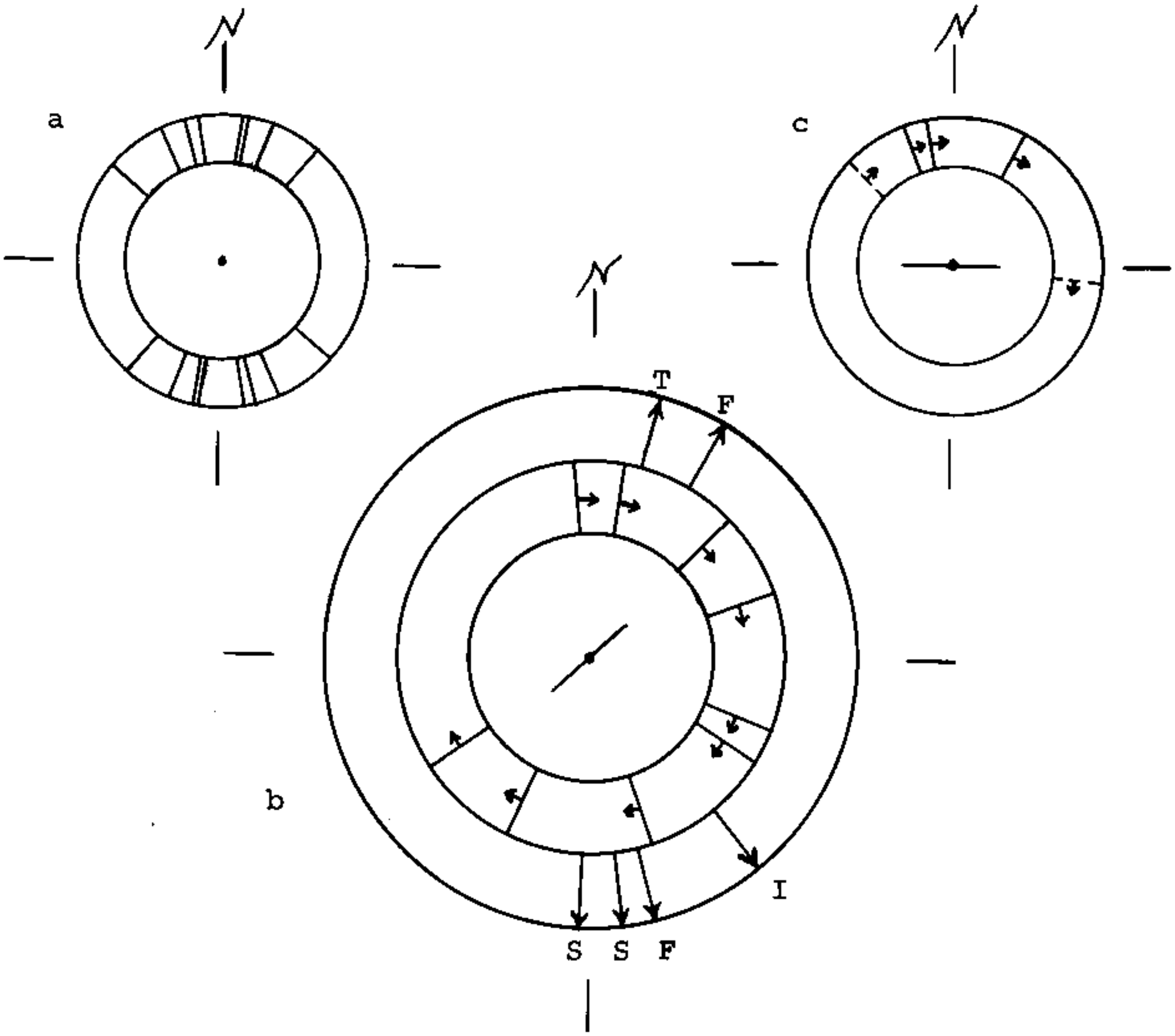


Figure 76. Directional structures in the thick middle member, Mortensnes Tillite, Digermul Peninsula.
a) channel axis orientation, unit 4; b) deformational structures in and at the base of unit 4, centre:mullion structure, inner circle: fold axis orientation with direction of overturning, outer circle: direction of stress for: normal fault system (F), thrust (T), shear planes (S), and pebble imbrication (I); c) overfolds in unit 5, solid line: bedded tillite, dashed line: laminated tillite, centre: grooves

(NB structures whose orientation could not be accurately determined are not included in this figure).

Several deformation structures occur just below unit 4 in unit 1, but they are relevant to an understanding of unit 4. These include faulted and folded blocks of ?Nyborg sediment near Larsholmen (Pls. 170, 171).

Unit 5

Unit 5, the top unit in the middle member consists of two lithologies: in the lower part bedded and thinly parallel-layered tillite (Pl.172), and in the upper part laminated tillite. Both are similar in composition and colour to unit 4 and are only locally developed between the continuous unit 4 and the upper member.

Unit 5 was observed near Innerelv (locality L-2) where it is up to 2 m thick, and 1 km north of Stappogiedde North where about 1 m is present. It is up to 6 m thick between Stappogiedde and Stappogiedde North. The laminated tillite is up to 2 m thick, rarely more than 1m; the bedded and banded tillite of the lower part is prominent where unit 5 is thickest.

The base of unit 5 is often a bedding plane, in one case, at locality S-22, bearing striations and grooves orientated east-west (fig. 76c) (Pl.173). Occasionally the contact is diffuse and irregular with intermixing of massive and banded tillite. Beds in unit 5, mostly 25-100 cm thick, are lenticular and often deformed. They may be traced for several metres, after which they die out, amalgamate, or terminate with a deformed margin against massive tillite. At locality L-22 where unit 5 thins rapidly to the south, beds wedge out against the top of unit 4, and thin gravel layers are developed. Most beds show thin, often deformed layering (fig. 77) (Pls. 174, 175), which consists of alternating brown and grey layering. The brown layers are sandy and may resemble sedimentary laminae and lenses (Pl.174). Deformation generally involves large areas of layered tillite, not just two or three bands; it is typically chaotic, and involves bedding planes as well.

Fold orientations are variable (fig. 76c).

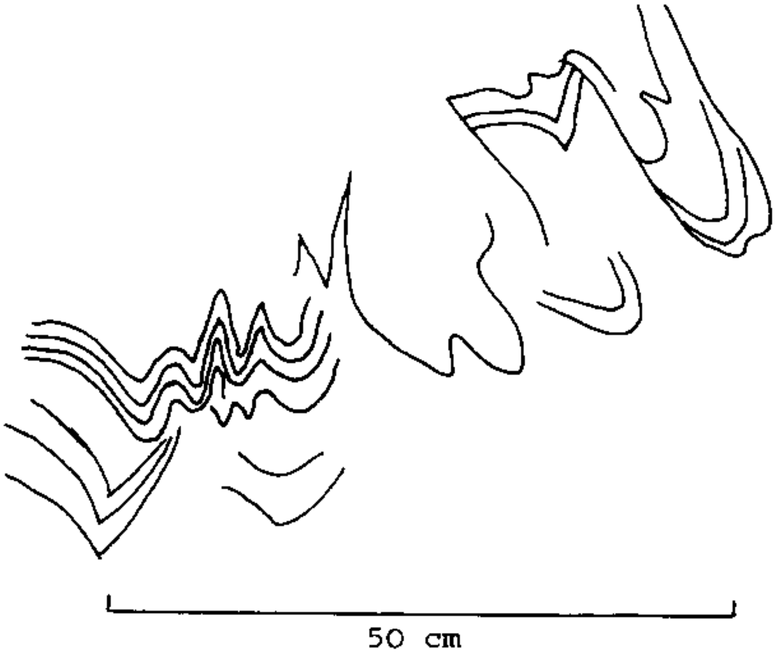


Figure 77. Deformed layering, unit 5, middle member, Mortensnes Tillite, Digermul Peninsula.

Four types of material occur as blocks in unit 5. Banded tillite blocks, often highly deformed (Pl.176) and similar in appearance to banded unit 5, are the most common. Blocks of dolomite fragments, similar to those in unit 4 are usually under 1 m in length. A third type of block contains grey-green sandstone and shale fragments in a fine-grained matrix; these appear to be Nyborg sediment. Several blocks consist of dark grey tillite with mainly crystalline clasts, and little dolomite in both clasts and matrix. A finely laminated phyllite is the most common clast type. The matrix is fine grained with scattered sand grains. The margins of these blocks are either sharp and regular, or somewhat diffuse, and swirled with the surrounding banded, sandy, dolomitic tillite.

A unique occurrence of sandstone dykes and wedges is found at locality S-5. The dykes and wedges extend downwards from a lenticular bed of gravel and sandstone (Pl.127), up to about 30 cm thick and 12 m long, and about 2 m above the base of unit 5. The sandstone bed has a concave shape which imparts the appearance of a channel. The 2 m of tillite above this bed contain blocks of poorly sorted sandstone, gravelly sandstone, similar to that found in the bed below and of unit 5 massive tillite. A thinner bed of gravel about 15 cm below the first forms the lower termination of some of the dykes. The dykes are both straight and sinuous (Pls. 178, 179), are up to about 40 cm long and 5 cm wide, and are composed of sandstone similar to that found in the overlying bed.

Laminated tillite locally occurs at the top of unit 5, gradationally overlying the bedded tillite. The lamination is composed of alternating sandy and muddy layers up to several millimetres thick; grading is rare. Clasts scattered in this matrix are mostly a few centimetres in diameter and consist mainly of dolomite clasts with subordinate crystallines, and clasts of massive, brown, sandy dolomitic tillite. The sediment is locally deformed into tight folds with subhorizontal axial planes; axes strike to 120° and 85° (fig. 76c), the direction of stress in one case to the northeast, in the other to the south. The unit is overlain sharply by unit 6 of the upper member.

Lavvonjargga

The thick middle member, about 7 m thick, composes most of the Mortensnes Tillite at Lavvonjargga (fig. 63). It rests erosively on member 3 parallel-laminated grey-green siltstones of the Nyborg Formation. Nyborg derived sediment imparts a grey-green colour to the lowest 2-3 m of the tillite, but this grades up into the normal buff-grey tillite with mainly dolomite clasts in a sandy, dolomitic matrix. A variety of crystalline clasts are present, including a 70 cm grey-white gneiss boulder at the base. Ghost clasts were not observed, but irregular, discontinuous stratification, largely as sandstone lenses, occurs throughout the tillite. The brown, sandy tillite grades up into 3 m of parallel-laminated grey tillite. At the contact, brown and grey laminae, thinner than 1 cm, alternate, and are folded into tight horizontal isoclines with sharp crests. The laminated, grey tillite is overlain (contact not exposed) by the dolomite tillite bed of the upper member.

Trollfjord

At Trollfjord (fig. 63), the northernmost locality studied, the Mortensnes Tillite is represented by about 7 m of the thick middle member, overlain by the thin conglomerate bed of the upper member. The tillite overlies member 5 of the Nyborg Formation, quartz sandstone with subsidiary shale and dolomite. The basal 35 cm of the tillite is largely a breccia of member 5. The tillite consists of predominantly dolomite clasts with minor sandstone and crystalline clasts in a sandy, dolomitic matrix. The upper 3 m of the tillite has highly deformed fine layering (Pl.180). The tillite, at one locality, grades up into approximately 30 cm of parallel-laminated siltstone with symmetrically rippled lenses and outsize clasts (Pl.181). This is overlain sharply by the conglomerate bed. At a nearby locality, a 6 x 1 m block of dolomite-rich tillite, with little sand is between the normal tillite and the conglomerate (Pl.182).

7.3.6 Interpretation: Thick Middle Member

Environmental Setting

The exposure of the thick middle member along the Digermul coast will be the focus of attention as it is apparently more complete than any other. The member at Vestertana appears to be equivalent to only unit 4 of the Digermul section, while at Lavvonjargga and Trollfjord the member is equivalent to unit 4 and the upper part of unit 5.

The thick middle member is probably a ground moraine, as suggested by:

1) the abundant lenticular stratification, and the absence of continuous lamination or bedding which rules out a subaqueous origin, and

2) the widespread deformation along the lower contact and internally which suggests overriding by an ice sheet, and rules out a supraglacial origin.

This will form the basis of the interpretation for most of the thick middle member.

Genesis of the Units

The units are interpreted below in their stratigraphic order although the sequence of events may not have been strictly in this order (see Discussion).

Unit 1

The abundance of brecciated Nyborg material in unit 1 and numerous deformation structures indicates that this is for the most part a locally derived ground moraine. Pebble imbrication and associated folds indicate that the overriding ice sheet moved to the south. A similar direction is shown by other folds and faults along the unconformity. The absence of stratification suggests that little free water was present during deposition.

Unit 2

The generally undeformed condition of the Nyborg sediment at the base of unit 2 blocks suggests that it was frozen onto the base of the ice sheet and emplaced on top of unit 1 without being incorporated into the body of the ice sheet.

The tillite in unit 2 lacks Nyborg sediment. If it is a ground moraine, then this might have been due to the shearing action having been below the Nyborg sediment in unit 2, rather than at the ice-substrate contact. In this way Nyborg sediment would not have been incorporated into the ice sheet. The breccia at the upper contact of the Nyborg in unit 2 may have thus formed when the Nyborg was emplaced, and differential movement occurred between the Nyborg and the debris laden ice sheet above.

Alternatively, the tillite could be considered a supraglacial flow till. However, the scarcity of stratification, and absence of bedding internally render this unlikely.

The sandstone in unit 2 was formed by erosion of channels into the tillite and subsequent filling by aqueous currents. It is uncertain whether the sandstone represents sub- or supraglacial activity.

The association of the three lithologies indicates that the three units formed before they were separated to form blocks. The similarity in Nyborg facies in all of the blocks, and the similarity in all aspects between the blocks suggests they originally were one continuous large block.

Unit 3

The lenticular distribution of the stratified sandstone and tillite in unit 3 suggests that it formed in a sub- or supraglacial position. The deformation associated with the unit 1 - unit 3 contact suggests a subglacial origin. The laminae in the channel at locality S-16 were deposited by waning currents as shown by the grading, with inverse grading at the base (see Fisher and Mattinson, 1968), and parallel-lamination. The large, outsize clasts may have been ice rafted.

The deformation in the laminated sandstones at the top of unit 3 was very likely related to the deposition of the overlying unit 4.

Unit 4

A ground moraine origin for unit 4 and for the thick middle member elsewhere in the Tanafjord area is indicated by:
1) the erosive base, as unit 4 has cut down through the Nyborg Formation north of Stappogiedde North, and contains much Nyborg sediment near the base,
2) the presence of lenticular stratification throughout, and
3) the deformation structures, both at the base and within.

As opposed to unit 1, unit 4 has not incorporated much Nyborg sediment, and it contains abundant evidence of flowing water. The thin laminae and zones of stratified tillite suggest that there was an intimate relation between the melting out of debris and the flowing of water. Sandstone-filled channels indicate that the power of flowing water was occasionally dominant.

Very much associated with the deposition of the tillite and sandstone was their deformation; sheared lamination, boudinage, mullions, folding, all testify to an overriding ice sheet deforming its newly formed deposits.

Probably the most distinctive and problematic feature is the ghost clasts. These may be remnants of an earlier, eroded till, or till formed in shear planes, more compacted than the melt-out till or till partially cemented by the precipitation of carbonate carried by the glacial meltwaters. (See 7.5.2). p.55

The orientation of the structures (fig. 76) favours an ice flow direction approximately to the south.

Unit 5

The prominent bedding in the lower part of unit 5 appears to rule out a subglacial origin. The deformed layering and the presence of blocks of banded till in massive tillite beds suggests that slumping and mass movement were important processes. The origin of the layering may be either by intermixing of two tills, or by fluctuations during the primary deposition of laminations. Lenses of sand, and patches of gravel where unit 5 wedges out, suggests that current activity was present, and that the layering may be lamination. The layered blocks of tillite in massive tillite beds which apparently slumped into place, suggest that layered till was an original deposit, while massive till was derived by the thorough mixing of laminated tillite. The designation of the layering as lamination and not banding is tentative.

The grooves occurring at the contact between units 4 and 5 may have originated either by subglacial moulding of the substrate (unit 4 is interpreted as a ground moraine) or by scouring beneath a slumping till mass. The deformed lamination in the overlying tillite bed suggests that not much lateral movement took place, and that grooves are thus of subglacial origin. This is supported by the absence of grooves on bedding surfaces within unit 5. The blocks of Nyborg clasts which occur in massive tillite beds suggest that these slumped into place. The dark grey tillite often occurs as smeared out layers in laminated (banded) tillite, its method of emplacement is uncertain.

The sandstone wedges and dykes are associated with the erosion of a channel, winnowing of a gravel and sandstone lag, and the slumping of gravelly sandstone and tillite blocks into the channel. Thus the dykes and wedges seem to be more related to soft sediment flowage than to freeze-and-thaw conditions. They may have formed as slabs of till moved by creep down the margins of the channel, the cracks which developed being filled by the sandstone lag.

The question of whether the bedded part of unit 5 is subaqueous or subaerial in origin does not seem answerable unless reference is made to the adjacent lithologies. The upper part of unit 5 consists of finely laminated tillite which is most likely of subaqueous origin. It follows that the bedded part of unit 5 most probably formed in subaqueous conditions. The upward change from subglacial to subaqueous deposits is similar to sequences in the Smalfjord Tillite Formation around Smalfjord (Chapter 5).

7.3.7 Discussion, Thick Middle Member

From the foregoing interpretation it is seen that units 2 and 3 are problematical in origin and have important consequences for the glacial history of the area.

The sequence of events involving units 1 and 2 is ambiguous. Unit 3 clearly followed unit 2 as shown by the block of unit 2 tillite and sandstone in unit 1 at locality S-17 (fig. 69). From the association of sandy brown tillite and white sandstone in unit 2 blocks, it is obvious that the deposition of the sandstone and tillite occurred before the separation of the blocks. The deposition could have occurred either while the Nyborg part of the block was still autochthonous, in which case the Nyborg-tillite boundary in unit 2 represents an earlier unconformity, or after a large block of Nyborg was emplaced above a Nyborg breccia - unit 1.

Two models are proposed to explain the development of stratified sediment in units 2 and 3 between the ground moraine deposits of units 1 and 4.

Model 1: Advance and Retreat

Fluctuations of the margin of an ice sheet may cause the alternate deposition of ground moraine and stratified proglacial sediments. During a glacial retreat unit 2 sandstone would be deposited, perhaps by proglacial streams (fig. 78). During the readvance unit 2 sediments would be separated into blocks.

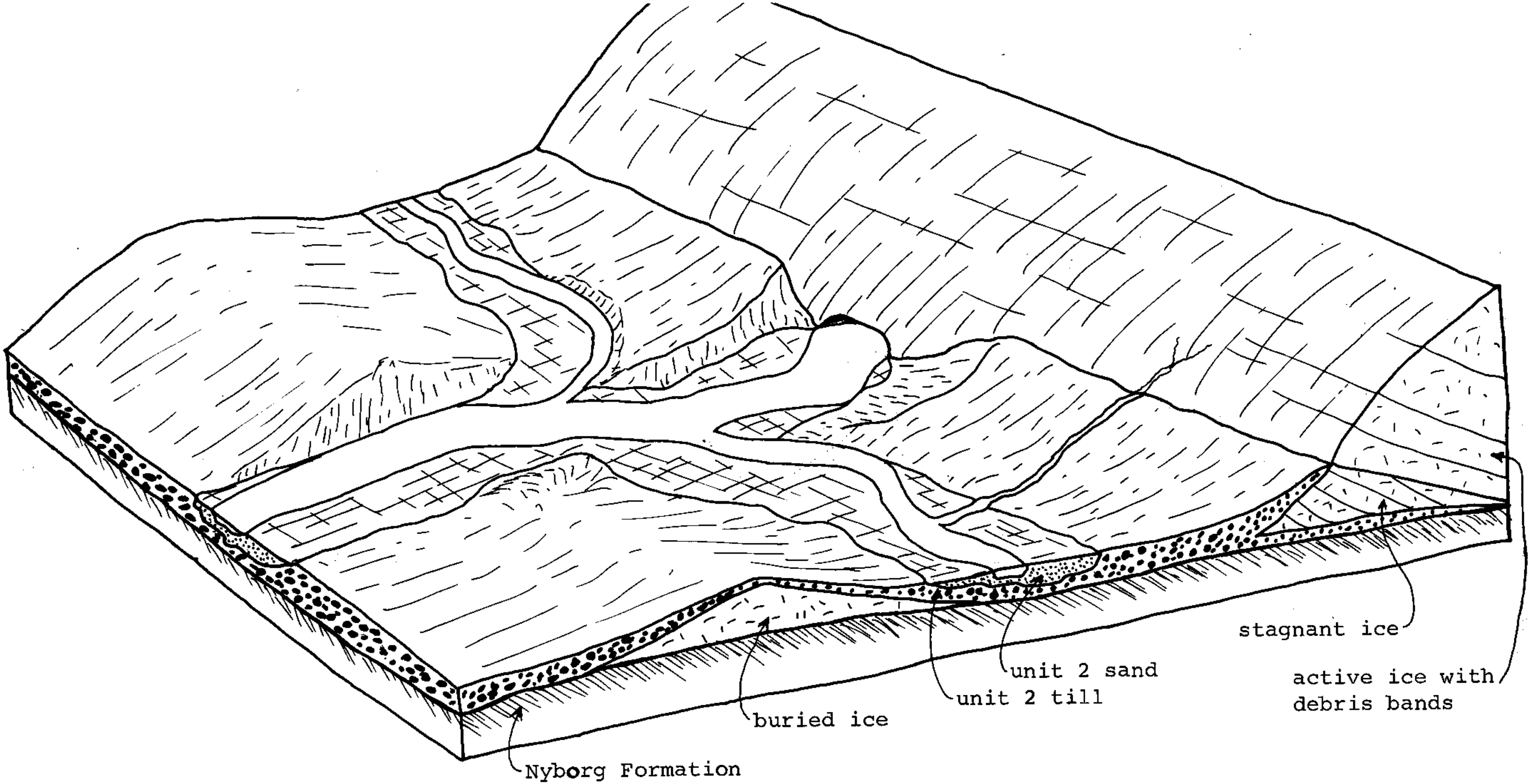


Figure 78. Simplified, hypothetical sketch of the environment of deposition of unit 2 according to model 1: fluctuations of an ice sheet margin. The massive nature of the tillite in unit 2 suggests melt-out of buried ice, rather than supraglacial mechanisms. During the retreat phase, part of the proglacial area is covered with a thin sand sheet. With subsequent readvance, the sand, till and subjacent Nyborg are overridden, transported and redeposited as unit 2. These blocks rest on a basal Nyborg breccia (unit 1) and are overlain by units 3 and 4.

Unit 3 stratified sandstone and tillite would be deposited either subglacially, or during a second, subsequent retreat of the ice sheet. Unit 4 would be deposited during a further advance.

Model 2: Thermal Fluctuations

Changes in the thermal regime of the ice sheet will determine whether freezing or melting is occurring at the base, and the rate and quantity of meltwater released. According to this model, the sequence could be formed away from the ice sheet margin. Unit 1 and the Nyborg part of unit 2 could be formed by the freezing of some of the Nyborg Formation onto the base of an ice sheet, with attendant brecciation along the underside of the Nyborg block. With a change to conditions of melting, the block would be emplaced, with tillite and then sandstone deposited as meltwater grows increasingly important. Because of the sandy texture of the tillite, it is apparent that relatively little winnowing would be required to form the sandstone. A change to freezing conditions could then deform unit 2 (fig. 79), and during subsequent melting unit 3 would be deposited in a subglacial position. Conditions of channellised meltwater flow occurred occasionally curing the deposition of unit 4. The sequence of unit 1 to 4 represents a progressive but irregular change from dry-based to wet-based conditions.

Model 1 Versus Model 2

Criteria for deciding which of the models, if either, is correct are not apparent to the author. Model 2 is favoured because of the similarity in composition and structure (excepting ghost clasts) amongst the tillites in the three units, and because it is simpler than model 1. Model 2 is also more satisfying because there is no evidence for glacial

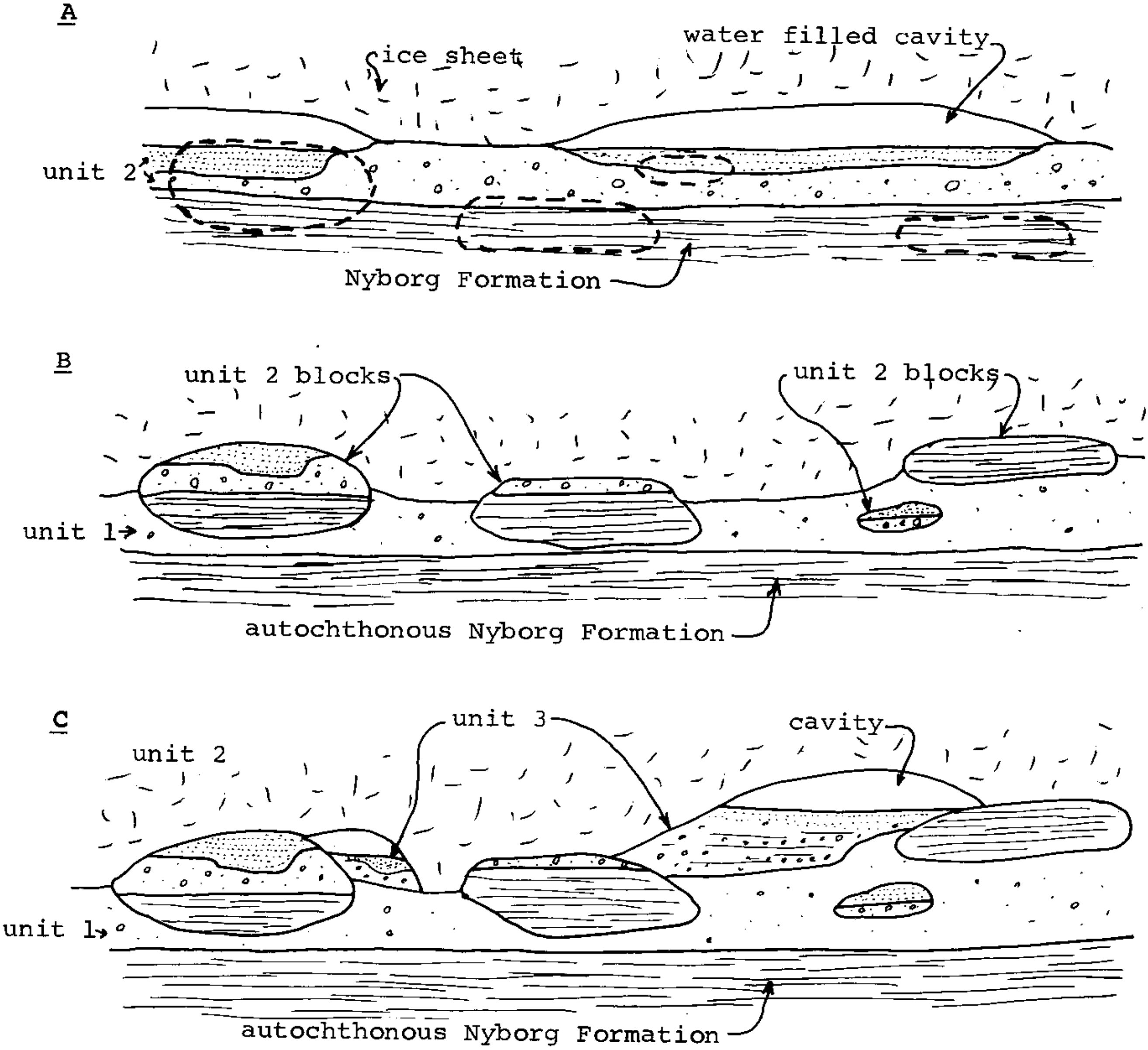


Figure 79. Diagrammatic representation of the deposition of units 1-3 according to model 2, thermal fluctuations at the base of an ice sheet. A) First melting phase, wet-based regime: deposition of unit 2 till and sand. Dashed outlines show blocks formed during ensuing dry-based, freezing phase. Nyborg at base may either be autochthonous, or rest on unit 1, Nyborg sediment tillite. B) Beginning of second wet-based phase: emplacement of unit 2 blocks above unit 1. C) Later in second wet-based phase: deposition of unit 3 stratified tillite and sandstone. This is succeeded by slight erosion and deformation before the deposition of unit 4 tillite.

advances and retreats in the thin middle member. On the other hand, the local occurrence of units 2 and 3 indicate that the conditions which were responsible for their formation may not have been widespread, suggesting deposition at an ice margin, rather over a wide area, subglacially. However, the local occurrence may be due to subsequent erosion at the base of unit 4. N.B. [illegible] in unit 4 [illegible]
[illegible] [illegible]!

Transition from Ice Sheet to Ice Shelf

It was suggested earlier that the bedded part of unit 5 of the thick middle member on the Digermul Peninsula was deposited during the lifting of an ice sheet to form an ice shelf. The association of unit 5 slump deposits with wet-based conditions of unit 4 offers support for Carey and Ahmed's (1961) model for deposition in the proglacial marine zone (Chapter 3, fig. 15).

In this environment large channels were scoured into the proglacial slumped deposits, and these were subsequently filled with slump deposits. Scouring was by currents, presumably at the base of the ice sheet. A characteristic, yet problematic feature of unit 5 is the various types of tillite which occur as blocks within the normal sandy, dolomitic tillite. These may have originally been deposited as ground moraine and then redeposited by slumping. This does not explain why they are not found in the ground moraine below, unit 4.

Palaeoflow

The numerous deformation structures and the varied lithologies derived from the Nyborg Formation in units 1 and 2 are the two major sources of data concerning the direction of the ice sheet flow, and of meltwaters at the base of the ice sheet.

In unit 1, lithologies are derived almost entirely from member 4 of the Nyborg Formation. These consist largely of purple sandstone in the lower 20-25 m of member 4, and grey-green sandstone and shale above. The distribution of these two lithologies along the unconformity between Larsholmen and Innerelv (fig. 70) suggests that when deposition commenced, movement had been almost entirely horizontal with little mixing, as the two lithologies occur separated from each other. The occurrence of purple sandstone above member 3 grey-green sandstone and shale indicates that movement was to the south, as no purple sandstone occurs within member 3. Also the contacts between the members in the Nyborg Formation are believed to strike approximately E-W against the sub-Mortensnes Tillite unconformity (fig. 6). The contact betwee the purple and grey-green parts of member 4 is truncated by the unconformity 3 1/4 km NE of where the transition in lithologies occurs in unit 1 around locality L-20. The scarcity of purple sandstone in unit 1 north of L-20 indicates that little cutting of the Nyborg Formation occurred after the blocks in unit 1 around L-20 were eroded, suggesting that 3 1/4 km may be the approximate distance of transport of the blocks, if movement is assumed to have been parallel to the present day coastline. If movement had been to the south, the distance of transport would be about 2.3 km.

The blocks of Nyborg sediment in unit 2 are believed to have been derived from the upper part of member 4 which also suggests movement to the south. As the sediment is above the contact between purple and grey-green sediment, the distance of transport was greater than the values cited above. Apparently, as the distance above the unconformity is increased, the transport distance of the material composing the tillite also increases.

Deformation structures along the contact and in the thick middle member indicate an overall movement approximately to the south. The single thrust fault observed just below the unconformity in the Nyborg Formation indicates the shear was to the south. Many deformation structures including folds, faults and pebble imbrication (fig. 76) support a southward movement. Many of the features are probably related to the formation of both units 1 and 4. The deformed southern margin of a large member 2 block at locality L-2 may indicate that movement was to the south (fig. 72). The occurrence of Nyborg sediment, which is usually the basal lithology, above the tillite and sandstone of unit 2, suggests overthrusting to the north, or underthrusting to the south. The northward dipping planes in the sandstone immediately to the south suggests movement was directed to the south.

Deformation structures at the top of unit 3 and within unit 4 tend to favour a movement to the south or southwest (fig. 76b). Folds and the grooves in unit 5 are scant evidence but suggest movement, perhaps by slumping, to the east.

Channel orientation in unit 4 indicates that meltwater flow was either to the north or south (fig. 76a).

7.3.8 Conclusions

1) The most complete sequence in the thick middle member is represented by units 1-5 along the Digermul coast.

2) Units 1-4 are ground moraine deposits which represent an irregular change from dry-based to wet-based conditions.

3) Unit 5 consists, in the lower part, of subaqueous slumped tills deposited during the lifting of an ice sheet to form an ice shelf, and, in the upper part, of laminated tillite formed by rafting from an ice shelf, or bergs, in a marine environment.

4) The entire sequence, units 1-5, comprises a glacial retreat sequence similar in overall aspects to those in the Smalfjord Tillite Formation around Smalfjord (Chapter 5). It may be the same retreat interpreted from the lower member to the top of the thin middle member in the Vestertana area.

5) The ice flow direction, based on deformation structures

and clast composition, was broadly from the north, not from the south as suggested by previous workers (Føyn, 1937; Reading and Walker, 1966).

7.3.9 Austerelva

Description

At Austerelva (fig. 63) the middle member is distinct from the member in the east. About 60 cm of parallel-laminated and thinly layered tillite rest gradationally on the lower member (Pl.183), and grade up into the upper member. Dolomite clasts predominate and some of the bands are largely fine-grained dolomite. Towards the top is finely parallel-laminated mudstone with scattered, small (< 1 cm) outsize clasts. The brown weathering colour of the middle member contrasts with the purple and green lower member, and the grey upper member.

Interpretation and Conclusion

The parallel-laminated tillite is subaqueous deposit formed by the rafting of clasts by icebergs or an ice shelf into a probable marine environment.

The middle member here represents the change from subglacial to subaqueous conditions. Coeval with this change was the influx of new exotic material, largely dolomite. The subsequent reduction in dolomite up into the upper member, marks no apparent change in environment.

7.4 Upper Member

7.4.1 Introduction

The upper member is thickest in the Vestertana area where it reaches a maximum of about 40 m (fig. 62). It thins in all directions, but cannot be observed along the southern margin of the area.

The upper member consists almost entirely of massive tillite. Weak banding can be detected in one fresh road exposure. It is dark grey, in contrast to the middle member, and is composed of dominantly crystalline clasts in a matrix of sand, silt and clay grade material. The carbonate content in clasts and matrix is low, probably less than 10%. Material from the Nyborg Formation is not observed in the upper member. Because of this fact, plus the nearly ubiquitous presence of the middle member, there is little confusion between the lower and upper members.

Above the tillite in the upper member, there are a variety of facies (fig. 62). In the Vestertana area the upper member grades up into the parallel-laminated mudstones of the lower submember of the Lillevatn Member. However, in the northern part of the area, the upper member tillite is overlain by a thin bed of tillite with a dolomite matrix. Above the dolomite tillite is a polymict conglomerate with subsidiary amounts of sandstone. This conglomerate is taken as the top of the upper member and of the Mortensnes Tillite Formation where it is present in the Tanafjord area.

7.4.2 Description

Vestertana Area

The grey tillite of the upper member comprises the bulk of the Mortensnes Tillite in the Vestertana area. In this area it averages 40 m thick, but it decreases quite rapidly to about 20 m in the northern part of the area. (Table 24).

Clasts compose 5-15% of the tillite and consist largely of a variety of crystalline types of which grey gneiss is dominant. About 10% of the clasts are dolomite. Small clasts, less than about 10 cm are most numerous, but clasts up to 30 cm are occasionally seen. Most clasts are rounded to some degree; angular clasts are infrequent. The matrix is composed of unsorted sand and silt grains in a fine-grained groundmass.

Table 24

Upper Member, Mortensnes Tillite, Vestertana

Colour: dark grey
Clasts:
  <u>Concentration</u>: 5-15%, decreases towards the top.
  <u>Composition</u>: mainly grey gneisses, granites, some schist, red granite, rare basic and ultrabasic rocks. Dolomite or marble and other metasediments are uncommon.
  <u>Average Diameter</u>: less than 10 cm.
  <u>Maximum Diameter</u>: clasts larger than 30 cm are scarce.
  <u>Shape</u>: mostly equant showing various stages of rounding.
Matrix: sand and silt in fine groundmass
Thickness: averages about 40 m, thins to about 20 m north of Sjursjok
Lower Contact: usually appears sharp, occasionally gradational or erosive.
Upper Contact: grades up into shales of the lower submember, Lillevatn Member.
Structures: mostly massive, faint banding, in part folded, visible in a road cut west of Vestertana.

The smaller grains tend to be more angular than the larger.

The upper member generally rests sharply on the sandy tillite of the middle member, but may appear to grade up from the laminated tillite at the top of the thin middle member. Where the middle member is missing, the upper member rests directly on the lower member. The thin middle member is highly deformed adjacent to where it is missing. At one locality, west of Njukcagaissa, unusual structures just above the base of the upper member were noted: two coarse, poorly sorted sandstones, one faintly laminated and about 50 cm wide and high, and another a massive bed, about 3 m long, and 20 cm high.

A remarkable feature of the upper member is that it appears to be massive over the whole Vestertana area. No coastal exposures exist. However at a large, fresh road exposure west of Vestertana (Føyn, 1960, locality 3) very faint and discontinuous banding is visible in the upper 10-15 m of the upper member, and it becomes more prominent upwards. The banding is visible only in patches, it cannot generally be traced laterally, but merges into massive tillite, a feature which may be due to weathering. Individual bands are up to about 1 cm thick. The thick bands cannot be seen to die out, but the thin bands, about 1 mm thick continue for only a few centimetres before dying out. Greenish-grey bands, which are fine-grained and lack sand grains compose about 30% of the tillite. The remainder of the tillite is brownish-grey bands with dispersed sand grains and small clasts. In the exposure, small folds with rounded crests and moderately dipping axial planes occur (Pl.184). In polished slabs a finer folding, isoclinal, with horizontal axial planes and sharp crests is seen (Pl.189d). The features described here, and the absence of sedimentary structures indicates that these bands are shear bands, and not sedimentary lamination. Concomitant with the increasing prominence of the banding upwards is the decrease in the number of large clasts, and overall percentage of clasts, which decreases from about 10-15% to 5% near the top.

Gradationally above the banded tillite is 50 cm of tillite with faint parallel lamination highly deformed by soft sediment flowage and the loading down of clasts, some of which are lumps of tillite up to 5 cm across (Pl.185). Above is about 25 cm of parallel-laminated siltstone with rare clasts, followed by 25 cm of massive tillite (Pl.186). This is overlain by laminated siltstone, lacking clasts which is the base of the lower submember of the Lillevatn Member. The shape of the contact between the two formations is undulating (Pl.185).

The only lateral change in lithology of the upper member is the appearance of unusually sandy, weathered-looking tillite in the upper 4-5 m of the member west of Alteberget (fig. 63). The upper contact is not exposed, but the bench topography suggests that it is a sharp one.

Digermul Peninsula

The upper member along the Digermul coast thins northward from about 8 to 3 m, and is overlain by the persistent dolomite tillite and conglomerate beds.

Tillite

Clasts, composed mainly of dolomite and grey gneiss, make up about 15% of the tillite. Other crystalline clasts include diorite, schist, and marble. The long axes of 63 clasts show a N-S preferred orientation (fig. 66c). The matrix is finer grained than that in the middle member, sand and silt grains float in a fine-grained groundmass with an appreciable amount of carbonate.

At the base of the tillite is a local, 1-2 cm thick layer of fine gravel which usually extends no more than 2-3 m laterally, and which has a sharp lower and upper contact.

At several localities tillites of the middle and upper members are intermixed.

Few structures are observed in the tillite, which is otherwise massive, even in coastal exposures. Most prominent are two isolated beds of stratified conglomeratic sandstone. One bed is 5 m long and 40 cm thick, cross-bedded and parallel-laminated, and with fairly sharp contacts with the surrounding tillite (Pls. 187, 188). It is gently folded with a NE-SW trending fold axis. The cross-bedding shows that the current flowed to the south. The other sandstone is about 5 m long and up to 20 cm thick, with an irregular, probably erosive base. It fines upwards and grades into the overlying tillite.

Several irregularly shaped blebs of massive gravel-rich tillite occur in the lower 2-3 m of the tillite. These are usually no more than 40 cm across. Their identical colour to the surrounding tillite makes them difficult to see.

Broadly spaced, horizontal, thick dolomitic banding occurs in the upper 3 m of the tillite at locality S-7 (fig. 69). The bands which are continuous and have sharp margins, become more closely spaced and thicker upwards.

Dolomite Tillite

Sharply above the Mortensnes Tillite at all exposures between Larsholmen and Areholmen is a bed of light brown-buff massive tillite 20-40 cm thick. It consists of less than about 5% clasts in a slightly sandy and silty fine grained dolomite matrix (Pl.190). Clasts are mostly rounded and consists of dolomite and a variety of crystalline clasts; sand grains are mostly monocrystalline quartz, with a few polycrystalline grains, the larger ones rounded, the smaller angular. The bed is overlain by the conglomerate.

Conglomerate Bed, and Associated Sandstone

Conglomerate, with subsidiary sandstone is found above the dolomite bed, and passes sharply up into the silty mudstones of the lower submember of the Lillevatn Member.

Resting upon the dolomite tillite bed, is polymict orthoconglomerate up to 20 cm thick, frequently with small pockets and depressions up to 5 cm deep along the base. Maximum grain size is about 40 cm, while most pebbles are under 5 cm, with occasional granule conglomerates developed. The clasts are composed of dolomite and other sedimentary clasts, and a variety of crystalline clasts. All of the clasts are rounded to some extent and the conglomerate varies from moderately to well sorted. Long axes of 33 clasts in the conglomerate showed no clear preferred orientation (fig. 65). The matrix is mainly a medium grained, moderately sorted sandstone, but at locality S-20 (fig. 69), it is a pyritic mudstone.

Above the gravel at a few localities is a thin sandstone, locally conglomeratic, up to 15 cm thick. Some of the conglomeratic sandstone has a dense haematite cement, and trimodal, with 2-3 cm very well rounded pebbles forming one mode, well rounded very coarse sand to granule grade material the intermediate mode, and very fine sand the third mode.

In most localities the conglomerate is succeeded by either the sandstone, or the silty mudstone of the lower submember of the Lillevatn Member. However, adjacent to Guoholmen there is about 20 cm of a dense and ferruginous shale occurring directly above the conglomerate which contains scattered very coarse sand grains and crystals of pyrite (see Chapter 8).

Other Localities

In addition to the extensive Digermul exposures, the conglomerate was observed at Leirpollen and Trollfjord. A loose block considered to be from the same horizon was collected at Lavvonjargga.

At Leirpollen the conglomerate is seen as isolated outcrops near the road. It has a minimum thickness of 50 cm and consists mainly of dolomite blocks of various sizes in contact with each other. The matrix is also highly dolomitic. It probably rests on the thick middle member of the tillite.

Above the finely layered tillite at the top of the thick middle member at Lavvonjargga is the dolomite tillite bed, here about 20 cm thick. It is finely parallel-laminated in the lower part, the laminae consisting of sand and silt-sized grains of quartz, feldspar and dolomite. The lamination is overfolded at the top. Truncating the folded lamination is dolomite with numerous scattered sand and silt grains, and a few clasts, with a vertically orientated colour banding. The grains are orientated parallel to this banding.

A loose block found on the beach adjacent to where the dolomite bed was observed contains sub-angular to rounded dolomite and crystalline pebbles in a moderately sorted sandstone matrix. It closely resembles the conglomerate bed on the Digermul Peninsula.

At Trollfjord the conglomerate occurs above normal thick middle member tillite and also the laminated grey tillite which occurs occasionally at the top of the member. It is 30 cm thick, consists of rounded dolomite and a wide variety of crystalline pebbles, and scours into the underlying sediment. It is overlain abruptly by the shales of the lower part of the Lillevatn Member (Pl.182).

7.4.3 Interpretation, Upper Member

Tillite

The upper member tillite is similar to the lower member in internal features except that it lacks locally derived material. It is considered to be a ground moraine because:

1) It is almost entirely massive, which rules out a supraglacial

origin,

2) It contains isolated sandstone beds which rule out a subaqueous origin, and

3) It is banded at the top, which strongly suggests a subglacial origin.

The lower contact of the upper member tillite is not strongly erosive, but the laminated siltstone at the top of the thin and thick middle members is folded and deformed in a manner that suggests shearing. Where the thin middle member is locally absent erosion by the upper member seems to have been the most probable cause. This was most likely accomplished by overriding of an ice sheet. The thin lenticular gravel at the base of the upper member on the Digermul is of uncertain origin.

The generally massive tillite is similar to the probable ground moraine in the Smalfjord Tillite around Smalfjord. Banding was noted in member D tillite of the Smalfjord Tillite only on the coastal exposure and not inland, suggesting that special conditions are required to detect it. The disappearance of the banding downwards in the upper member suggests that it may not have been developed throughout the entire thickness of the tillite. The sandstone lenses in the lower part of the tillite suggest local current activity shortly after deposition began. The deformation of the sandstones suggests that the moraine was subject to shearing after deposition. The significance of the apparently weathered, sandy tillite west of Alteberget is unknown. Irregular gravelly tillite patches near the base of the tillite on the Digermul may be deformed stratified tillite, or bodies of unmixed primary till.

In the Vestertana area, the gradational contact with the overlying parallel-laminated mudstones suggests the retreat of the ice sheet, either by lifting up as an ice shelf, or retreat with a marine margin (see fig. 40). The relatively thin transition suggests that deglaciation was quite rapid. The undulating contact may represent the subglacial topography prior to uplifting.

Dolomite Tillite

The continuous dolomite tillite bed which caps the middle and upper members in the Tanafjord area is of problematic origin. The absence of lamination where clasts and scattered sand grains are present, and the fact that no concentrations of grains were observed indicate that the carbonate matrix and the grains were deposited simultaneously in a low energy environment. A diagenetic origin for the dolomite matrix appears unlikely because of the sharp lower contact, its absence at Trollfjord, and the much less dense distribution of sand and other clasts as compared to the underlying tillite. A further alternative is slow deposition, with a supply of clasts and sand grains from icebergs, and the simultaneous formation of dolomite. Such an origin is distinct from the precipitation of dolomite from cold, sub-ice shelf brines, proposed by Carey and Ahmed (1961) and would seem to cast further doubt on the accepted association of warm conditions for the formation of dolomite, at least in the late Precambrian. Considering the conglomerate above, it remains uncertain if the dolomite was the final glacial deposit. If so, it makes an interesting contrast with the Vestertana area where at the end of the glaciation influx of ferruginous, non-glacial sediment was relatively high. This may have been related to the proximity of the sediment supply, or to the relief of the area at the time. The question is discussed in Chapter 9.

Conglomerate and Associated Lithologies

The conglomerate bed was obviously derived from the underlying tillite, either with considerable lateral transport, or by winnowing. Waves are quite capable of transporting the largest clasts in the bed, but the irregular shapes of some of the clasts suggests that they have not been transported very far. Considering the persistent small thickness of the bed it seems more probable that it developed as a lag, which then prevented further erosion of the underlying tillite. Such winnowing suggests very shallow, possibly emergent, conditions. On the other hand, the overlying sandstone which is well sorted and very well rounded, with well rounded pebbles indicates a long period of reworking. The overlying mudstone, locally iron rich suggests a rapid switch to quiet conditions and slow deposition (see Chapter 8).

The conglomerate bed at Trollfjord is slightly thicker than at Stappogiedde, but considerable erosion does not seem to have occurred. The absence of the upper member tillite at Trollfjord may thus have been either primary or due to subsequent erosion.

7.4.4 Conclusions

1) The upper member tillite is predominantly a ground moraine.

2) The dolomite tillite bed above the upper member in the north seems to have formed when icebergs were rafting sediment into an environment in which dolomite was forming. If this were true it would dispel the notion that dolomite can form only in warm water, at least for seas in the late Precambrian.

3) The conglomerate bed represents a largely in situ lag deposit which may have protected the underlying deposits from considerable erosion. It formed in very shallow water.

4) The thinning of member 3 tillite to the north may be primary and not due to subsequent erosion.

7.4.5 Austerelva

The upper member near Austerelva, south of Laksefjord (fig. 63) consists of about 4 m of finely parallel-laminated grey tillite. It rests gradationally above the laminated middle member and passes up gradually, with the dying out of clasts, into the lower submember of the Lillevatn Member. It contains both crystalline and dolomite clasts. The laminae are depressed and raised around the clasts, the rupturing of laminae was not seen.

The upper member was probably formed in a subaqueous environment by rafting and slight current agitation. The gradational contact with the middle member suggest that a grounded ice sheet did not reach this area. The gradational upward contact with the dying out of clasts presumably represents the diminishing influx of icebergs during the waning of the glaciation.

7.5 <u>Discussion</u>

7.5.1 Channel Structures

The Mortensnes Tillite contains gravel and sandstone lenses which have been interpreted in most cases as subglacial channel deposits, and possibly proglacial deposits in the case of units 2 and 3 of the thick middle member, Digermul Peninsula. In the lower member, channel fills are almost all horizontally stratified sandstone, although the fill includes gravels and graded units of sand and silt. Gravel lags infrequently occur at the base of the sandstone fills.

Channel structures in the thick middle member are composed predominantly of sandstone. In most cases the sandstone is horizontally bedded and laminated. The four sandstone lenses in a row, west of Alteberget, suggest a sinuous subglacial stream pattern. On the Digermul Peninsula, massive filled channels and fills composed of sandstone and tillite were also observed. The latter suggests that soft till slumped into the channel while currents were depositing sand.

In the upper member of the Digermul Peninsula there is a unique occurrence of cross-stratification in a subglacial channel fill.

All of these structures contrast with eskers characteristic of Pleistocene deposits (Charlesworth, 1957), and with fossil eskers of Pennsylvanian tillites in Brazil (Frakes _et al_. 1968). Eskers are composed of gravel or cobble conglomerate and may have stratification inclined away from the central ridge. However, eskers are late-stage features associated with deglaciation; the structures in the Mortensnes Tillite are embedded in massive ground moraine and appear to have formed during steady-state conditions of glacial deposition.

The shape of the basal surface of the deposits is most often horizontal, suggesting that little erosion of the underlying till occurred. This is supported by the scarcity of coarse lag material in most deposits. The broad, flat shape of the deposits is consistent with that expected from the flow of water through ice at the base of an ice sheet, with low rates of melting (Shreve, 1972, p.212).

Shreve (1972, p.213) has suggested that secondary currents in the turbulent flow in non-circular passages might cause the characteristic stratification of eskers. The absence of this pattern in the present deposits suggests that either his proposed mechanism is incorrect, or that the shape of the passage, or other factors are important in controlling the flow.

A fundamental difference between subglacial and subaerial channel flow is that subglacial streams are driven by hydrostatic pressure and have no upper air-water interface, while subaerial streams are driven by gravity, and do have an upper air-water interface. The air-water interface is important in the depositional processes that form bars in braided channels. The scour-and-fill structure typical of braided stream deposits (Doeglas, 1962) could not form in a subglacial channel. Thus, the scour-and-fill conglomeratic sandstone in unit 2, member B, of the Smalfjord Tillite at Smalfjord

(Pls. 24, 25) almost certainly are subaerial deposits. However, it is important that certain types of scour-and-fill structure can form below the air-water interface, such as that formed by migrating linguoid dunes (Allen, 1963). These can usually be distinguished from bar structures.

Most of the structures in the Mortensnes Tillite are distinct from subaerial fluvial channel deposits and, in view of the contrasting features of subglacial and subaerial channel deposits, the channels in units 2 and 3 of the thick middle member, Digermul Peninsula may be tentatively ascribed to a subglacial origin. These channels clearly have an erosive base (Pls. 147, 150). Filling of the channels was horizontal in both cases, with the lamination draping onto the steep margins of the channels. The entire history of the channels may be divided into four stages (fig. 80):

1) formation of the subglacial channel by the build-up of meltwater at the base.
2) increase of hydrostatic pressure causing enlargement of the channel by erosion into the bed, and/or increased rate of ice melting.
3) decrease in hydrostatic pressure resulting in a decrease in size of the channel by deposition, and/or a decrease in the rate of ice melting.
4) Cutting off of the supply of water resulting in abandonment of the channel and renewed sedimentation of till.

7.5.2 Comparison of Tillite Facies

As with the Smalfjord Tillite, the Mortensnes Tillite consists largely of ground moraine, which in each member has a distinct composition. Considering the exotic material, the lower member contains a wide variety of crystalline clasts, the middle member is dominated by dolomite and sand, and the upper member is again dominated by crystalline clasts. Locally derived Nyborg sediment is only important along the unconformity

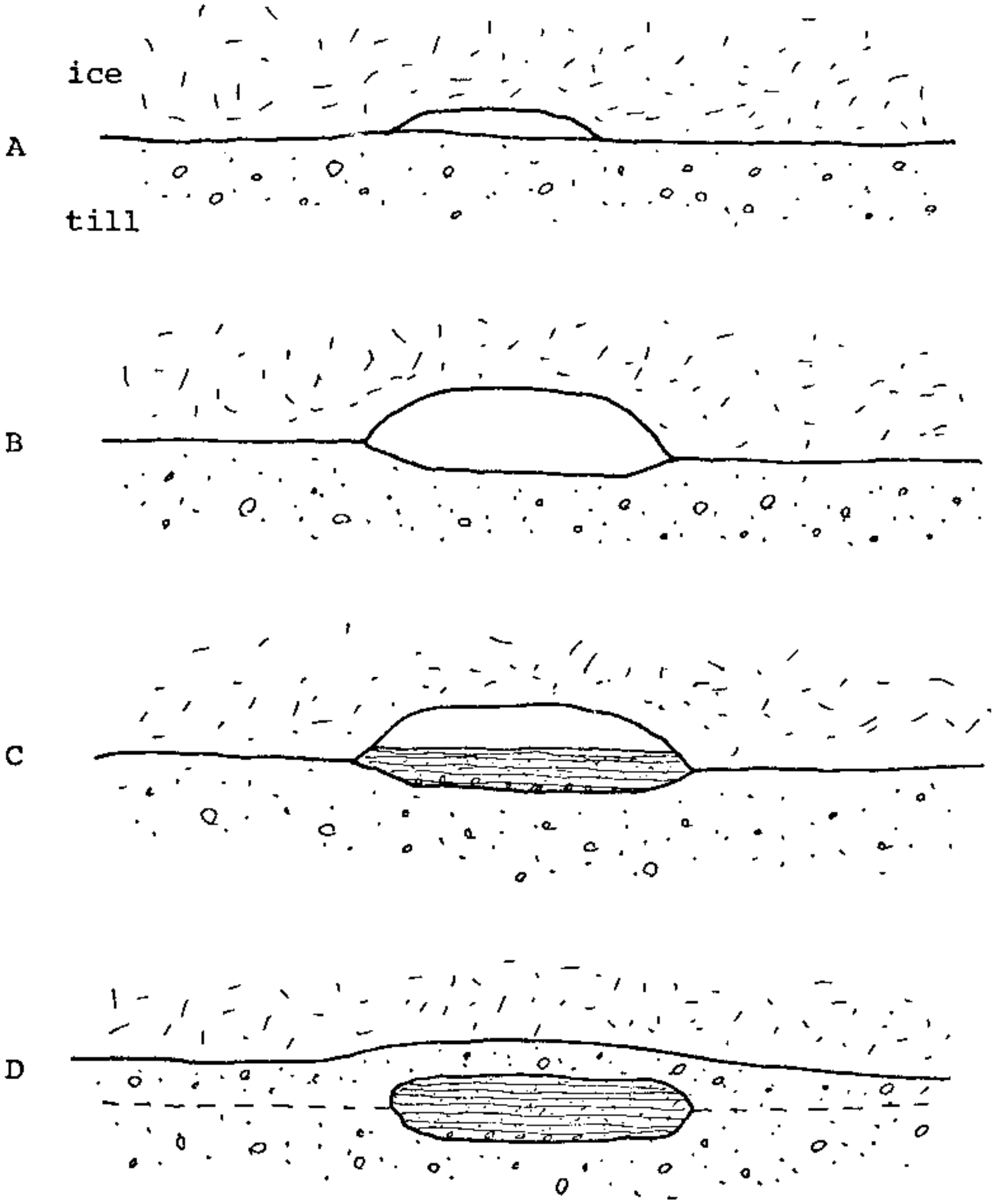


Figure 80. History of a subglacial channel. A) Development of the channel by the buildup of subglacial meltwater. B) Increase of pressure causes the enlargement of the channel by increased melting and erosion. C) Decrease in hydrostatic pressure allows deposition and decrease in cross-sectional area. D) Cutoff of supply causes abandonment of the channel and deposition of till on top of the channel deposits. Dashed line indicates former ice-till contact.

in either the lower or middle member, depending on the location (fig. 62). Considering the cutting out of the formations in the Older Sandstone Series to the south (fig. 5) it appears that the only remaining source for the Porsanger Dolomite (Grasdalen Formation) would be to the north. If the dolomite in the middle member was derived from the north, then it seems that the Mortensnes Tillite must cut down to the north, through the Nyborg Formation and Smalfjord Tillite (if they are present), into the dolomite horizon. On the other hand, the crystalline material of the lower and upper members is readily derived from the crystalline shield to the south. The presence of large grey granite boulders in the middle member, to an extent not noted in either the lower or upper members, suggests that crystalline rocks may have been exposed to the north of the area as well as to the south.

The structure of the lower and upper members is typical of ground moraine: massive, with some banding, and rare stratification. However, the ghost structure, and abundant stratification in the thick middle member distinguish this ground moraine from the others. Two features associated with the ghost structure may help explain this. The abundant sedimentary structures indicate abundant meltwater, and high dolomite content suggests that the meltwater was saturated with salts. Based on observations of present day glacial environments, Page (1971) has suggested that pressure changes beneath a glacier may cause solution or precipitation of carbonates. Meltwater, driven by hydrostatic pressure, would be subjected to less pressure as it travelled towards the glacier margin, thus favouring net precipitation of its dissolved salts. From inspection of the other ground moraines it is seen that banding, produced by glacier shear, was an important feature. Perhaps ghost structure results from glacial shear of partially consolidated till, thus resembling, in mode of formation, boudin structure in plastic metamorphic rocks.

Aside from ground moraines are two distinct tillite facies in the Mortensnes Tillite, the deposits of the thin middle member and of unit 5 of the thick middle member. The occurrence of the relatively coarse deposits of the thin middle member (most subaqueous glacial deposits are siltstones or mudstones) may have been related to the obviously large quantities of meltwater being released by the ice sheet depositing the thick middle member to the north. However, rather than suggesting that the thin middle member was deposited over its whole outcrop at once, it seems more likely that it is a diachronous deposit, particularly with the parallel-laminated siltstone which it is overlain by. It would be expected that meltwater currents would be most effective where the depth of the water was least, i.e. around the zone where an ice sheet would have begun to float. In deeper water, weaker currents would have deposited the siltstone. In view of the occurrence of the thin middle member to the south and the thick middle member to the north it appears that lifting of the ice sheet into an ice shelf began in the south and gradually shifted northwards.

The bedded tillite in unit 5 of the thick middle member is unique in Finnmark tillites. They have been interpreted as slumped till, formed, as with the thin middle member, near the lifting zone of the ice shelf.

7.5.3 Controls of Thickness

The decreasing thickness of the lower member away from the shield area may have been a function of increased distance from the source and/or a change in slope as the ice flowed from the shield onto the shelf. If the thick middle member was transported from the north, then the thickness was not controlled by the distance from the source area as it thins to the north. A further problem with the thick middle member is the rapid transition into the thin middle member. The thinness and deformation in the middle member just north of

Sjursjok at the transition between the thin and thick middle members suggests that some erosion of the middle member might have occurred there.

As no remarkable change in thickness occurs in the Mortensnes Tillite north and south of Sjursjok, it appears that the upper member does not drape over the middle member, but thins to the north (fig. 62) across the transition from the thin to the thick middle members.

The thinning of the Mortensnes Tillite to the north was due partly to primary deposition, and to subsequent erosion, indicated by the conglomerate bed at the top of the formation. The centre of the basin, if defined by the maximum accumulation, was apparently around the Vestertana area.

7.5.4 History

A precise history of the deposition of the members in the Mortensnes Tillite cannot be determined as it is uncertain whether the deposition of the lower member and the thick middle member overlapped in time, or whether the entire middle member was deposited after the lower member. Keeping this uncertainty in mind the following history for the Mortensnes Tillite is proposed:

1) Vigorous subglacial erosion, at least during the final moulding of the unconformity beneath the Mortensnes Tillite.

2) Deposition of the lower member in all areas by a dry-based ice sheet. Flow was to the west around Varangerfjord, and to the north around Vestertanafjord. The exotic component of the tillite is mainly crystalline clasts, derived from the Fennoscandian shield.

3) Deposition of the thick middle member first by dry-based, and then by wet-based ice north of Sjursjok, flowing to the south. Deposition of the thin middle member south of Sjursjok, and of the middle member at Laksefjord, by an ice shelf. Subaqueous conditions later prevailed where the thick middle

member had been deposited.

4) Readvance of dry-based ice sheet with slight erosion into the underlying middle member; deposition of the upper member tillite. At Laksefjord, glacial marine conditions prevailed. Direction of ice flow uncertain.

5) South of Tanafjord, subglacial deposition gave way rapidly to glacial marine, and then normal marine sedimentation. However, to the north rafting continued into an area of dolomite formation. A period of erosion followed, during which time a basal conglomerate developed at the top of the Mortensnes Tillite. Subsequently, the area was rapidly submerged, and fine sediment was deposited.