SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C NR 789 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 76 NR 2

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ABSTRACT

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The autochthonous Torneträsk Formation is treated from a lithological and sedimentological point of view. It has been analyzed in various sections distributed over a distance of 100 km in northern Norrbotten County. The formation is dominated by quartzites, sandstones and siltstones with minor shaly intercalations. It is part of a Vendian to Lower Cambrian quartzite-shale unit extending along the eastern margin of the Scandinavian Caledonides from southern Norway, via central and northern Sweden into northern Norway; a distance exceeding 1800 km.

In northern Norrbotten County, a weathered basement surface is overlain by a transgressive sequence containing basal coastal plain deposits, overlain by bay or lagoon sediments and terminated by sediments influenced by tidal activity. A conspicuous mass flow deposit, the Vakkejokk Breccia, overlies this sequence to the north of Torneträsk. An overlying sedimentary cycle starts with a characteristic red and green siltstone unit deposited in an offshore marine environment. Shallowing of the sea resulted in the deposition of interbedded silt and sand and development of tidal sand flats. An overlying unit dominated by quartzite suggests beach environments and possible tidal and/or coastal fluvial activity. This regressive sequence is separated by a thin, extensive, calcareous phosphorite-bearing conglomerate from overlying transgressive shallow marine siltstone. An uppermost black shale of the Alum Shale Formation is the uppermost rock unit seen beneath the allochthon. Lithostratigraphic correlations between the Torneträsk area and adjancent areas to the south and north are discussed.

INTRODUCTION

Vendian to Lower Cambrian quartzites, sandstones and siltstones have been deposited over extensive areas in the Scandinavian Caledonides. Due to Caledonian thrusting they now occur at several tectonic levels. A narrow autochthonous zone can be traced along the eastern margin of the Caledonides from southern Norway via central and northern Sweden into northern Norway. The sedimentary sequence occurring in this zone has been referred to by a variety of names in different regions. In this paper, the name Torneträsk Formation is proposed for the unit outcropping in the northern part of the Norrbotten County (Fig. 1). Together with overlying Cambrian black shales of the Alum Shale Formation they constitute the Dividal Group, which continues into Troms and Finnmark of northern Norway (Føyn 1967). The Torneträsk Formation thins out southwards and only a few metres remain in the area of Stora Sjöfallet (Fig. 2). Corresponding autochthonous sediments reappear further south as the Laisvall Formation (Lilljequist 1973), and the overlying Grammajukku Formation (Willdén 1980), in southern Norrbotten County (Fig. 1), the Gärdsjön Formation in southern Västerbotten and northern Jämtland Counties (Gee *et al.* 1974), the Vassbo Formation in northern Kopparberg County (Tegengren 1962, Christoffersson *et al.* 1979), and the Vangsås Formation in southern Norway (Bjørlykke *et al.* 1967, Bjørlykke 1978). Comparable sediments also rim many of the windows of Proterozoic basement rocks occurring along or close to the Norwegian/Swedish border (Vigelen, Tømmeråsen, Grong-Olden, Nasafjället, and Rombak or Sjangeli Windows). The sediments of the Torneträsk Formation, about 100 m thick in its type section, were deposited on a levelled surface of Proterozoic rocks. In the northern and central parts of the outcrop area, the basement is composed of gneisses, acid volcanites, granites, and syenites. In the southernmost part, the basement is composed of Proterozoic quartzites and sandstones of the Snavva-Sjöfall Series (Ödman 1957).

The Torneträsk Formation is flat-lying on the basement but in places the formation has been submitted to gentle folding or imbrication. The Torneträsk Formation and overlying Alum Shale Formation are in turn overlain by thick allochthonous units, principally derived from the west. The sole thrust at the base of this allochthon cuts the autochthonous sequence at deeper levels westwards, but a thin veneer of the Torneträsk Formation has been preserved on the Proterozoic basement within the Sjangeli (Rombak) Window west of the Torneträsk area (Kautsky & Tegengren 1952, Kulling 1964).

The allochthon shows a great complexity and is divided into the Lower, Middle and Upper thrust rocks (Kulling 1964). The Lower thrust rocks contain sediments correlatable to the Torneträsk and Alum Shale Formations (Kulling 1964, Ahlberg 1979). Proterozoic basement has also been involved and is included in the Lower thrust rocks. The degree of deformation and metamorphism is higher in the overlying thrust units. The Middle thrust rocks contain mylonitic basement and banded sediments characterized by biotite grade regional metamorphism. The Upper thrust rocks are of an even

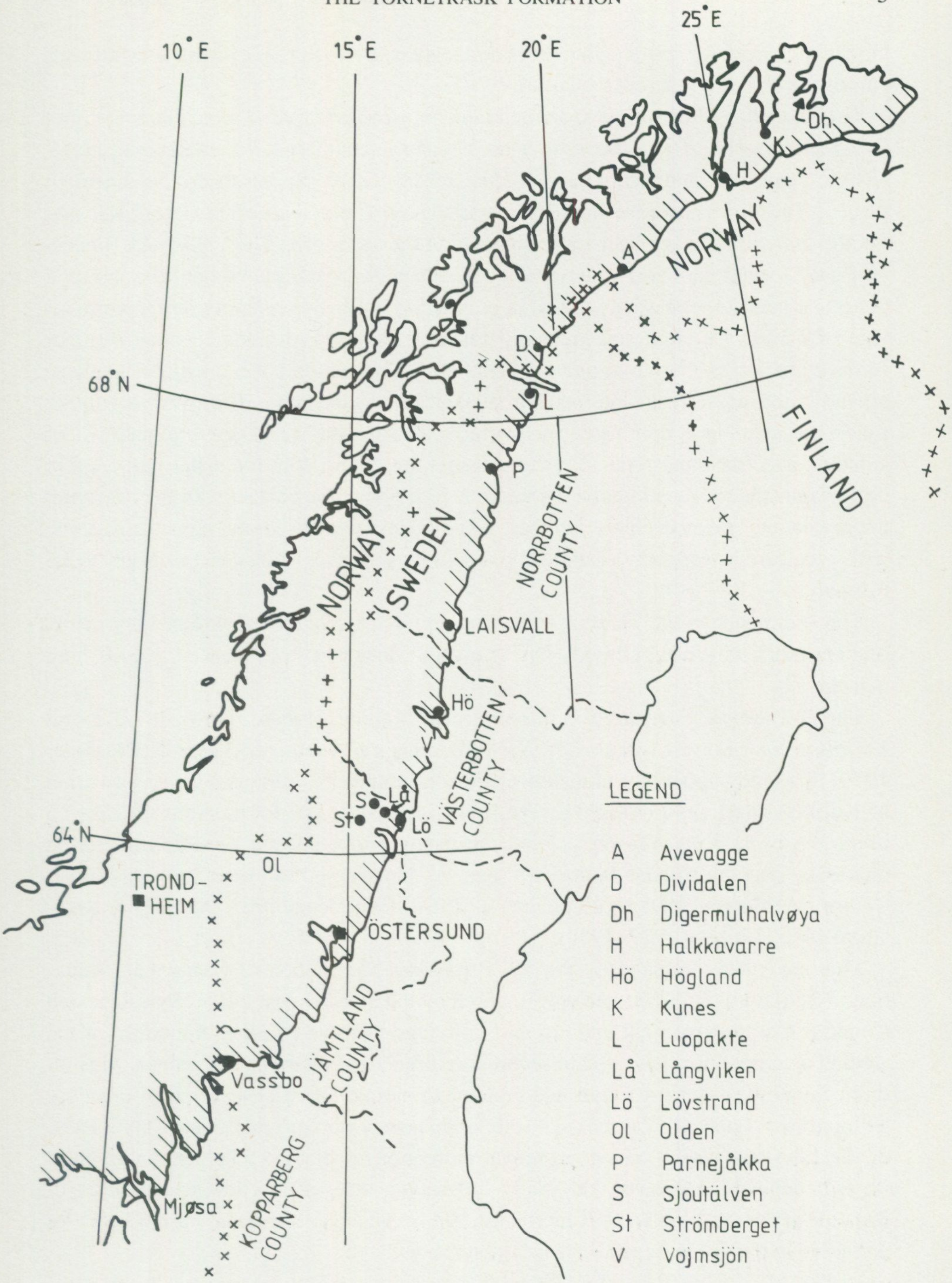


Fig. 1. Map showing the present erosional front of the Scandinavian Caledonides and location of some key sections and other names referred to in the text.

higher metamorphic grade, often containing garnet. Amphibolites form a significant part of the Upper thrust rocks (Kulling 1964).

The Torneträsk Formation is divided into six members, five of which here are only informally named. The lower sandstone member is composed of conglomerate, feldspathic sandstone and quartzite. Residual rocks overlie the weathered basement in places. The lower siltstone member has a siltstone- and shale-dominated lower and middle unit with sandstones locally dominating the upper part. The Vakkejokk Breccia (the only formal member) consists of angular pebbles, cobbles and boulders within a matrix of sandstone or siltstone and is only recognized with certainty on the northern side of Torneträsk. Red and green siltstones of the red and green siltstone member form a marker horizon within the Torneträsk Formation. The member coarsens upwards and passes into interbedded siltstones and sandstone. The overlying upper sandstone member is dominated by quartz sandstone with occasional thin interbeds of siltstone and fine sandstone. Bluish quartzites are common in the upper part. A thin unit of phosphorite-bearing conglomerate is common at the contact with the overlying upper siltstone member. This member, being mainly composed of a greenish siltstone with a calcareous uppermost unit, is overlain by the black shales of the Alum Shale Formation.

The sediments of the Torneträsk Formation reflect a variety of sedimentary environments such as coastal alluvial, bay or lagoon, deltaic, tide-influenced and offshore marine.

The Torneträsk Formation is fossiliferous. Kulling (1960a, 1964, 1972) found *Kullingia concentrica* (previously *Spriggia annulata* Southcott; Føyn & Glaessner 1979) in a sandy upper part of the lower siltstone member (Middle sandstone formation of Kulling 1964) and proposed a very latest Proterozoic age for this unit. Studies on microfossils by Vidal (1979) showed the member to be upper Vendian. Overlying members contain fossils dating this part of the Torneträsk Formation as Lower Cambrian (Moberg 1908, Kulling 1960a, 1964, 1972, Vogt 1967, Ahlberg & Bergström 1978, Ahlberg 1979, 1980).

This study was initiated by the IGCP project ''Correlation of Caledonian Stratabound Sulphides'' (CCSS) and was financed by the Swedish Natural Science Research Council. Comparable rock units to the south (and to some extent to the north) of the studied area are known to contain several occurrences of disseminated galena. Most of these mineralizations are small and without economic interest but some of them are being mined (Laisvall, Vassbo). The aim of this study is to provide a better knowledge of the lithostratigraphy and depositional environments of the rocks containing these Pb-rich deposits. However, the study has shown that, with a few exceptions (for instance at the eastern part of Rautasjaure, Fig. 2), galena disseminations are absent or unknown in the northern part of Norrbotten County.

TERMINOLOGY

The Torneträsk Formation is part of the Dividal Group, which has also been named the ''Hyolithus-serie'' or ''Hyolithus-zone''. The concept of the Dividal Group (Dividalsgruppen) was introduced by Pettersen (1878) and originally it included the presently described Torneträsk and the Alum Shale Formations, as well as some overlying metamorphosed rocks. Later, however, Pettersen (1887) redefined the term to be almost identical with the present Dividal Group. The ''Hyolithus-serie'' was introduced by Svenonius (1892) and apart from the Dividal Group it included deformed and metamorphic rocks (Ramanskiffer), later included in the Middle thrust rocks (Kulling 1960b, 1982). The ''Hyolithus-serie'' or ''Hyolithus-zone'' was then used in preference to the Dividal Group, at least in Sweden. As it became evident that the ''Hyolithus-serie'' not only included Cambrian strata but also strata of uppermost Proterozoic devoid of hyolithids, a change of name was considered relevant. Føyn (1967) re-introduced the term Dividal Group and summarized that ''the Dividal Group is an autochthonous group of sedimentary rocks, mainly shales, siltstones and sandstones, resting with erosional unconformity on the Precambrian crystalline basement, and upwards confined by thrust planes of Caledonian age. The thrust planes cut the Group within the alum shale formation or at stratigraphically lower levels. The Group occurs along the margin of the Caledonian mountain range in Norrbotten (Sweden), Enontekis (Finland), Troms and Finnmark (Norway).'' In 1967, Kulling, at a meeting at the Geologiska Föreningen (GFF 89: 484–485), suggested that the term ''Hyolithus-serie'' should be replaced by the Torneträsk Group (Torneträskgruppen). Subsequently, the name was not used by Kulling (1972) but reappeared in Kulling (1982). Kulling did not discuss the name or concept Torneträsk Group in relation to the earlier Dividal Group. The present author has not visited the Dividalen valley but it seems that the autochthonous sedimentary succession is by far better exposed in the Torneträsk area than it is in the Dividalen valley. This was stated already by Pettersen (1887, 1888), but priority has to be given to the Dividal Group and Føyn's (1967) definition has been followed in this paper.

The Torneträsk Formation here is suggested to ascribe to the sedimentary sequence overlying Proterozoic basement and underlying the black shales of the Alum Shale Formation in northern Norrbotten County. The lithology of the Torneträsk Formation is quite different from that of the Alum Shale Formation, and elsewhere in Scandinavia these lithologies have not been placed within the same group; the Dividal Group is used in this paper by convenience.

The Torneträsk Formation extends from the Torneträsk area south to Stora Sjöfallet. The Torneträsk Formation is almost continuously exposed in a stream section at the north-eastern slope of the mountain Luovare (Luovarri) on the southern side of the lake Torneträsk. The sharp eastern escarpment of Luovare is called Luopakte and the section is known by this name in previous literature. This name is also used in this paper. The sequence was described in great detail by Moberg (1908) and has also been thoroughly studied by Kulling (1960a, 1964, 1972). Additional biostratigraphic studies have been carried out by Ahlberg & Bergström (1978) and Ahlberg (1979). Kulling (1960a, 1964, 1972) distinguished six units, by him classified as formations, within the present Torneträsk Formation. Some of these have, however, been difficult to identify as mapable units outside their type section at Luopakte, and therefore it is preferred to change their status from formation to member. Some adjustments of the boundaries of the members have also been made. With the present insufficient knowledge about the members it is therefore preferred to keep the members informal with the exception of the Vakkejokk Breccia. Additional studies of the Torneträsk Formation may show that the upper siltstone member, and possibly the red and green siltstone member possess such characteristic lithological features that they can be regarded as formations of their own. In that case, the hierarchy of the Torneträsk Formation may be changed again. A comparison between Kulling's terminology and the one proposed in this paper is shown in Table 1.

TABLE 1. The nomenclature of the Dividal Group used in this paper compared to Kulling (1960a, 1964, 1972).

Kulling (1964)	This paper		
Alum shale formation	Alum Shale Formation		DIVIDAL GROUP
Upper shale formation	Upper siltstone member	TORNETRÄSK FORMATION	
Upper sandstone formation	Upper sandstone member		
Middle shale formation	Red and green siltstone member		
Middle sandstone fm. / Vakkejokk Breccia	Lower siltstone member / Vakkejokk Breccia		
Lower shale fm. / Vakkejokk Breccia			
Lower sandstone formation	Lower sandstone member		

DESCRIPTION OF THE TORNETRÄSK FORMATION

The section at Luopakte is the most complete section through the Torneträsk Formation, hitherto known, and the description of the formation is thus largely based on this section. However, the lower sandstone and lower siltstone members are better known elsewhere (*e.g.* north of Torneträsk), and it has been preferred to describe these members from localities outside Luopakte.

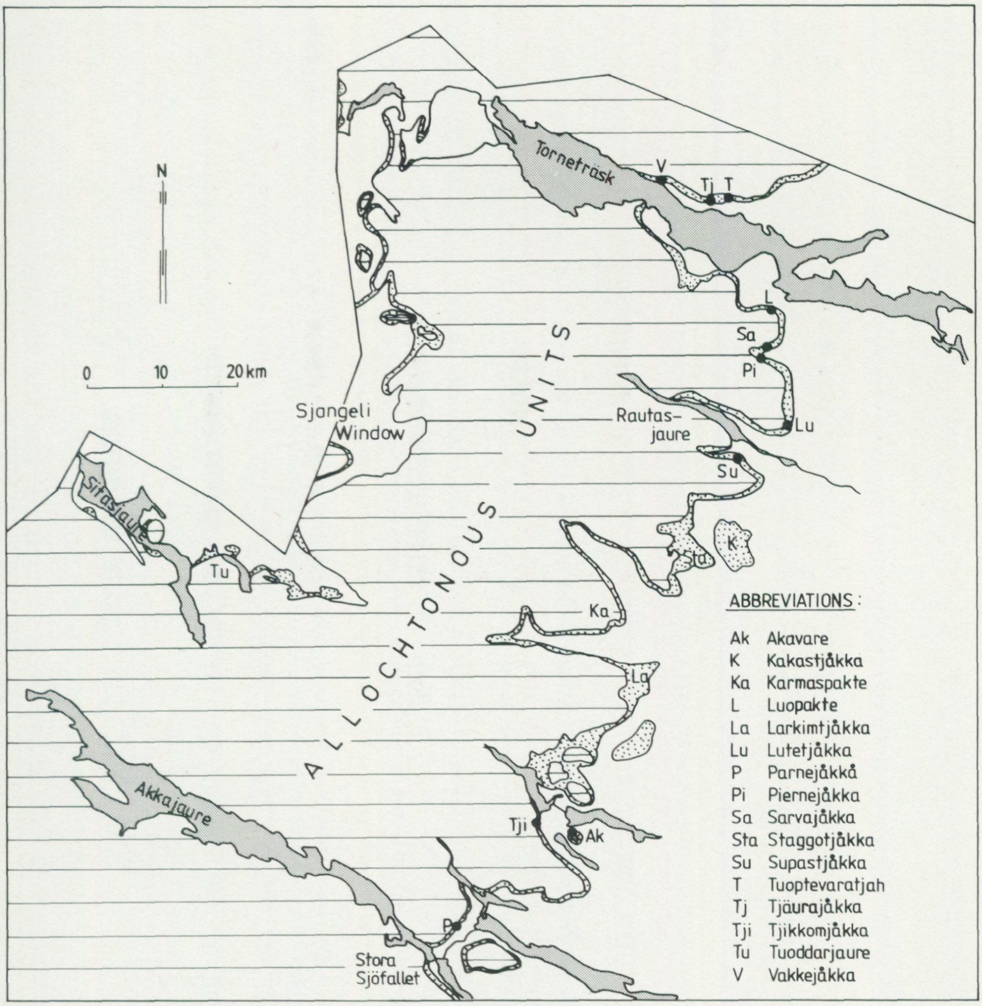
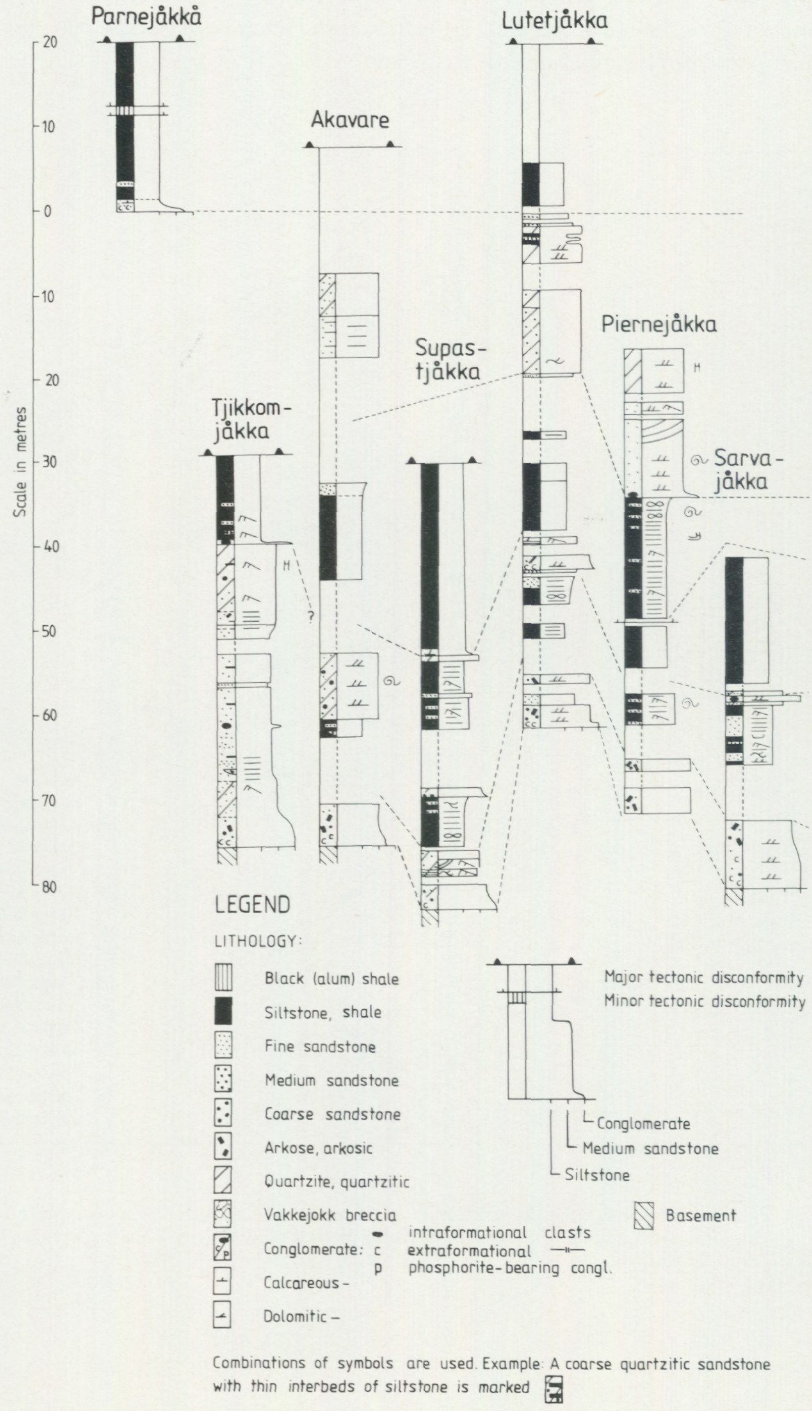


Fig. 2. Distribution of the Dividal Group within northern Norrbotten County (stippled), after Kulling (1964). Location of the lithostratigraphic profiles shown in Fig. 3 and place names referred to in the text.


Parnejåkkå
Lutetjåkka
Akavare
Supas-
tjåkka
Piernejåkka
Sarva-
jåkka
Tjikkom-
jåkka
Scale in metres
20
10
0
10
20
30
40
50
60
70
80
LEGEND
LITHOLOGY:
Black (alum) shale
Siltstone, shale
Fine sandstone
Medium sandstone
Coarse sandstone
Arkose, arkosic
Quartzite, quartzitic
Vakkejokk breccia
Conglomerate: c
p
intraformational clasts
extraformational
phosphorite-bearing congl.
Calcareous -
Dolomitic -
Major tectonic disconformity
Minor tectonic disconformity
Conglomerate
Medium sandstone
Siltstone
Basement
Combinations of symbols are used. Example: A coarse quartzitic sandstone with thin interbeds of siltstone is marked

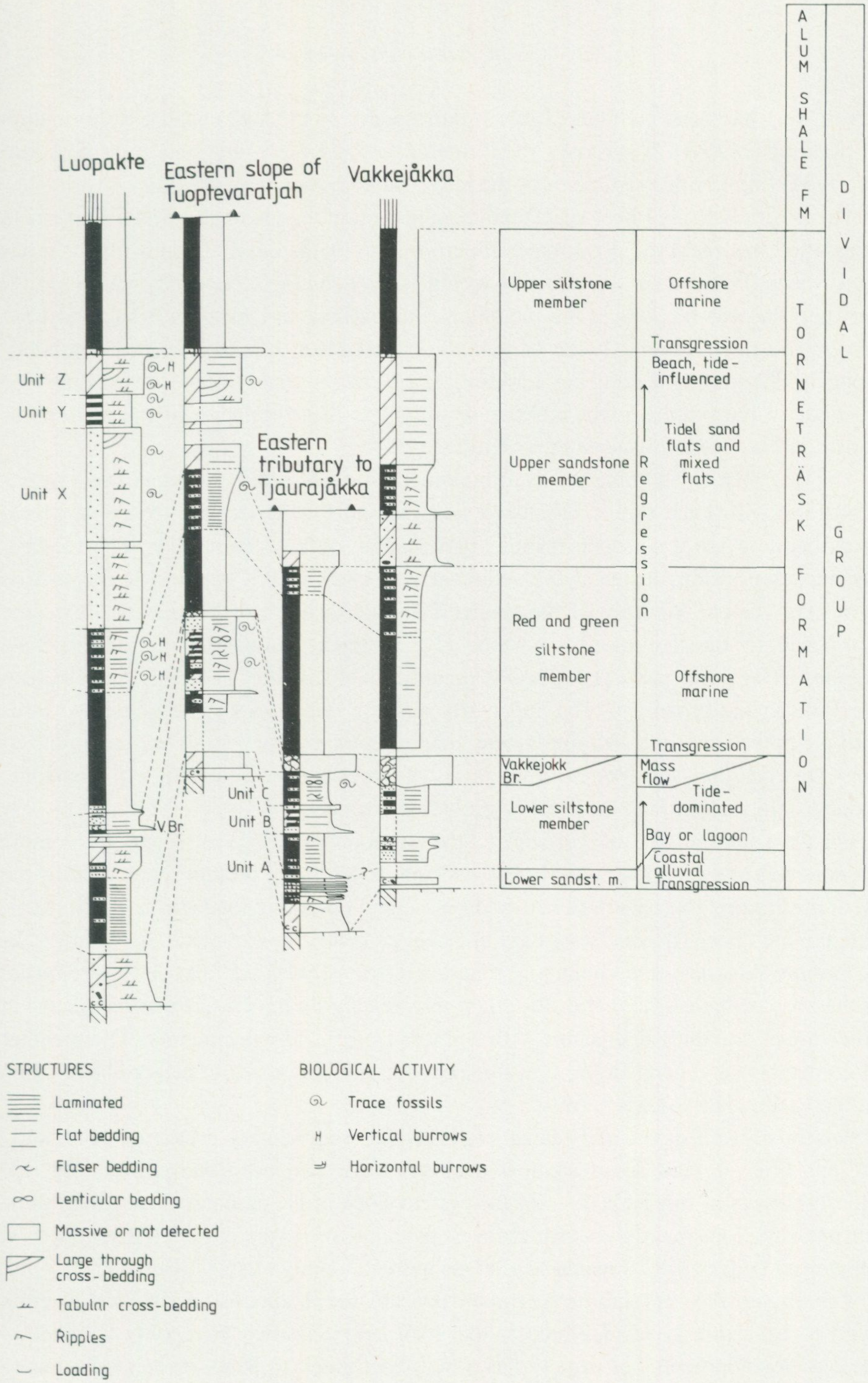


Fig. 3. Lithostratigraphic profiles of the Torneträsk Formation. Location of sections is shown in Fig. 2.

THE LOWER SANDSTONE MEMBER

The lower sandstone member (Table I) corresponds to the lower sandstone formation of Kulling (1964). It overlies the Proterozoic basement, and the transition into overlying fine-grained sediments of the lower siltstone member is gradual.

The position of the lower sandstone member within the lower part of the Torneträsk Formation has sheltered it from tectonic truncation by the overlying allochthon. It has hence been preserved at a number of localities between the sections shown on Fig. 3; between the two sections at the mountains Supastjåkka and Akavare it has also been recognized (Fig. 2) on *e.g.* the mountains Staggotjåkka, Kakastjåkka, the south-east slope of Karmaspakte, and on Larkimtjåkka. The presence of the lower sandstone member in these areas gives additional support to the correlation of the member as shown in Fig. 3 and as suggested by Kulling (1964).

The member is dominated by conglomerate, feldspathic sandstone and quartz sandstone with local thin interbeds of siltstone and fine sandstone. Cosets of planar cross-bedding are a common feature, particularly south of Torneträsk. The member and its relationships to overlying sedimentary rocks are well exposed in the section along the eastern tributary of the rivulet Tjäurajåkka north of Torneträsk. It is here composed of bluish, coarse sandstone (3.5 m thick), containing a few dispersed pebbles in its lower part. The member unconformably overlies gneissose basic rock of the Proterozoic basement. The apparently massive quartz sandstone grades upwards into a rippled quartzite. An uppermost zone, approximately 4 m thick, composed of siltstone and fine sandstone with interbeds of thinly bedded coarse quartz sandstone, indicates the transition to the overlying siltstone member.

On the southern side of Torneträsk, the variation of grain size seems to be more pronounced and conglomeratic layers and lenses are often present together with the medium-grained to coarse-grained feldspathic and quartzitic sandstones which dominate the member. The sandstones are in places cemented by carbonate. Conglomerates of varying thickness and containing rounded quartz pebbles are frequently recognized at the base of the member. Locally, they rest directly on the Proterozoic basement, in other areas on residual breccias with a thickness of a few decimetres. The member often displays a general fining-upward sequence and this seems to be accompanied by an increasing quartz/feldspar ratio.

Cosets of well-developed planar cross-bedded sedimentary rocks are commonly present (Fig. 4) and some shallow channels have also been recognized (Fig. 5). Measurements of foreset beds from the eastern slope of the mountain Lutetjåkka show current directions mainly towards the west or south-west, whereas the few readings on the foreset beds of the Luopakte section are more randomly oriented (Fig. 6).

The Proterozoic crystalline basement beneath the Torneträsk Formation is often mantled by a thin layer of a breccia-like rock here classified as regolith. It displays various developments but usually has a matrix of greenish, fine- or medium-grained

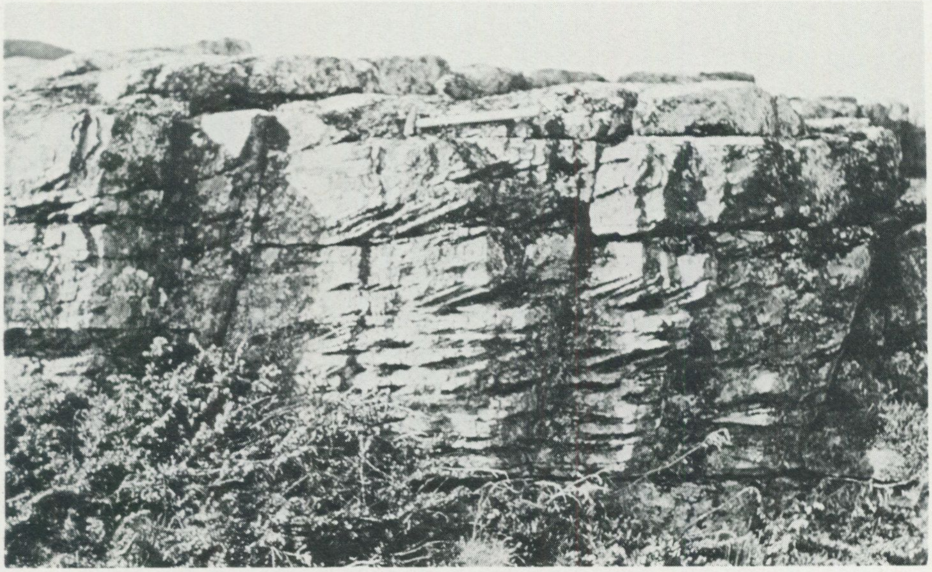


Fig. 4. Planar cross-bedded, coarse feldspathic sandstone in the lower part of the lower sandstone member. – Lutetjåkka section.

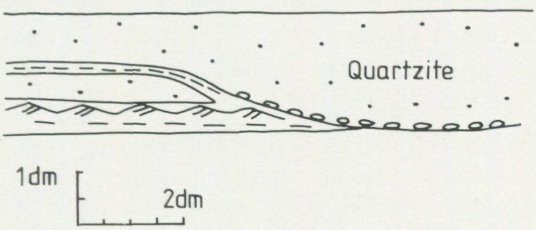


Fig. 5. Channel deposit cutting rippled siltstone and fine sandstone. – Lower sandstone member at Supastjåkka section.

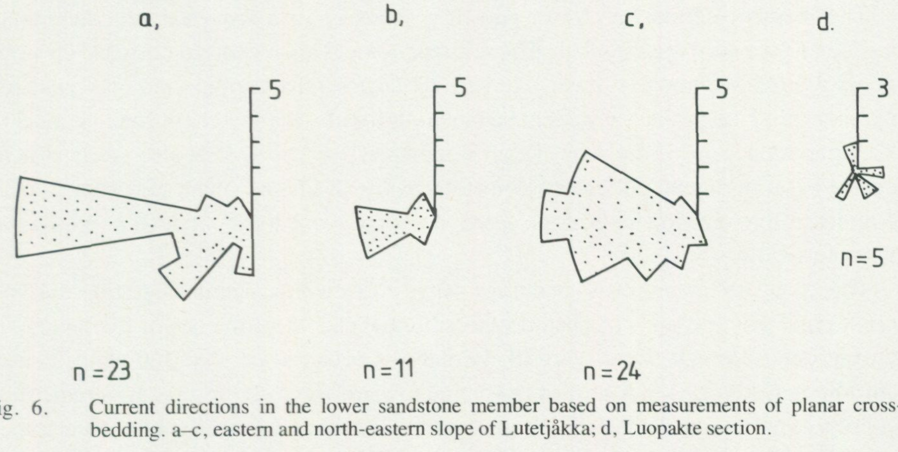


Fig. 6. Current directions in the lower sandstone member based on measurements of planar cross-bedding. a–c, eastern and north-eastern slope of Lutetjåkka; d, Luopakte section.

sandstone containing scattered angular clasts, which include dominant granules and pebbles, but also cobbles and boulders can be seen. Most fragments are composed of rock types similar to those underlying the regolith, and they are likely to be very locally derived. On the southern slope of the mountain Karmaspakte (Fig. 2), the boundary to the underlying crystalline basement is somewhat diffuse and it seems that the basement is penetrated by dark cracks filled with material resembling the matrix of the overlying 0.5 m thick regolith. The regolith is in turn overlain by 1.5 m of medium-grained sandstone with a few scattered pebbles. This sandstone is also seen elsewhere in the vicinity directly overlying the crystalline basement (acid lavas; Ödman 1957); the regolith being absent. In other places (*e.g.* north-east of the mountain Lutetjåkka), it is difficult to define the boundary between the basement and the regolith because weathered basement passes ''gradually'' upwards into the regolith. Regolith has also been observed at several places on the mountains Larkimtjåkka, Staggotjåkka and Kakastjåkka (Fig. 2).

Some of the occurrences of regolith have previously been referred to as tillites (Kautsky 1949, Kulling 1951), and they are marked as such on the Geological map of Sweden (Sveriges geologiska undersökning 1958, Scale 1:1 000 000). The present author has had the opportunity to examine Vendian tillites (Långmarkberg Formation) unconformably overlying the crystalline basement in northern Jämtland County and these deposits have sharp and well-defined lower boundaries. They are also closely associated with laminated siltstone containing dropstones (Thelander 1981). Such deposits, interpreted as glacio-marine or glacio-lacustrine, have not been found together with the deposits of regolith. The differences mentioned are important, and a glacial origin for the regolith is considered less probable.

Sedimentary environments — The lower sandstone member was deposited on a weathered basement surface during a transgressive cycle. Several criteria indicate that deposition occurred on a coastal plain, influenced by fluvial activity, and successively in near-shore environments as the transgression proceeded.

The member defines the lower part of a fining-upward sequence which continues into the lower siltstone member. The feldspar content also seems to decrease upwards. A weathered basement surface overlain by coarse terrigenous sediments gradually passing into fine-grained sediments containing fossils (the lower siltstone member) is strong evidence for deposition within a transgressive cycle. It is also likely that the coarse basal sediments (often conglomeratic and with a high content of feldspar), when compared to overlying sediments, were deposited close to the area from which they were derived.

The cosets of planar cross-beddings suggest deposition within migrating dunes or point bars. The presence of channels possibly indicate the influence of fluvial activity during deposition. It seems very likely that this occurred on a coastal plain. Palaeocurrent data suggests transport of the debris towards the west. In spite of a rather high supply of terrigenous material, from an assumed largely easterly situated sediment source area, the transgression continued. The shoreline moved eastwards and the coastal, often feldspathic sands were overlain by sands exposed to wave activity during deposition which resulted in more quartz-rich lithologies.

The composition and sedimentary structures of the sediments in the transitional zone to the lower siltstone member as seen in the eastern tributary of the rivulet Tjäurajåkka suggest that the medium-grained sands were gradually submerged while deposition of silt and fine sand increased. Occasional strong current activity occurred as suggested by the interlayers of coarse quartz sandstone. Judged by the shape of these coarser sediments, at least some were brought into the deepening basin as channel deposits. ''A common expectation among stratigraphers is to find tidal deposits where marine strata merge with nonmarine strata, either in laterally or vertically exposed sequences'' (Walker and Harms 1975, p. 103). Such deposits are to be expected within the transitional zone between the lower sandstone and lower siltstone members. However, present information about the sedimentary structures in the transitional zone gives no evident support to any interpretation involving periodic flood and ebb of tides. Shore lines with weak tidal activity are likely to develop within partly enclosed epicontinental seas. Deposition of the lower sandstone member within such an environment thus possibly explains the absence of tide-influenced structures within the transitional zone. The type of currents causing the coarse-grained infilled channels are uncertain but wind-driven currents (*i.e.* storm surges) seem to be a possible explanation; such deposits are likely to be important in epicontinental seas where tide-activity is low (Johnson 1978).

THE LOWER SILTSTONE MEMBER

The lower siltstone member corresponds to the lower shale formation and middle sandstone formation of Kulling (1964). The upper boundary is placed beneath a dolomitic bed which in places occurs at the base of the red and green siltstone member. However, on the northern side of Torneträsk, where the siltstone and sandstone of the lower siltstone member are overlain by a characteristic,coarse, fragment-rich breccia, the Vakkejokk Breccia, it is preferred to place the boundary at the base of this breccia.

The lower siltstone member is composed of a number of different lithofacies and continued work needs to be carried out before detailed correlations between the studied sections can be made. The member is dominated by siltstone and fine sandstone, which in places contain thin rippled, coarse sandstone. Fining-upward sequences are seen within the member, but other sections, particularly the section at Luopakte, show an increased sand input in the upper part of the member.

The lower siltstone member is well exposed in the eastern tributary of the rivulet Tjäurajåkka and is here overlain by the Vakkejokk Breccia. At this locality the member is divided into three subunits (Fig. 3): a lowermost shale forms unit A, a quartzite/siltstone unit B, and a siltstone/very fine sandstone unit C. The shale unit A

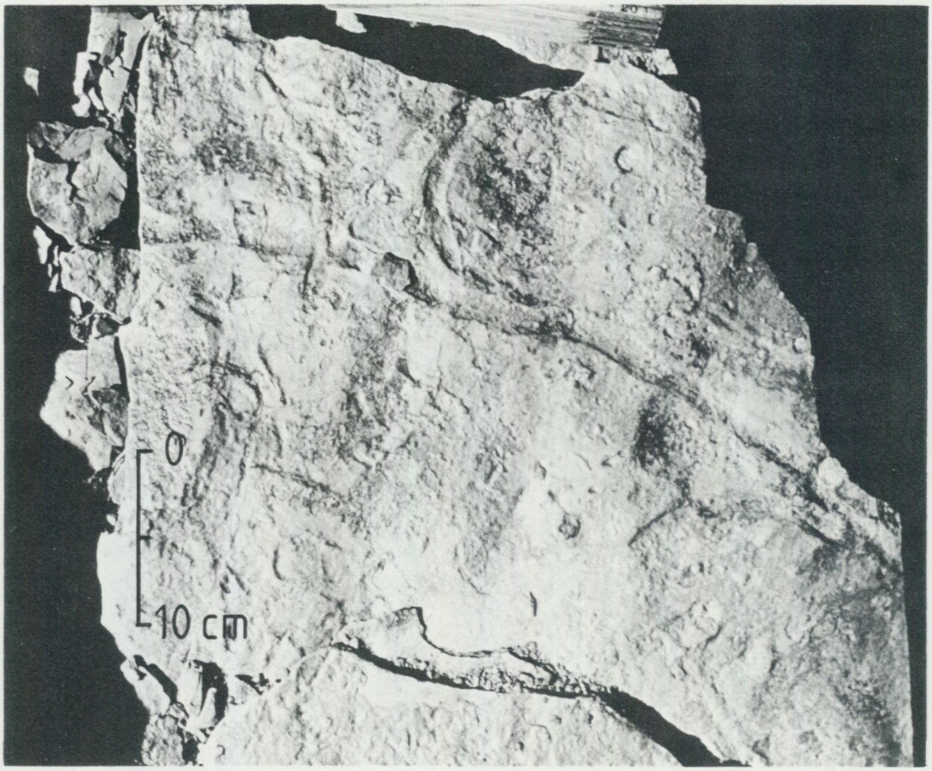


Fig. 7. Trace fossils on bedding plane. – The lower siltstone member, Luopakte section.

consists of a grey shale which is 5.3 m thick. The basal part (approx. 2 m) of this contains a few ripples of coarse quartz sandstone. Rippled medium-grained quartz sandstone occurs within the uppermost part (approx. 1.3 m) of the grey shale. The shale is overlain abruptly by the quartzite/siltstone unit B. This consists of a thin basal mudflake conglomerate (0.05 m) overlain by thinly bedded quartzite and siltstone (0.35 m), very fine sandstone (0.6 m), thinly bedded quartzite and siltstone (2.3 m), and finally greyish blue massive quartzite (0.5 m). The uppermost unit C consists of laminated and very thinly bedded siltstone and very fine sandstone (approx. 4 m), which in places is quartz-rich. Flaser and lenticular bedding occur and trace fossils on bedding planes are common.

The lower part of the member has not been observed on the eastern slope of the mountain Tuoptevaratjah (the section shown in Fig. 3 has been established in the western tributary of the rivulet Tuoptejåkka). The middle and upper parts of the member have, however, a similar development as in the Tjäurajåkka section. A silty shale (2.5 m) with interlayers of dune and ripple shaped quartz sandstone (partly very coarse sandstone) composes the lowermost unit observed and occurs approximately 5 m above sediments of the lower sandstone member. The unit of silty shale, which

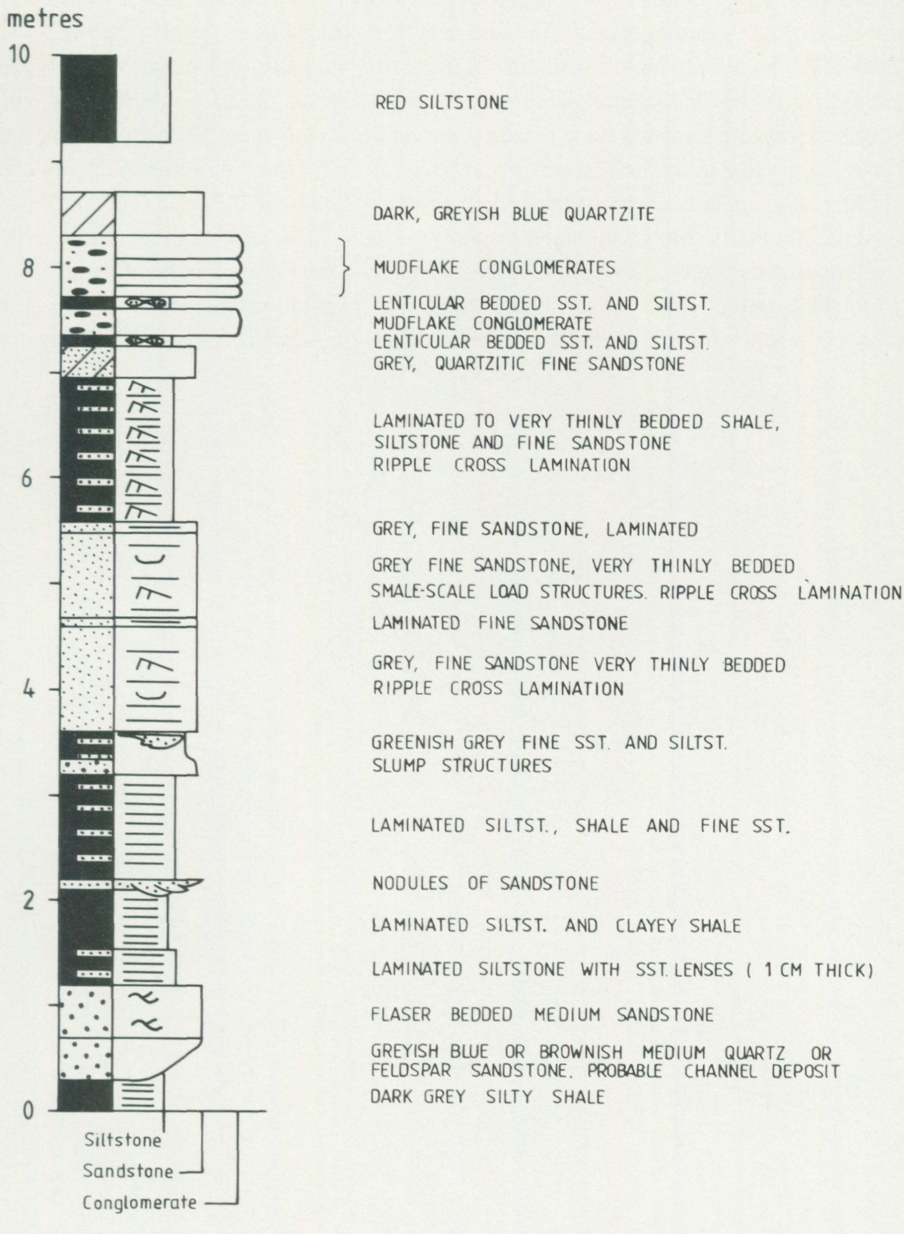


Fig. 8. Logged profile showing the upper part of the lower siltstone member and lowermost part of the red and green siltstone member at Sarvajåkka. The sediments are interpreted to have been deposited in tide-dominated environments.

possibly corresponds to unit A of the Tjäurajåkka section, is overlain abruptly by a mudflake conglomerate (0.1–0.2 m) with a matrix of quartz sandstone. It is followed upwards by grey homogeneous fine and very fine sandstone (1.8 m) which in some cases displays a faint planar bedding. This passes gradually (0.5 m) into very thinly bedded, cross-bedded quartzite, siltstone and fine sandstone (2.5 m). Ripples with truncated tops are seen and trace fossils occur on bedding planes. The following unit is a grey, laminated quartzite and siltstone, about 3 m thick, showing flaser and lenticular bedding, trace fossils occur on the bedding planes of this unit as well. The unit passes upwards gradually into a laminated to thinly bedded bluish grey quartzite and greyish green quartz-rich fine sandstone (1.5–2 m) containing trace fossils on bedding planes.

On the southern side of Torneträsk the upper part of the member shows a pronounced influx of sand. In the Luopakte section, for instance, interbedded siltstone

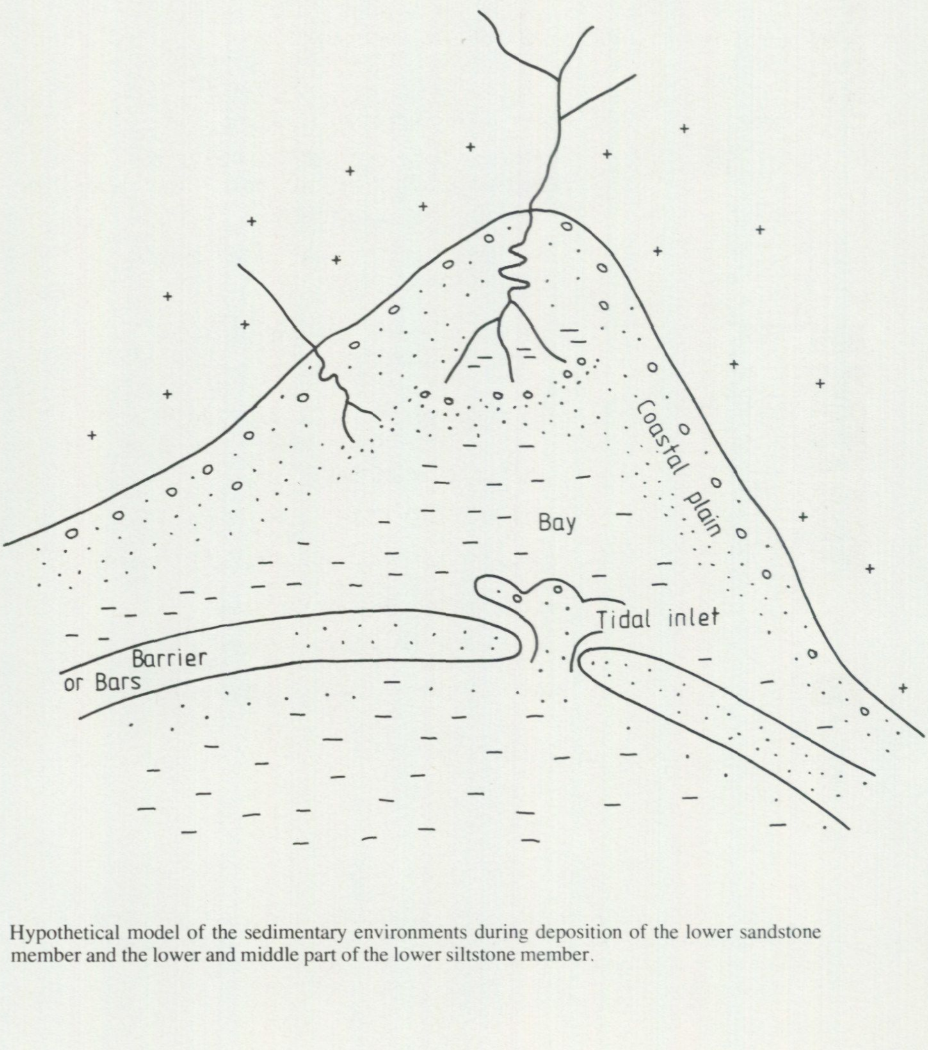


Fig. 9. Hypothetical model of the sedimentary environments during deposition of the lower sandstone member and the lower and middle part of the lower siltstone member.

and fine sandstone grade upwards into an uppermost 6–7 m thick sandstone-dominated unit (broadly the Middle sandstone formation of Kulling 1964). The basal 3–4 m of this unit is dominated by whitish grey quartzite and medium-grained feldspathic quartz sandstone, the lower part of which, in places, is slightly calcareous. A very weak galena dissemination has been observed. Cross-bedding and ripples on bedding planes occur, as do trace fossils (Fig. 7). The sandstone unit is overlain by a greenish, laminated siltstone and fine sandstone bed (0.5–1 m thick). It was possibly in this bed that Vighi (Kulling 1964) and Kulling (1960a, 1964, 1972) found *Kullingia concentrica* (Føyn and Glaessner 1979). This bed is overlain by a bed of sandstone (0.2 m) containing dispersed rounded pebbles and shale fragments (marked V.Br. on Fig. 3). A greenish, mediumly bedded, feldspathic sandstone (1.5 m) completes the lower siltstone member. The thin bed of conglomeratic sandstone was suggested by Kulling (*e.g.* 1964) to be correlated with the Vakkejokk Breccia which according to Kulling marked a major unconformity in the Torneträsk Formation separating late Vendian rocks from rocks containing Lower Cambrian fossils (the red and green siltstone member and overlying members).

Detailed measurements of the lower siltstone member have also been obtained in the rivulet Sarvajåkka and a log from this section is shown in Fig. 8, which illustrates the diversity of grain-size variation.

Much of the member is also exposed further south in the northern slope of Supastjåkka where the following sequence has been measured through the member (Fig. 3):

max 20–25 m.	Red and green siltstone.	Red and green
0.3 m.	Dolomitic sandstone.	siltstone member
0.7 m.	Dark greyish blue quartzite.	
4 m.	Laminated siltstone. Occasional thin layers of fine sandstone. A few ripples of medium sandstone in basal part.	
0.4 m.	Grey fine sandstone with low angle cross-bedding.	Lower
c. 4 m.	Siltstone and fine sandstone, usually laminated or very thinly bedded. Occasional thin lenses of coarse quartz sandstone and conglomerate. Ripples.	
c. 7 m.	Covered, probably the same rocks as overlying unit.	siltstone
1 m.	Quartzite and quartz sandstone. Basal 5–10 cm consist of fine conglomerate.	
6 m.	Silty shale with subordinate lenticular interlayering of quartz sandstone, sligthly coarsening upwards due to increased frequency of interbeds of sandstone. Flaser bedding in the upper part.	member
0.3 m.	Covered.	
c. 7 m.	Quartzite, sandstone and conglomerate.	Lower sandstone member

Sedimentary environments — The variations in lithostratigraphy of the lower siltstone member between different sections suggest contemporaneous deposition in sligthly different sedimentary environments. The erosional nature of the contact between the Vakkejokk Breccia and underlying units indicates the possibility of non-contemporaneity of deposition of the different successions. The discussion of sedimentary environment will therefore first be outlined within a minor area on the northern side of Torneträsk where the member is best known.

In this area, the sections at the eastern tributary of the rivulet Tjäurajåkka and the eastern slope of the mountain Tuoptevaratjah are closely spaced to each other and rather well-exposed. The three lithological units, A–C, recognized in the former of the two sections are thought to reflect deposition within three related sedimentary environments; 1, bay or lagoon, 2, bars or barrier and 3, tide-dominated deposition, respectively.

As the submergence of the coastal plain deposits of the lower sandstone member continued, sediments of the transitional zone at the top of this member (eastern tributary of Tjäurajåkka) were overlain by the fine-grained sediments of unit A, lower siltstone member. Sandstone occurring as ripples in the lower part of the grey shale suggests occasional influx of coarse material. Eventually this input ceased and argillaceous detritus alone was deposited which required a calm basin, and deposition is thought to have occurred within a bay or lagoon (Fig. 9).

The slowly increasing content of sand within the upper part of the bay or lagoon deposit suggests shallowing which is also supported by the overlying body of interbedded siltstone and sandstone, unit B, explained as a landward advancing system of bars and tidal flats. The lower part of the lower siltstone member (unit A) is not exposed in the Tuoptevaratjah section and the lagoon or bay deposits have thus not been seen here. However, the silty shale with thin interbeds of coarse quartz sandstone may well correspond to the upper part of this facies and deposition on the landward side of the bars or barrier (the barrier plain), seems possible.

The intercalations of sandstones at the base of unit B suggest that the sand input suddenly increased. The reason for this is unclear and various depositional models can be advocated. At the eastern slope of Tuoptevaratjah, the clean, fine sandstone bed (1.8 m thick) with the occasional faint planar stratification above the mudflake conglomerate, may represent a beach deposit. The mudflake conglomerate is regarded as a shore line conglomerate marking a discontinuity of unknown but probably short duration. In the section at the eastern tributary of the Tjäurajåkka, there is no obvious counterpart to the presumed beach deposit. The basal mudflake conglomerate of unit B here may rather have been deposited as a channel lag conglomerate and possibly favouring tidal inlet sedimentation behind the barrier.

The overlying unit C of siltstone and fine sandstone in the two sections discussed contains abundant trace fossils on bedding planes suggesting marine conditions. Flaser bedding and lenticular bedding are characteristically seen within tidal deposits (Reineck 1972). Their presence within the upper part of the lower siltstone member could thus indicate tidal activity. Mud cracks have not yet been observed and deposition may thus have been within the subtidal zone.

Sedimentation influenced by tidal activity is also inferred from other sections of the lower siltstone member. The logged section (Fig. 8) through the top of the member at Sarvajåkka (mainly interbedded shale, siltstone and fine sandstone) has a grain-size distribution and contains structures (flaser bedding, ripples, load and slump structures, trace fossils) which are common within recent mixed tidal flats (Reineck 1972).

The approximately 4 m thick unit of siltstone and fine sandstone in the lower upper part of the lower siltstone member at the northern slope of Supastjåkka is another example where a facies influenced by tidal activity during deposition is thought to be represented. In this section the tidal sediments do not compose the top unit of the member. A low-angle cross-bedded layer of fine sandstone overlying the presumed tidal sediments suggests beach deposit. The overlying shale without observed intercalations of sandstone, except in the lowermost part, indicate renewed deposition in a sheltered, possibly lagoonal environment.

In the Luopakte section, the lower part of the member is less well exposed. The coarsening-upward sequence clearly indicated by the increased sand content in the middle and upper part of the member, supports increased current activity. Present information is insufficient to demonstrate whether this is due to marine shallowing or deepening. In the case of continued transgression and bearing in mind the presence of tidal deposits in neighbouring areas, the grain-size distribution may be explained as a mixed flat passing into a sandy tidal flat. Thereafter, however, it seems possible that the depositional cycle was interrupted and that the overlying thin conglomerate and feldspathic sandstone belongs to a depositional environment related to the deposition of the Vakkejokk Breccia. This latter unit has been suggested (see below) to be a mass flow deposit and, possibly, the thin conglomerate and overlying sandstone represent redeposition of this unit.

THE VAKKEJOKK BRECCIA

The Vakkejokk Breccia is a conspicuous marker-horizon overlying the lower siltstone member on the north-eastern side of Torneträsk. The breccia has previously been claimed to be a tillite (Kulling 1951), but recent studies emphasize an origin by mass flow possibly related to a periglacial area (cf. Kulling 1972).

Kulling (*e.g.* 1972) concluded on the basis of fossil content that in the Luopakte section a bed of conglomeratic sandstone is a possible but not very characteristic counterpart to the Vakkejokk Breccia separating sediments of Vendian age from overlying Lower Cambrian. He also pointed out that the stratigraphic position of the Vakkejokk Breccia approximately corresponds to the upper of the two tillite formations, the Mortensnes Tillite, of Finnmark in northern Norway. However, on the basis of lithostratigraphic comparison between sections at Torneträsk, Avevagge (Troms, Norway), Halkkavarre, Kunes, and Digermulhalvøya (Finnmark, Norway) it was suggested by Føyn (1967) and Vogt (1967) that the Vakkejokk Breccia was deposited later than the Mortensnes Tillite. Studies of microfossils (acritarchs) by Vidal (1979) independently show that a time-correlation between the two rock units cannot excist.

In its type section at the rivulet Vakkejåkka the breccia reaches a thickness of 3–4 m. Kulling (1964), however, describes the thickness as 7 m in the same section. There has been no opportunity to control the measurements. The Vakkejokk Breccia thins towards the ESE and 7.5 km in this direction, in the western tributary of Tuoptejåkka on the eastern slope of Tuoptevaratjah, it is only 0.5 m thick. The development of the breccia varies but a high percentage of pebbles, cobbles and boulders are commonly inbedded within a silty or fine sandy matrix. Lens-shaped bodies of breccia containing a low percentage of larger clasts are occasionally seen as interbeds within the clast-rich breccia. The boundaries between different types of breccia are sharp or transitional over some decimetres. Erosional contacts have been observed (Fig. 10) and a faint stratification is occasionally recognized within the low-clast type of breccia. Siltstone and sandstone without pebbles are also developed as interbeds with thickness less than about half a metre. They can be traced over some metres, sometimes showing a faint, even lamination.

The roundness of the pebbles and boulders within the Vakkejokk Breccia varies from angular to well-rounded. No statistic treatment has been carried out but sub-angular clasts seem to predominate. Fragments of shale and sandstone are locally abundant (Kulling 1972) but the larger fragments are generally composed of granitic rock types. Bent shale fragments demonstrating soft sediment deformation have been observed in a few cases. Reddish syenite and fine-grained greenstone are also found sparsely as fragments within the breccia. Granitic boulders in the breccia are in some cases penetrated by cracks injected by the silty matrix of the breccia; these boulders could therefore hardly have survived any longer distance of transport.

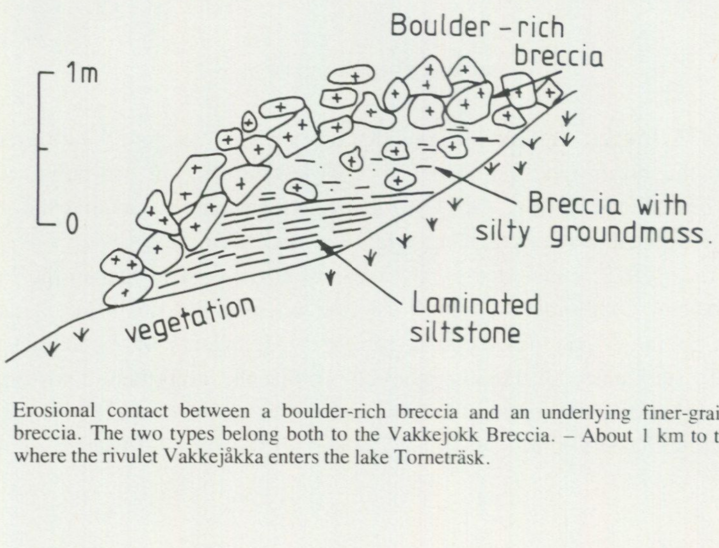


Fig. 10. Erosional contact between a boulder-rich breccia and an underlying finer-grained type of breccia. The two types belong both to the Vakkejokk Breccia. – About 1 km to the east from where the rivulet Vakkejåkka enters the lake Torneträsk.

The Vakkejokk Breccia abruptly overlies the fine-grained sediments of the lower siltstone member. Load cast phenomena along the boundary (Fig. 11) suggest a soft sediment condition for the underlying sediments at the time of deposition of the Vakkejokk breccia. Boulders within the breccia have deformed the stratification of the underlying siltstone and sandstone. Isolated boulders also seem to have sunk down into the substratum. Interfingering contacts between the breccia and underlying sediments have been described by Kulling (1964).

Sedimentary environments — Kulling suggested that the Vakkejokk Breccia was deposited by rock slides from basement islands. He explains the ''breccia in breccia'' structure as a seasonal freezing and thawing phenomenon and suggests that ''solifluction processes may have taken place in the creation of the Vakkejokk breccia'' (Kulling 1972, p. 172). He mentions that periglacial conditions may have been present.

The characteristic features of the Vakkejokk Breccia, namely large grain-size variation, lack of sorting and the presence of bent shale fragments, are features commonly reported from deposits resulting from gravitational processes. These deposits can be divided into several types depending for example on the content of fine-grained materials, liquefaction, grain shape, and transporting mechanism, but most of the deposits can be classified within four main genetic groups; rock falls, slides and slumps, mass flows, and turbidites (Dott 1963). At the same time, these downslope deposits powered by gravity have many features in common with certain glacial deposits. The subject has been discussed in detail by Harland *et al*. (1966),

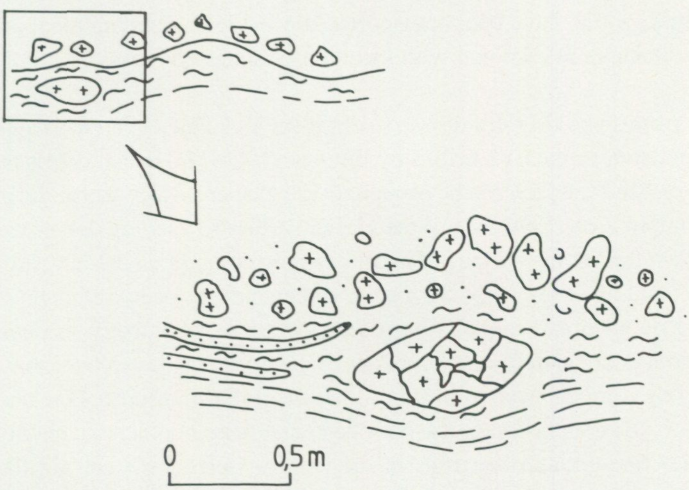


Fig. 11. Soft sediment deformation along the lower boundary of the Vakkejokk Breccia. – Same locality as in Fig. 10.

Spencer (1971), and others. The Vakkejokk Breccia was deposited on a soft substratum, and interfingers with waterlain sediments. It contains stratified interbeds and is overlain conformably by shallow marine sediments of the red and green siltstone member. These features suggest that the Vakkejokk Breccia was deposited subaqueously. It seems less probable that slumps or slides, mass flows and turbidity currents alone could explain the presence of the abundant extrabasinal clasts within the breccia. However, as Kulling (1964) suggested, the granitic fragments could have been brought into the basin by rock falls or avalanches. This caused instability and initiation of slumps and slides, which possibly developed into mass flows or even turbidity currents.

The presence of Proterozoic basement rocks as fragments in the Vakkejokk Breccia strongly suggests that basement heights (islands) still existed when the Vakkejokk breccia was deposited. It is true that the Vakkejokk Breccia contains features resembling those present in many tillites. Taken into consideration that the basement heights could possibly have been glaciated and that the Vakkejokk Breccia previously has been interpreted as a glacial deposit (Kulling 1951), it is thought valuable to discuss the possibility of a glacial origin for the breccia, although it cannot be correlated with the Mortensnes Tillite. The Vakkejokk Breccia has a rather restricted areal distribution and the hypothetical glacier is therefore also likely to have had a limited extension, thus assuming that neither non-deposition nor complete erosion of the glacial deposits over certain areas have occurred. The dominance of Proterozoic crystalline rocks indicate the hypothetical glacier to have eroded a basement height. The ice front possibly reached the sea but any extensive floating ice sheet did not develop as suggested by the apparent absence of laminated sediments with drop-stones. In the hypothetical glacial model, it seems possible that the material which was deposited as the Vakkejokk Breccia was brought into a waterfilled basin as flow tills. Such deposits are till debris, which have been transported downslope by gravitational processes and have many features in common with the slumps, slides and mass flows of non-glacial debris.

The mechanism of flow-till development from high glaciers on Vestspitsbergen and Nordaustlandet have been described by Boulton (1968). Englacial debris is transported as a series of bands, which can be brought to the glacier surface where the glacier snout is under compression. Lowering of the glacier surface by melting causes parallel debris ridges to develop on the surface. The ridges may collapse as the interstitial ice melts and highly fluid tills flow down the glacier and onto the adjacent sediments.

The two depositional models discussed above are very likely to develop similar features and it is difficult to rule out either of the processes. In spite of this, the present author prefers a model which does not include glacial transport. One major point of evidence for this conclusion is the presence of granitic boulders penetrated by cracks infilled with fine-grained materials in the breccia; such clasts are not likely to have survived ice-transport. The clasts have possibly been part of a regolith and transported downslope into the Vakkejokk Breccia.

THE RED AND GREEN SILTSTONE MEMBER

The red and green siltstone member has a siltstone-dominated lower and middle unit containing sandy interbeds in its most basal part. In the upper part, a successively increasing influx of sand occurred, resulting in deposition of interbedded sands and silts. The siltstone-dominated unit, corresponding to the Middle shale formation of Kulling (1964), is composed of a characteristic red and green siltstone. The unit has a wide-spread extension in the Scandinavian Caledonides. It is marker-horizon in the Torneträsk area and can be traced southward to Supastjåkka. South of Supastjåkka the sole thrust of the allochthon has truncated the autochthonous sequence at a level below the member and it has not been seen on the mountains Staggotjåkka, Kakastjåkka, Karmaspakte or Larkimtjåkka (Fig. 2). However, further south, in the Akavare section, it has been preserved. Westwards, in a section at the rivulet Tjikkomjåkka previously described by Marklund (*in* Kulling 1964), a unit of siltstone containing interbedded fine sandstone is tectonically truncated and overlain by allochthonous units. The siltstone overlies a unit dominated by sandstone and quartzite containing coarse, poorly sorted, conglomeratic, feldspathic sandstone at its base; a log of the Tjikkomjåkka section is listed below.

Thrust units of mylonite quartzite (Lower thrust rocks).

11 m. Siltstone, green in the lower part, otherwise grey. Thin rippled interbeds of sandstone in basal 3–4 m.

0.1 m. Fine-grained conglomerate.

8 m. Bluish grey quartzite with argillaceous drapes. Minor interbeds of fine-grained conglomerate. A few vertical burrows. Ripples preserved on bedding surfaces.

2 m. Thinly bedded quartzite and quartzitic feldspathic sandstone, brownish on weathered surfaces, otherwise whitish grey. The matrix is in places slightly calcareous. A few thin interbeds of siltstone occur. Sharp contact with overlying unit.

3 m. Covered.

15 m. Grey and greenish grey, fine-grained and medium-grained sandstones dominate. Thin parallel bedding in lower part. Thin interbeds of fine-grained conglomerate.

5 m. Bluish grey quartz sandstone, transitional upper boundary.

3.5 m. Greenish, poorly sorted feldspathic sandstone with scattered subangular fragments. Transitional upper boundary.

Granite (Basement).

By comparison with the neighbouring section at Akavare, the position of the siltstone unit in the upper part of the Tjikkomjåkka section is thought to correspond to the red and green siltstone member. However, the correlation remains uncertain and it is difficult to exclude the possibility that the siltstone unit at Tjikkomjåkka belongs rather to the upper siltstone member. Lithostratigraphic correlations in the area are complicated because the red and green siltstone member southwards wedges out; it is absent in the Parnejåkka section, in the vicinity of Stora Sjöfallet.

Red and green siltstones typical of the red and green siltstone member have not been recognized in southern Norrbotten County, but southwards, in the Tåsjön area of southern Västerbotten and northern Jämtland Counties, red and green siltstones of the Gärdsjön Formation (Member VI; Gee *et al*. 1974, Kumpulainen *et al*. 1981) reappear again as a marker-horizon in a lithostratigraphic position similar to the red and green siltstone member.

North of Torneträsk the unit of red and green siltstone can be recognized in several sections of the autochthon in Troms and Finnmark (Føyn 1967, Vogt 1967) and further north, on the Digermul halvøya, it corresponds more or less to the Breivik Formation of the Vestertana Group (Reading 1965, Føyn 1967).

The red and green siltstone unit is fossiliferous. The Lower Cambrian fossils *Platysolenites antiquissiumus* Eichwald and *Volbortella tenuis* Schmidt have been reported (Moberg 1908, Kulling 1964) within the area described. *Platysolenites* has also been reported by Føyn (1967) and by Føyn and Glaessner (1979) from the continuation of the unit in northern Norway.

The red and green siltstone member is well exposed in the Luopakte section, and it is here approximately 25 m thick. It overlies abruptly the older sediments. The

Fig. 12. Interbedded siltstones and sandstones belonging to the upper part of the red and green siltstone member abruptly overlain by sandstone of the upper sandstone member. The contact is approximately at the hammer. – Luopakte section.

lowermost bed of the member is composed of a dolomitic fine sandstone (0.2 m thick) with scattered shale fragments at the top. This bed is overlain by siltstone with sandy interbeds (c. 0.5 m), which disappear upwards, and the member thereafter consists of a siltstone with a very massive appearance which is due to only slight variation of grain size. The siltstone is greenish in its lower part, while the upper part is reddish with occasional green spots (often with abrupt boundaries); stratiform green layers also occur. Some fifteen metres above the base, the siltstone unit gradually passes into interbedded fine sandstone and siltstone (8 m thick; Fig. 12). The bed thickness varies mainly from laminated to thinly bedded, but, in common with the grain size, it tends to increase slightly upwards in the sequence. Parallel stratification is the most frequent sedimentary structure but ripple cross lamination and lenticular bedding are observed in places. Trace fossils on bedding planes are common, some burrowing also occurs.

The pattern observed in the Luopakte section, a lower, fine-grained unit gradually passing into a unit of interbedded siltstone and sandstone, is also present in the sections to the north (eastern tributary of Tjäurajåkka and eastern slope of Tuoptevaratjah) and south (Sarvajåkka and Piernejåkka). The Vakkejåkka section differs slightly in that the lower fine-grained unit is a clayey shale rather than a siltstone. In the Supastjåkka section and in a rivulet about 1 km further west, a thin (0.3 m) dolomitic sandstone bed occurs at the base of the member. A similar dolomitic layer at the same lithostratigraphic level also occurs in the sections north of Torneträsk. Thin interbeds of dolomitic sandstone also occur in the upper unit of the member.

Sedimentary environments — The dolomitic sandstone bed at the base of the red and green siltstone member suggests a deficiency of clastic grains at the time of deposition. Recognition of the red and green siltstones far outside the Torneträsk area indicates that underlying sediments had been submerged over extensive areas. The fine-grained sediments therefore have most likely been deposited as a result of wide-spread transgression. The gradual disappearance upwards of the sandy interbeds in the basal part of the member suggests deepening water. However, the increase of sand upwards in the middle and upper part of the red and green siltstone member as well as in the overlying upper sandstone member are thought to reflect deposition during a subsequent regressive cycle.

The vertical grain-size distribution within the red and green siltstone member resembles that described from regressive sequences deposited on a shelf as offshore marine and nearshore sediments (Hechel 1972, Selley 1970). Deposition within a marine environment is probable because of the presence of fossils, trails and burrows at different levels of the member. The apparently homogeneous development of the red and green siltstones within the lower part of the member suggests deposition out of suspension below the wave base. As regression continued, the wave base moved seaward and deposition within more wave and current agitated areas occurred. This resulted in the development of the interbedded siltstone and sandstone unit of the upper part of the member.

THE UPPER SANDSTONE MEMBER

The upper sandstone member is dominated by quartzite and sandstone, with siltstone and fine sandstone occurring generally as thin interbeds only. In places, however, these interbeds reach a thickness of several metres. A thin phosphorite-bearing conglomeratic quartz sandstone in places occupies the uppermost part of the member. In other sections a similar conglomerate seems rather to belong to the upper siltstone member. The member is exposed almost continuously in the Luopakte section and it is here about 35 m thick. Southwards, the member can be traced to Lutetjåkka. About 7 km further to the south-west, in the Supastjåkka section, the member has been tectonically truncated and allochthonous units of the Lower thrust rocks directly overlie the red and green siltstone member. Still further south, it has been established at several localities that the thrust at the base of the Lower thrust rocks has cut the autochthonous sediments at a level below the upper sandstone member, and the member has thus not been recognized southwards until the Akavare section. North of Torneträsk, the member has been identified within a number of sections (Fig. 3).

In the Luopakte section, the member is subdivided in three different lithological units, X, Y and Z. The lowermost of these, unit X, is composed of a white or pale brownish, medium-grained sandstone with a thickness of approximately 25 m. A sharp-bound bed (0.5 m thick) of laminated siltstone and fine sandstone occurs about 10 m above the base of the unit. The medium-grained sandstone contains scattered mudflakes but otherwise larger clasts are not commonly observed. Quartz and feldspar

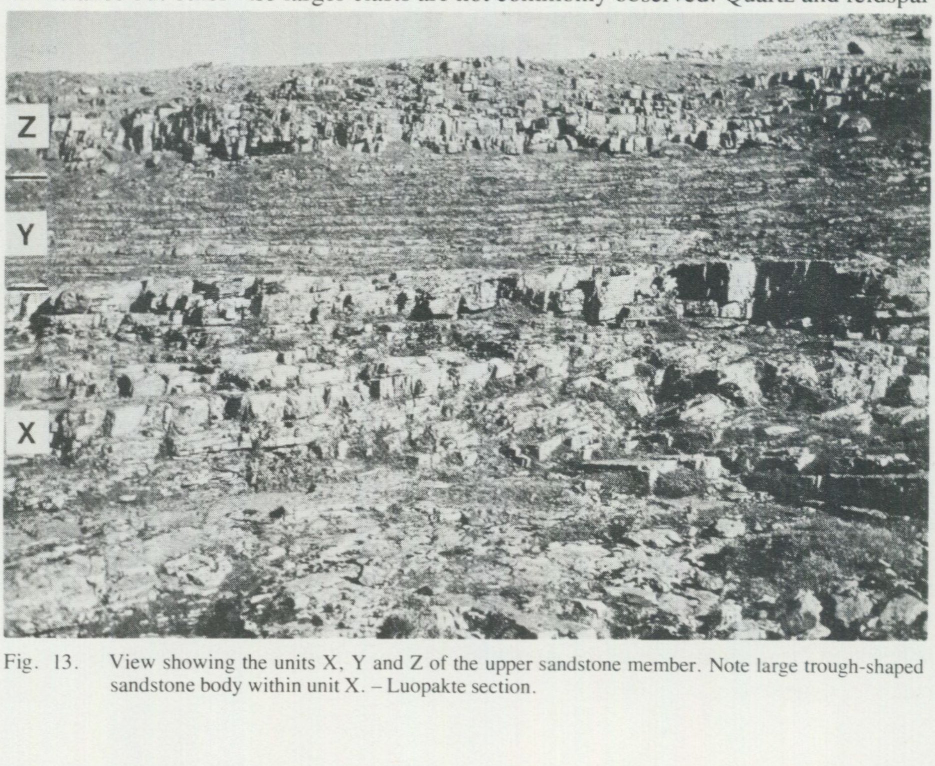


Fig. 13. View showing the units X, Y and Z of the upper sandstone member. Note large trough-shaped sandstone body within unit X. – Luopakte section.

are the main constituents, while rock fragments other than the mudflakes are rare. Glauconite is an accessory mineral. The sandstone is quartz-cemented but the rounded to well-rounded clasts are easily recognized. A large trough cross-bed, a few metres wide, occurs in the upper part of unit X (Fig. 13), ripples additionally occur on the top of individual sedimentation units in the trough. In fact, cross-bedding and ripples are common throughout the unit X and measurements of foreset beds suggest easterly directed currents to have dominated at the time of deposition (Fig. 14a, b), although currents towards the west and south-west suggest a weak bipolar current pattern. Trace fossils on bedding planes occur and are particularly common in the upper part.

The overlying unit Y (approximately 4 m thick), is composed of a thinly bedded sandstone with interbeds (cm-scale) of dark-grey shale and siltstone. The sandstone layers show cross-bedding with current directions towards northwest (5 measurements). Trace fossils on the bedding planes are very common.

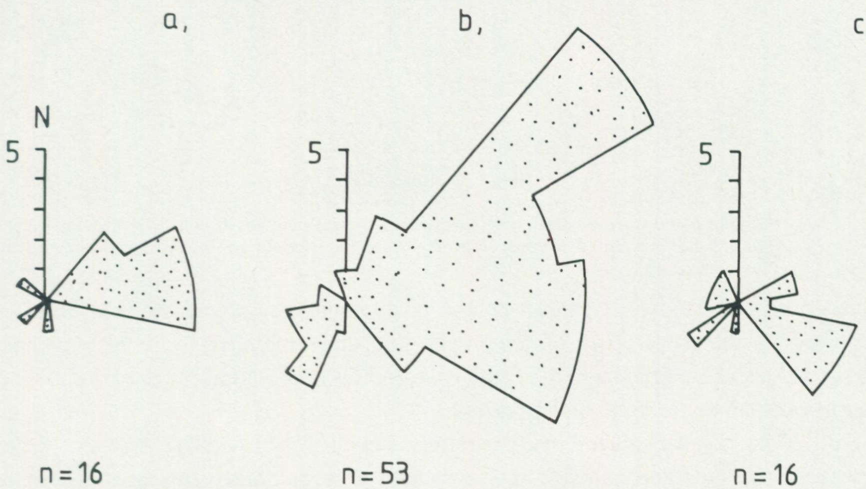


Fig. 14. Current directions based on foreset beds in the upper sandstone member. n = number of measurements. a–b, Luopakte section, lower and upper part of unit X respectively, c, Vakkejåkka section, lower part of the member.

The unit Z (6.5 m thick) is composed of grey or bluish grey quartzite with scattered mudflakes on the bedding planes. These quartzite layers are 1–3 dm thick. Trough cross-beds and dunes with transverse ripples on top have been observed (Fig. 15). Orientation of foreset beds suggests a random current direction. Bedding planes are often coated with argillaceous layers, and trace fossils and burrows are frequent.

A conglomeratic quartz sandstone (0.2 m thick) with horizons of dark shale fragments and phosphoritic pebbles defines the uppermost part of unit Z. Small lensoid bodies of calcareous sandstone are also observed in this part.

The three units X, Y and Z of the upper sandstone member in the Luopakte section have not been distinguished in the other localities of the Torneträsk area. However,

Fig. 15. Bedding plane surface within unit Z, upper sandstone member. A dune of sandstone (long axis trending bottom-top of picture) with abundant trace fossils and transversing ripple crests. – Luopakte section.

whitish or brownish white sandstone and/or quartzite resembling those of unit X are observed in the lower part of the upper sandstone member from the sections at Piernejåkka and Lutetjåkka to the south of Torneträsk, as well as in the eastern slope of Tuoptevaratjah to the north of Torneträsk.

Unit Y is not recognized with certainty outside the Luopakte section. Unit Z, however, can be traced outside this area as a grey or bluish grey quartzite or as a coarse-grained quartz sandstone, and is observed in a number of localities such as the sections of Lutetjåkka, Piernejåkka, eastern slope of Tuoptevaratjah and Vakkejåkka.

The upper sandstone member is also exposed in a brook about 2 km south of the locality at Luopakte. The section is composed of two fining-upward sequences overlain by whitish brownish sandstone (12–15 m thick) resembling that of unit X. The sandstone passes apparently gradually into a bluish grey quartzite with burrows (unit Z). The lowermost fining-upward sequence is a thinly bedded greenish grey fine sandstone (2–3 m thick) passing into a laminated thinly bedded siltstone/fine sandstone (2 m). The overlying fining-upward sequence has a similar development; a basal fine- and medium-grained feldspathic sandstone (4 m) passes into a laminated thinly bedded siltstone/fine sandstone (3 m).

The lower boundary — In the Luopakte section, the upper sandstone member has a sharp lower boundary to the underlying red and green siltstone member. A thin layer of mudflake conglomerate, which in part has a calcareous matrix, occurs locally within the most basal part. The corresponding contact within the Piernejåkka and Vakkejåkka sections has similar abrupt development and a basal mudflake conglomerate is present also in these two sections; the conglomerate in the Vakkejåkka section is 0.4 m thick and has a dolomitic matrix. The same boundary within the eastern slope of Tuoptevaratjah, however, seems to be transitional through a thickness of about 1 m; the underlying red and green siltstone member shows an upward increasing frequency of interbeds of quartzite. In the Tjäurajåkka section, the contact is similarly gradual through a thickness of 0.5 m.

Sedimentary environments — The upper sandstone member is the top part of a coarsening-upward sequence starting with massive siltstone of the red and green siltstone member, passing upwards into interbedded siltstone and sandstone of the same member and continuing, generally with an abrupt boundary, into the sandstone of the upper sandstone member. The sequence suggests a regressive cycle, and vertical grain-size distribution within the overall upward coarsening sequence — red and green siltstone member → upper sandstone member — is comparable to grain-size variations exhibited be seaward prograding lobate (deltas) or linear coastlines (shoals, barrier islands). (See Selley 1970, Blatt *et al*. 1972.)

The abrupt boundary beneath unit X of the Luopakte section suggests that the influx of sand rapidly increased. The abrupt lower boundary and the basal mudflake conglomerate (generally also seen elsewhere at the base of the member) are consistent with structures developed by prograding delta-front sands. However, if one accepts that an easterly situated sediment-feeding area existed at the time of deposition, the presence of foreset beds showing a dominating current direction towards the east is not compatible with deposition as delta-front sands. Furthermore, the abundance of trace fossils seen on bedding planes and the existence of glauconite rather suggest a marine environment. The quartz-rich, sorted and cross-bedded sandstones of the unit X also suggest a fairly high energy environment at the time of deposition. Siltstone draping on bedding planes and random mudflakes within the sandstones show the high energy levels to have been replaced occasionally by low energy levels allowing fine-grained sediments to have been settled from suspension. The planar cross-bedding and asymmetric ripples show that tractive currents played a major role in the deposition of the sandstones of unit X. The features described are represented in many modern tidal sand flats. The silt-draping on bedding planes possibly settled during slack water between ebb and tide. Another possible indication of tidal activity is the fining-upward sequence mentioned from the river section 2 km south of the Luopakte section. The grain-size distribution of these resembles tidal sequences developed at the transition from a sandflat to a mixed flat (Reineck 1972). However, the characteristic structures of these sequences (cross-bedding, flaser bedding, lenticular bedding) have not been identified in these sequences and therefore the tidal origin for unit X is still uncertain.

The increased content of silt shown in the overlying unit Y suggests that deposition took place within an area largely protected from strong currents. In view of the underlying tidal sand deposits it seems possible that unit Y was deposited within a mixed flat.

The quartzite and quartz sandstone dominating the unit Z reflect a return to more active conditions. The abundant number of trace fossils on bedding planes indicate that marine conditions continued. The mature quartz-sandstone deposits suggest a thorough reworking of the detritus and some of them could well be ancient beach sands. The apparent absence of low angle cross-bedding, a structure typical for this type of deposit, is possibly explained by diagenetic events obscuring the presence of these structures. The presence of argillaceous thin layers or drapes on bedding planes suggests that current velocity was very low at times. The unit also displays deposition within channels and this indicates coastal fluvial or tidal activity.

The depositional model outlined above is largely based on the Luopakte section. Modern marginal coastal sands may show rapid facies changes, a fact that has to be expected within ancient deposits as well. Two of the sections on the northern side of Torneträsk (Tuoptevaratjah and Tjäurajåkka), however, have a gradational contact to underlying sediments without the sudden influx of coarser sediments from migrating channels as proposed within most of the other sections. The interbedded siltstone unit in the middle part of the member at Vakkejåkka indicates, that protected conditions landward of the bars and shoals of the sand flats had a longer duration in this area.

THE UPPER SILTSTONE MEMBER

The upper siltstone member corresponds to the upper shale formation of Kulling (1964). The member overlies abruptly the upper sandstone member and underlies the Alum Shale Formation. It is composed mainly of greenish grey, rather massive siltstone. Complete sections through the member are rare since the member has often been tectonized or truncated by overlying nappes.

The upper siltstone member is well exposed in the Luopakte section where it is about 18 m thick. Immediately above the 0.2 m thick conglomeratic quartz sandstone defining the top of the upper sandstone member, a few loose boulders of limestone were found containing dark, rounded phosphoritic pebbles and scattered, well-rounded grains of quartz. Such a lithology was expected at this stratigraphic position because Moberg (1908, profile II, layer 20), Kulling (1960a) and Vogt (1967, Nivå F1) described a conglomeratic, dolomitic limestone (0.5–1.0 m thick) at this level in the Luopakte section. Kulling mentions the presence of scattered pebbles of phosphorite, quartzitic sandstone and rare fragments of ''Archean'' rock types. He also reports stromatolite structures in the bed. A greenish siltstone overlying the conglomeratic limestone dominates the member and is, according to Moberg (1908), 15.5 m thick.

Moberg (1908) described the uppermost 1.7 m of the member as being a grey thick-banded calcareous shale with an uppermost impure dark limestone (0.15 m thick). This upper unit of the member contains trilobites placing the unit in the uppermost faunal zones of the Lower Cambrian (Moberg 1908, Kulling 1972, Ahlberg and Bergström 1978, Ahlberg 1979). The following fossils have been reported from the limestone: *Arionellus primaevus* Brögger, *Ellipsocephalus nordenskioeldi* Linnarsson, *Obolus* (Moberg 1908), and *Strenuella linnarssoni* Kiaer (see Kulling 1972). Ahlberg and Bergström (1978) re-examined Moberg's two originals of *Ellipsocephalus nordenskioeldi*. They concluded that these originals could not be referred to the species. Probably, they do not even belong to *Ellipsocephalus* and the two specimens were referred to the genus *Comluella* (?). Ahlberg (1979) refers them to *C*. ? *lapponica* n.sp. Ahlberg and Bergström (1978) re-examined also specimens of *Arionellus primaevus* (=*Strenuaeva primaeva*). According to them the specimens are not *S*. *primaeva* and at least one specimen is classified as *Proampyx triangularis* n.sp.

North of Torneträsk, the upper siltstone member is recognized at Vakkejåkka and Tuoptevaratjah. Between these sections, in a brook at the southern slope of the mountain Vaivantjåkka about 2 km east of Vakkejåkka, Vogt (1967, p. 25) describes the basal bed (Nivå F1 of Vogt) of the member as a 0.5 m thick layer consisting of calcareous sandstone, conglomeratic limestone and greenish calcareous shale. The layer is overlain by about 8 m of shale of the upper siltstone member. According to Vogt the greenish calcareous shale is fossiliferous at the transitional zone to overlying shale and Braastad (*in* Vogt 1967) classified the following fossils: *Ellipsocephalus* sp., *Obolus* cf. *favosus* Linnarsson, and *Lingulella* sp. Vogt's specimens have been re-examined by Ahlberg (1980) who describes one of the cranidia as *Ellipsocephalus* cf. *gripi*. In a similar lithostratigraphic level, a calcareous conglomerate (0.7 m thick) containing rounded phosphoritic fragments and quartz grains also occurs below siltstone of the upper siltstone member in the section at Tuoptevaratjah.

The upper siltstone member can be traced from Luopakte south to Lutetjåkka. South of Lutetjåkka, it is known from several localities to have been truncated by detachment surfaces of the overlying allochthon and it is not recognized before Parnejåkka at Stora Sjöfallet. In this section, quartzite of the Snavva-Sjöfall Series (Ödman 1957) belonging to the Proterozoic Basement is overlain by approximately 1 m of coarse, in places conglomeratic, sandstone with a basal conglomerate layer. The unit passes gradually upwards into an overlying grey siltstone (about 10 m thick) containing minor interbeds of very fine sandstone. This is, in turn, overlain by a thin slice (0.5–1 m) of black shale of the Alum Shale Formation. Above this shale occurrence, the siltstone unit (here 5–10 m thick) is tectonically repeated and overlain by a thrust quartzite unit.

In the Stora Sjöfallet area, the upper siltstone member is also known from a number of drill-cores described by Kulling (1964). The siltstone being separated from the underlying Snavva-Sjöfall Series by a thin phosphorite-bearing conglomerate. At a locality approximately 15 km to the south of these drill-cores, Kulling has reported *Hyolithelus micans* Billings from the siltstone, thus referring this member to the upper Lower Cambrian.

Sedimentary environments — The upper siltstone member is part of a lithostratigraphic unit which can be traced far to the south and north of the area studied in this paper (and discussed in further details on page 36). The corresponding lithostratigraphic units (*e.g.* Holmia Series in southern Norway; Gärdsjön Formation member X in northern Jämtland County; Grammajukku Formation in the Laisvall area; Dividal Group avd. F1–F3 in northern Norway) have generally been accepted as being deposited as the result of an eastward directed transgression recognized along most of the eastern margin of the Scandinavian Caledonides.

In the Torneträsk area, the transgression was preceeded by a low supply of terrigenous debris as supported by the calcareous, phosphorite-bearing conglomerate underlying the siltstone of the upper siltstone member. The well-rounded quartz grains frequently occurring within the matrix of the conglomerate suggest that reworking of the underlying sandstone took place. Deposition from suspension of apparently rather homogeneous silt followed. The apparent lack of sand interbeds, the presence of fossils and the large areal extension of the member support the conclusion that the member represents an offshore marine deposit. The supply of terrigenous debris decreased even more and the limestone was developed at the top of the member.

COMPARISON BETWEEN THE TORNETRÄSK FORMATION AND OTHER VENDIAN TO LOWER CAMBRIAN UNITS IN THE SCANDINAVIAN CALEDONIDES

The sediments of the Torneträsk Formation were deposited within a basin extending far to the south, north and west of the area described in this study. Sediments similar to those of the Torneträsk Formation have been traced almost continuously from southern Norway (Vangsås Formation) into central and northern Sweden (Vassbo Formation, Gärdsjön Formation, Laisvall and Grammajukku Formations) and further north to northern Norway (Dividal Group). Broad lithostratigraphic correlations between these rock units have long been proposed. Comparable sedimentary rocks also rim many basement windows along the Norwegian/Swedish border. Detailed correlations between the Torneträsk area and the Västerbotten and northern Jämtland Counties have been discussed by *e.g.* Kulling (1942, 1955, 1964, 1972, 1982). Recent papers concerning the unit in northern Norway have presented rather detailed lithostratigraphic correlations between the autochthon in northern Norway and the Torneträsk area (Vogt 1967) as well as further south (Føyn 1967). Recent and on-going work along the eastern margin of the Swedish Caledonides has given an increased knowledge of the Laisvall and Grammajukku Formations and the Gärdsjön Formation and thus added further information concerning correlations between these rock units and the Torneträsk Formation.

The lithostratigraphy of this Vendian to Lower Cambrian quartzite-shale unit at different localities along the eastern margin of the central and northern part of the Scandinavian Caledonides is summarized in Fig. 16. The Laisvall section is taken

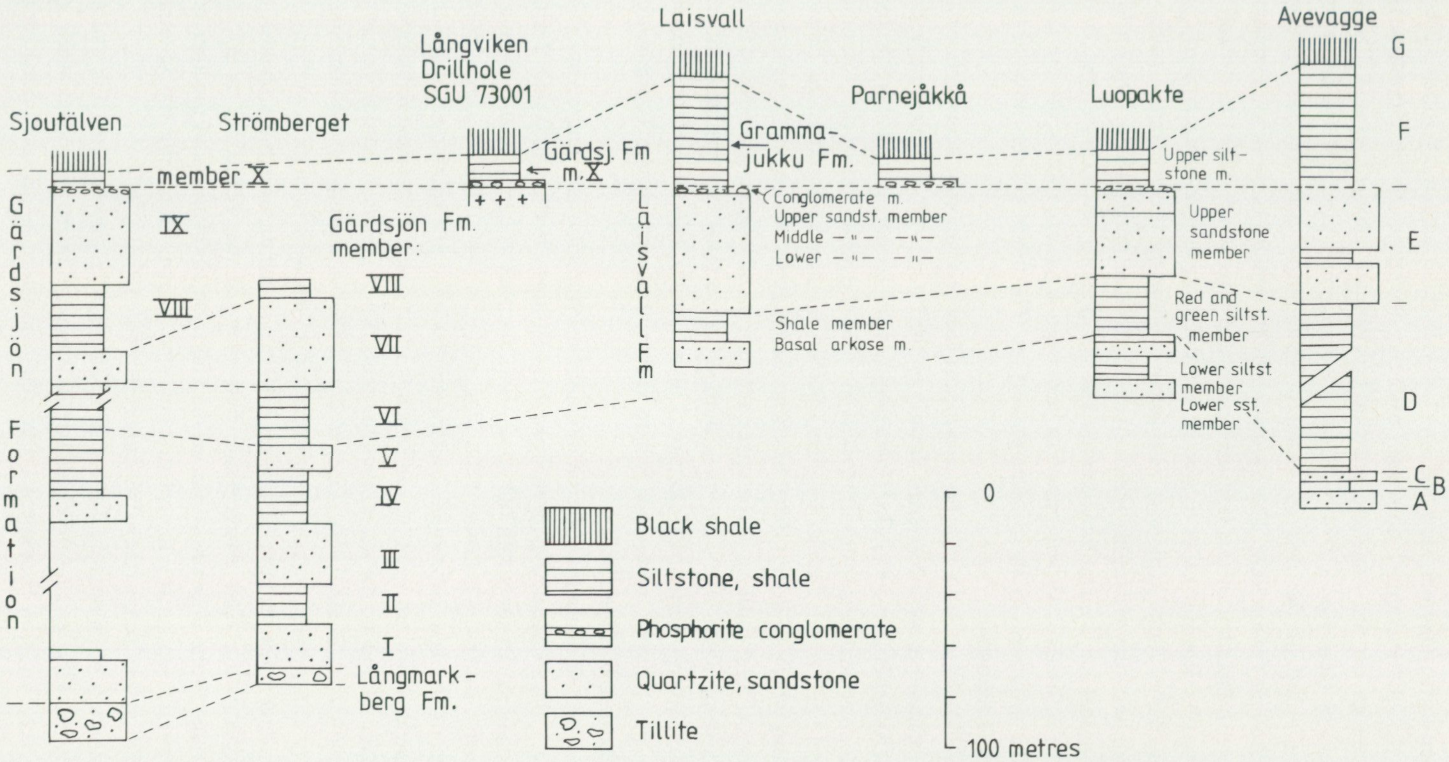


Fig. 16. Lithostratigraphic comparison between the Torneträsk Formation and other Vendian to Lower Cambrian sequences in the Scandinavian Caledonides. The location of sections is shown in Fig. 1. – Sections from Sjoutälven, Strömberget and Långviken are taken from Gee *et al.* (1978), the Laisvall section from Willdén (1980). Information pertaining to the Parnejåkka and Luopakte sections are from the present study, the Avevagge section is from Vogt (1967). All but the Sjoutälven section belong to the autochthon or parautochthon (Strömberget).

from a palaeo-environmental study of the Laisvall mine area by Willdén (1980). Concerning the nomenclature, however, with the exception of the Grammajukku Formation, names on the rock sequence at Laisvall are adopted from Lilljequist (1973). Papers by Gee *et al*. (1974, 1978) and Kumpulainen *et al*. (1981) summarize the lithostratigraphy of the unit in southern Västerbotten and northern Jämtland Counties (Gärdsjön Formation). The Sjoutälven section belongs to an allochthonous unit and nappe translation of this unit was calculated (Gee *et al*. 1978) to exceed 70 km. The section is shown in order to give an impression of the pre-thrust westerly part of the basin. Such rock sequences also occur within the Lower thrust rocks at Torneträsk but here they are highly imbricated and the lithostratigraphy is little known. The Gärdsjön section is parautochthonous and the distance of displacement is unknown but the sediments are interpreted to have been deposited east of the pre-thrust position of the sediments of the Sjoutälven section. The other sections referred to in Fig. 16 are autochthonous.

Kulling (1964) has shown that the uppermost Lower Cambrian sediments of the upper siltstone member were deposited directly on the Proterozoic basement in the area around Stora Sjöfallet. He concluded that a peninsula of basement rocks here protruded into the depositional basin during most of the time the sediments of the Torneträsk Formation were deposited. Similar basement heights are also known from the Laisvall mine area from where Willdén (1980) has described their influence on the sedimentation. Siltstones similar to those of the upper siltstone member have been traced by the author south from Stora Sjöfallet via a number of sections (for instance Skierfe, Tjakkeli, Kådtjåjåkkå, Tarfek, Skieltavare, Lulep Ramanj, Gibnotjåkkå and Laisvikberget) into the Laisvall mine area where they correspond to the Grammajukku Formation (see also Kulling 1982).

The southern continuation of the Grammajukku Formation and underlying sandstones in the Laisvall area have been treated by Kulling (1942, 1955) and Willdén (1980). The sandstones units thin out southwards but they occur, with a thickness of some 20 metres, underneath Lower Cambrian shales at the village Högland, on the northern side of the lake Storuman. Further southwards, just south-east of the lake Vojmsjön, these shales are again unconformably overlying the Proterozoic basement. East of the lake Ormsjön, the autochthonous sequence is known from drillings at the village Lövsjön (Du Rietz 1960, Gee *et al*. 1978). A lowermost autochthonous phosphorite-bearing conglomeratic sandstone (up to about 2 m thick) overlying the crystalline basement passes into a siltstone (5–10 m), which underlie black shale of the Fjällbränna Formation (*i.e*. Alum Shale Formation in the Torneträsk area). The siltstone belongs to the uppermost part of the Gärdsjön Formation and together with the conglomeratic sandstone, the siltstone is also known to overlie the basement south-east of Norråker (Långviken drill-core, Gee *et al*. 1978).

The sedimentary sequences thicken west of Tåsjön (*e.g*. Asklund, *in* Asklund and Thorslund 1935, Gee *et al*. 1978) and thick units of quartzites, sandstones and siltstones of the Gärdsjön Formation occur. The formation has been divided by the author into ten informal members, the uppermost of which lithologically corresponds to the autochthonous siltstone overlying the basement in the drill-cores at Långviken and Lövstrand.

Further south-west, around the basement culmination of Grong-Olden, a thin quartzite unit (0–10 m thick) separates a greenish grey siltstone (0–5 m) from overlying black shale corresponding to the Alum Shale Formation (Frödin 1916, Asklund 1938, Walser 1980). The absence of major quartzite-shale units of the Gärdsjön Formation suggests that the (Early Cambrian) coastline turned south-westwards from Lövstrand to the Olden area.

The offshore marine red and green siltstones of the red and green siltstone member is another unit of the Torneträsk Formation which apparently has a wide extension along the eastern margin of the Scandinavian Caledonides. Vogt (1967) has shown that these fine-grained sediments can be traced from Torneträsk northwards to Avevagge (Reisadalen, Troms) in northern Norway. Føyn (1967) compared the unit with his member (Ledd) IV of the Dividal Group at Halkkavarre (south-east of Alta, Finnmark). Southwards the red and green siltstone member has no obvious counterparts within the Laisvall area. Correlations with this area are complicated by the basement peninsula which existed over a prolonged period in the Stora Sjöfallet area. The peninsula was apparently not submerged until the sediments of the upper siltstone member were deposited. Willdén (1980) suggests that the Basal arkose member and the Shale member of the Laisvall Formation (Lilljequist 1973) contain glaciogenic and distal glacial deposits (Ackerselet Formation and Saivatj Member of Willdén), and he considered them to have been deposited during the Varangian period of glaciation. If this conclusion is correct, then deposition of the lower two units of the Laisvall Formation shown on Fig. 16 predates the entire Torneträsk Formation. South of the Laisvall area, the Gärdsjön Formation contains a red and green siltstone unit (member VI) known to have a wide extension in southern Västerbotten and northern Jämtland Counties (Gee *et al.* 1978, Kumpulainen *et al.* 1981). The fact that this unit occurs here in different tectonic units indicates that its pre-thrust extension was by far more extensive than is shown by its present distribution. In the type section of the Gärdsjön Formation, the red and green siltstone unit abruptly overlies underlying sedimentary rocks. In its uppermost part it contains thin interbeds of coarse sandstone. Together with an overlying thick quartzitic sandstone the red and green siltstones define a coarsening-upward sequence. A correlation between the discussed siltstone unit (the red and green siltstone member) of the Torneträsk Formation and the Gärdsjön Formation is supported by 1, lithological similarities (texture, grain-size, colour), 2, the fact that the two units both occur within coarsening-upward sequences and 3, the fact that they broadly occur on the same lithostratigraphic level beneath the phosphorite-bearing conglomerate and overlying Lower Cambrian siltstone of the upper siltstone member.

SUMMARY AND DISCUSSION

The sediments of the Torneträsk Formation were deposited during regional transgression onto the Baltoscandian Platform in Vendian and Early Cambrian time. Within this overall transgression, three transgressive events have been recognized, and at least the second of these was followed by a regression.

The first transgression occurred during the Vendian when largely coarse sediments were laid down on a weathered basement surface, partly covered by residual rocks. In spite of the coarse-grained basal sediments, suggesting a high supply of terrigenous debris and deposition on a coastal plain, transgression continued and the coastal plain was overlain by lagoon or bay deposits. These were covered by bodies of interbedded siltstone and fine sandstone showing flaser and lenticular bedding. The detailed development of the sedimentary environments was complex but tidal activity is believed to have been a major controlling depositional agent. Bars and beaches are other environments inferred in association with the tidal deposits.

On the northern side of Torneträsk, the tide-influenced sediments are abruptly overlain by the Vakkejokk Breccia which is composed of rock fragments in a silty or sandy matrix. Most larger fragments consist of granitic rock fragments. Sedimentary rock types present seem to be intrabasinal. The model of deposition is uncertain. A flow-till origin of the Vakkejokk Breccia is discussed, but it seems more likely that the breccia resulted from mass-flows without glacial activity.

The second transgressive event is confined to the base of the red and green siltstone member. Deposition of thin dolomitic sandstone was succeeded by deposition of silt with thin interbeds of sand. The number of these interbeds decreases upwards, possibly as a result of deepening. Offshore marine, red and green silts were probably settled from suspension. An increased sand content in the upper part of the member reflects shallowing of the sea and a change from transgressive to regressive relationships. The red and green silts form a unit of wide-spread extension and are correlatable with units far outside the depositional basin of the Torneträsk Formation. In particular, this is true to the north where Vogt (1967), Føyn (1967) and Føyn and Glaessner (1979) traced the unit from the Torneträsk area into Finnmark of northern Norway. Correlation is here based on lithological evidence as well as on fossils. *Platysolenites antiquissimus* is present within the unit both in northern Sweden and northern Norway. Southwards a red and green siltstone unit of the Gärdsjön Formation (southern Västerbotten and northern Jämtland Counties) has a lithology similar to the red and green siltstone member. The Gärdsjön Formation is not known to be fossiliferous at this level and the suggested correlation between the two units is based on lithological evidence and environmental analysis; the two units were both deposited within a regressive, offshore marine to marginal (coastal) sequence.

Regression within the depositional basin of the Torneträsk Formation continued and tide-dominated sedimentation started. Extensive sand flats were built out when the sediments of the upper sandstone member were deposited. It seems likely that the increased supply of sand partly emanated from deltas, although the delta sands were later redistributed by tidal and possible storm activity. The upper sandstone member also contains lithofacies resembling those developed within mixed tidal flats. An upper quartzite-dominated unit may contain beach facies associated with possible tidal or coastal fluvial activity.

The third transgression represented by the upper siltstone member achieved the largest extension. In the Scandinavian Caledonides the fine-grained sediments deposited during this transgression have been traced from southern Norway, via central and northern Sweden into northern Norway. It is possible that the transgression is diachronous over this area but in the basin of the Torneträsk Formation it occurred in late Early Cambrian.

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