SKRIFTER NR. 174

Upper Devonian (Famennian) - Middle Carboniferous succession of Bjørnøya

A study of ancient alluvial and coastal marine sedimentation

By JOHN G. GJELBERG

NORSK POLARINSTITUTT
OSLO 1981

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Contents

Abstract

The Upper Devonian — Middle Carboniferous succession of Bjørnøya comprises three formations with a maximum composite thickness of about 800 meters, overlying Hecla Hoek basement. There is more or less continual transition between Røedvika, Nordkapp and Landnørdingsvika Formations as well as gradual change up into the overlying Kapp Kåre Formation.

Røedvika Formation (lower coal and shale unit of the «Ursa sandstone» of HORN and ORVIN 1928) consists mainly of sandstone and mudstone interstratified with coal and coaly shales. Conglomerates are subordinate. This formation has been subdivided into three members by WORSLEY and EDWARDS (1976): Vesalstranda Member (oldest), Kapp Levin Member and Tunheim Member. Vesalstranda Member contains the Misery coal series (HORN and ORVIN 1928) while Tunheim Member contains the Tunheim coal series (HORN and ORVIN 1928). Fining-upwards channel sandstones deposited by meandering streams and coarsening upwards lacustrine delta sequences dominate Vesalstranda Member. Thick flood basin sequences are also present. Flow direction of the fluvial system was towards north or northwest. The sediments of Kapp Levin Member were deposited mainly by low-sinuosity meandering streams and braided streams, probably flowing towards east or north-east, while Tunheim Member originated from meandering streams flowing largely towards north or northwest.

Nordkapp Formation consists mainly of cross-stratified sandstones in the lower part. Conglomerates and mudstone become more important in the upper part. For convenience the formation has here been informally divided into two units. Eastward flowing sandy braided streams dominated the paleogeography of the lower unit. The upper unit is more complex, but braided streams probably associated with alluvial fans dominated the deposition.

Landnørdingsvika Formation is composed of an interbedding red mudstone, drab sandstones and red conglomerates representing a complex interfingering of fluvial, alluvial fan and marginal marine sediments. Fluvial sediments dominate in the lower part, alluvial fan conglomerates dominate in the middle part while marginal marine sediments become more important in the upper part.

Variation in facies, together with paleocurrent patterns suggests that Bjørnøya lay near the western or southwestern margin of a repeatedly rejuvinated depositional basin during much of the Upper Palaeozoic. This gave rise to repeated influx of coarse material from uplands in the west and more continuous aggradation of finer sediments in the north north/west/south southeast axial tract of the basin.

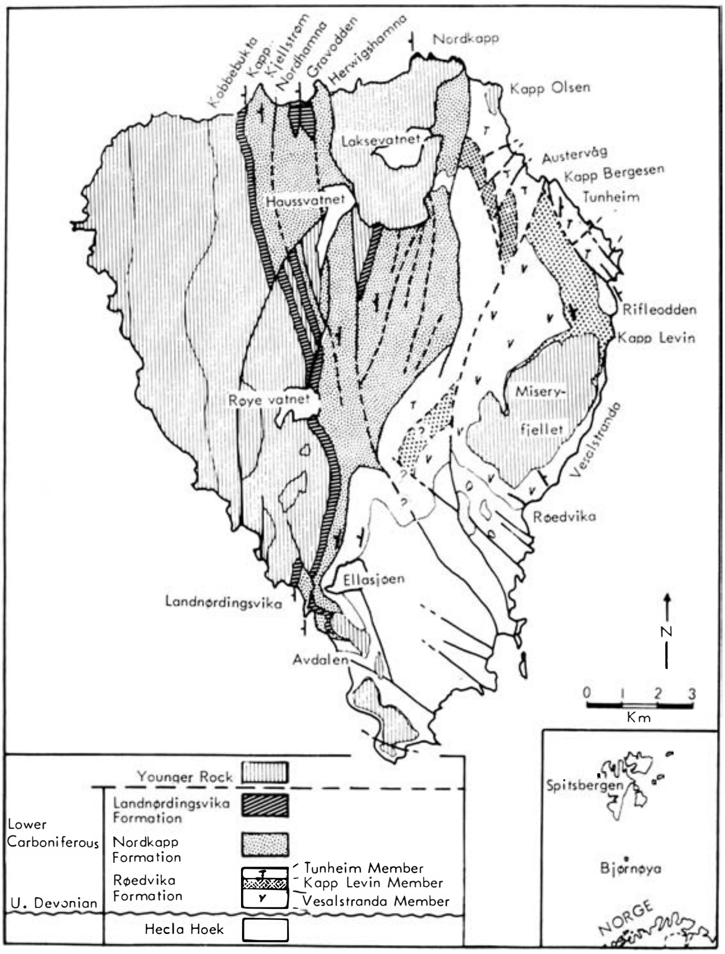

Fig. 1. *Geological map showing the distribution of the studied Formations* (*based on* HORN *and* ORVIN *1928*).

I. Introduction

Because of its position near the western margin of the Barents shelf, midway between Spitsbergen and Finnmark, Bjørnøya is of considerable geological significance. Bjørnøya represents part of a structural high (Senja Ridge), where extensive faulting and tilting has taken place, and where sediments from Cambrian (Hecla Hoek) to Triassic are exposed. The exposures are excellent along the coast (though continually falling debris make the work rather hazardous), while the interior of the island is more or less a large block-field. Figure 1 shows a generalized geological map of Bjørnøya, while in Figure 2 there is a summary vertical log of the Upper Devonian — Middle Carboniferous succession, with an outline interpretation of depositional environments. The investigated strata form three formations: Røedvika Formation (Famennian — Tournaisian), Nordkapp Formation (Viséan) and Landnørdingsvika Formation (pre-Moscovian).

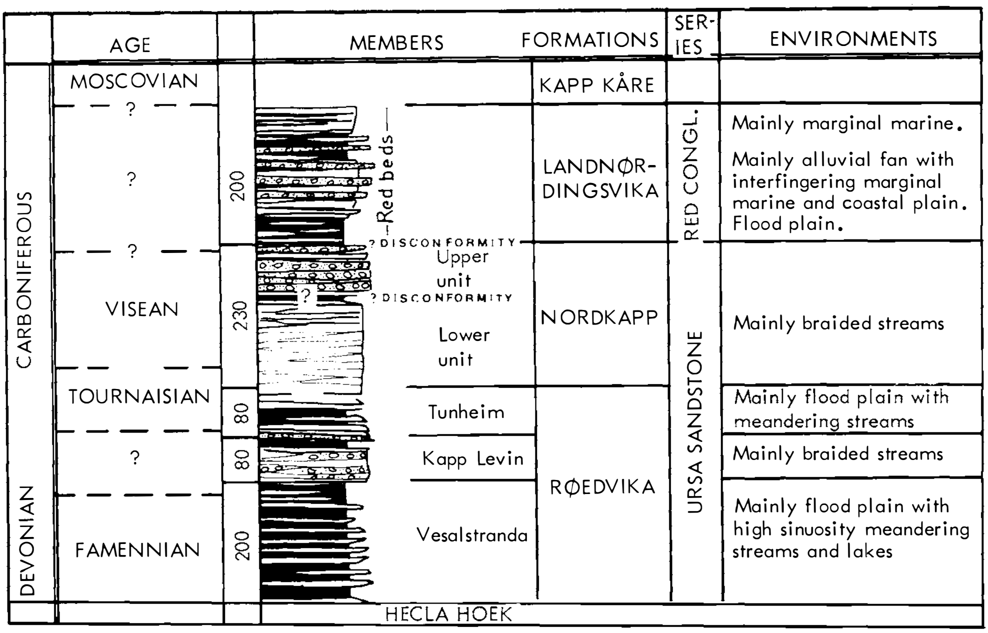

Fig. 2. *Generalized profile of the Upper Devonian-Middle Carboniferous succession of Bjørnøya (based on* WORSLEY *and* EDWARDS *1976).*

Røedvika Formation was divided into three members by WORSLEY and EDWARDS (1976): Vesalstranda Member (oldest), Kapp Levin Member and Tunheim Member (youngest). For convenience Nordkapp Formation has here been divided into two units: lower unit and upper unit.

The classic geological work on Bjørnøya, by HORN and ORVIN (1928), includes a study of the entire stratigraphic record of Bjørnøya, including the Hecla Hoek basement. Their work concentrated on the coal bearing portion ("Ursa sandstone"), and included a valuable geological map in scale 1:50,000. The most recent geological work on Bjørnøya (WORSLEY and EDWARDS 1976) consisted of a general study of the entire Upper Palaeozoic succession, providing summary information on stratigraphy, rock description and a general interpretation of the stratigraphic sequences.

The present study concentrates on a detailed facies analysis with emphasis on facies sequences, dynamic stratigraphy and basin evolution in relation to the important paleo-Hornsund Fault system.

1. STRATIGRAPHIC AND TECTONIC FRAMEWORK

The pre-Upper Devonian rock of Bjørnøya comprises four different "series" of the Hecla Hoek basement (HORN and ORVIN 1928):

> Tetradium Limestone series (240 m) (Middle Ordovician), Younger Dolomite series with fossiliferous zone in lower part (440 m) (Early Ordovician), Slate quartzite series (175 m), Older Dolomite series. In lower part with oolites, oolithoids, and stromatolites; in upper part strongly arenaceous (400 m).

The Hecla Hoek basement has become faulted, folded and thrusted prior to the deposition of Upper Devonian rock. The slate-quartzite series has been more extensively folded than the associated dolomite and limestone. The degree of deformation and metamorphism is, however, much lower than for Cambrian—Ordovician rock on the northern Norwegian mainland, and the slate-quartzite series consists mainly of slightly deformed sandstone and shales.

As noted above, Bjørnøya represents an important fragment of the Senja Ridge, on which extensive faulting and tilting of the strata has taken place. Most of the Carboniferous (and older) sediments have been extensively affected by tectonic movements, while the Miseryfjellet Formation (Kungurian — ?Upper Permian), has been largely unaffected. This implies that the most active faulting took place prior to the deposition of Miseryfjellet Formation and probably post-Carboniferous, probably during two distinct periods of instability in Lower Permian (prior to the deposition of Hambergfjellet Formation and Miseryfjellet Formation respectively (WORSLEY and EDWARDS 1976, Fig. 2).

On the north coast of Bjørnøya Miseryfjellet Formation lies unconformably over the tilted and faulted strata of Røedvika, Nordkapp and Landnørdingsvika Formations (Fig. 1). Most of the fractures are north-south oriented normal faults, but east-west faults are also present, some of which intersect Miseryfjellet Formation.

The very complex fault system on Bjørnøya inhibits the investigation. This combined with insufficient exposures on the interior of the island makes lateral correlation rather difficult. This is especially the case for the coal bearing units.

II. Røedvika Formation

1. INTRODUCTION

Røedvika Formation (Famennian—Tournaisian), the lower coal and shale unit of the Ursa Sandstone of earlier investigators (eg. HORN and ORVIN 1928), was renamed by CUTBILL and CHALLINOR (1965). On the basis of lithostratigraphy WORSLEY and EDWARDS (1976) divided the formation into three members: Vesalstranda Member (oldest), Kapp Levin Member and Tunheim Member.

The total thickness of the formation is about 360 metres on the eastern coast. HORN and ORVIN (1928) realized that the thickness decreased dramatically towards the south and southwest, and borehole data from the area just north-west of Ellasjøen indicate that only 100 metres of Røedvika Formation is present (about 120 m is present at Avdalen on the south-west coast). The reason for this thinning out is unclear, although HORN and ORVIN (1928) suggested that it could be the result of an unconformity between Røedvika and the overlying Nordkapp Formation. However, a somewhat similar thickness variation also occurs within Nordkapp Formation and the above authors concluded that the only feasible explanation is a general thinning of the formations towards the south and south-west. As discussed further below, this lateral variation may well be a result of syn-depositional tectonic activity.

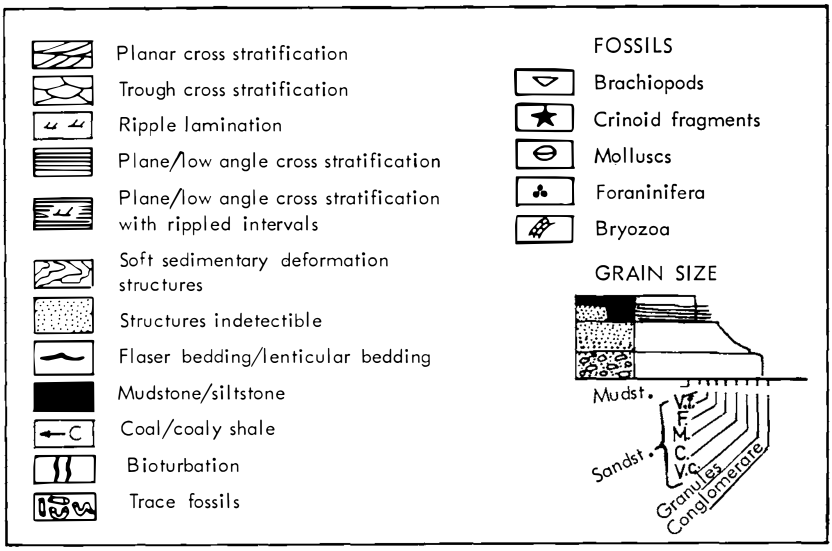

Fig. 3. *Legend for both structures and grain size as used in subsequent figures.*

2. VESALSTRANDA MEMBER

Depositional environment

Detailed facies analysis of Vesalstranda Member is already available (GJELBERG 1978), so only a short review of the most significant data will be given here.

Two significant environments of deposition were recognised for Vesalstranda Member:

a) Flood-plain environment constructed largely from sedimentation in and adjacent to north-westward flowing streams of high sinuosity.
b) Lacustrine deltaic environment constructed largely from prograding delta lobes into standing water bodies (lakes).

Because of their close association with the deltaic sequences it is most likely that the fluviatile sediments accumulated in floodplain areas dominated by high sinuosity meandering streams and lakes. Crevasse channels and main distributary channels brought classic sediments into the lakes and caused a progradational infilling.

An overall time trend of sedimentation from lacustrine deltaic in the lower and middle parts to fluvial in the upper part suggests a general progradational, basin filling episode, which probably culminated in the overlying coarser-grained, alluvial Kapp Levin Member. A generalized vertical log showing facies sequences and interpretations for Vesalstranda Member is shown in Figure 4.

The Upper Devonian sediments of Vesalstranda Member reflect typical continental despositional conditions on low paleoslopes, while paleocurrent analysis suggests a source area to the south or south-east of Bjørnøya (see Fig. 41).

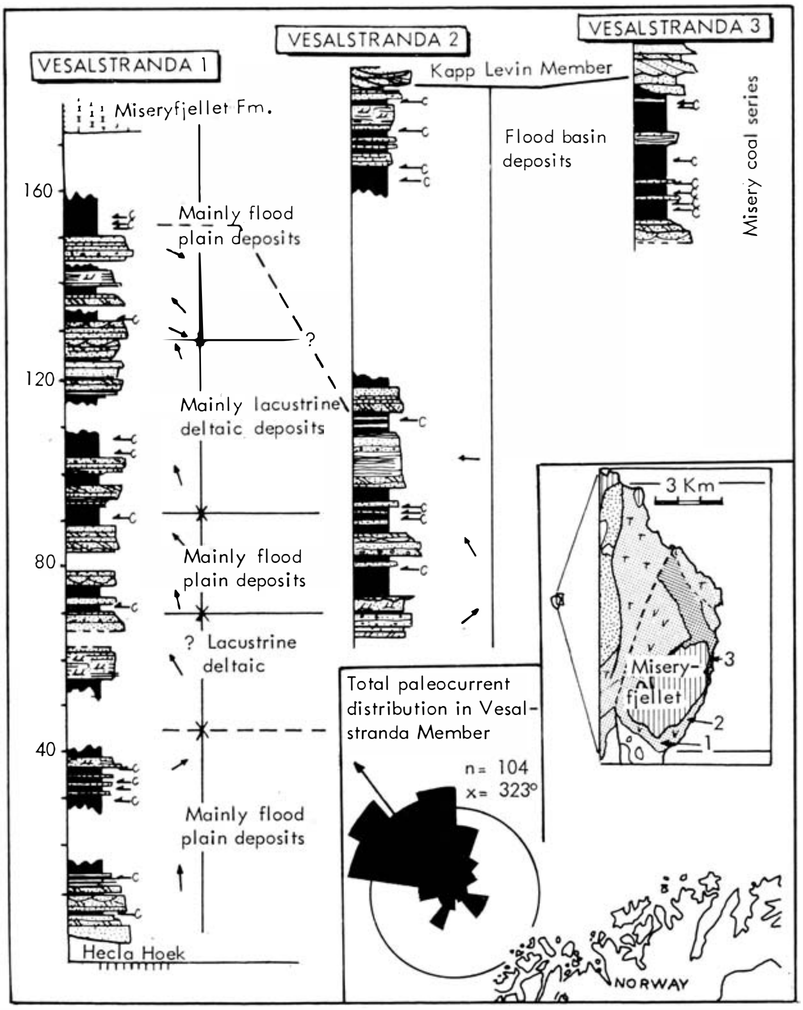

Fig. 4. *Generalized vertical log of Vesalstranda Member (Røedvika Formation). Location map for the three profiles is shown to the right.*

3. KAPP LEVIN MEMBER

The only accessible complete section through this Member is exposed from the area on the north-east side of Miseryfjellet and north to Rifleodden. (Fig. 1). The total thickness of the exposed strata here is about 75 m (Fig. 5). The relatively coarse-grained sediments of Kapp Levin Member contrast with the fine-grained, coal-bearing deposits of the conformably underlying Vesalstranda Member (Fig. 2). WORSLEY and EDWARDS (1976) defined the upper boundary of Kapp Levin Member as the base of Rifleodden Conglomerate. Consequently WORSLEY and EDWARDS (1976) included the latter in the lowermost part of Tunheim Member.

Grey cross-stratified sandstone, conglomeratic sandstone and conglomerate are the dominating lithologies. Drapes of organic-rich mudstone frequently

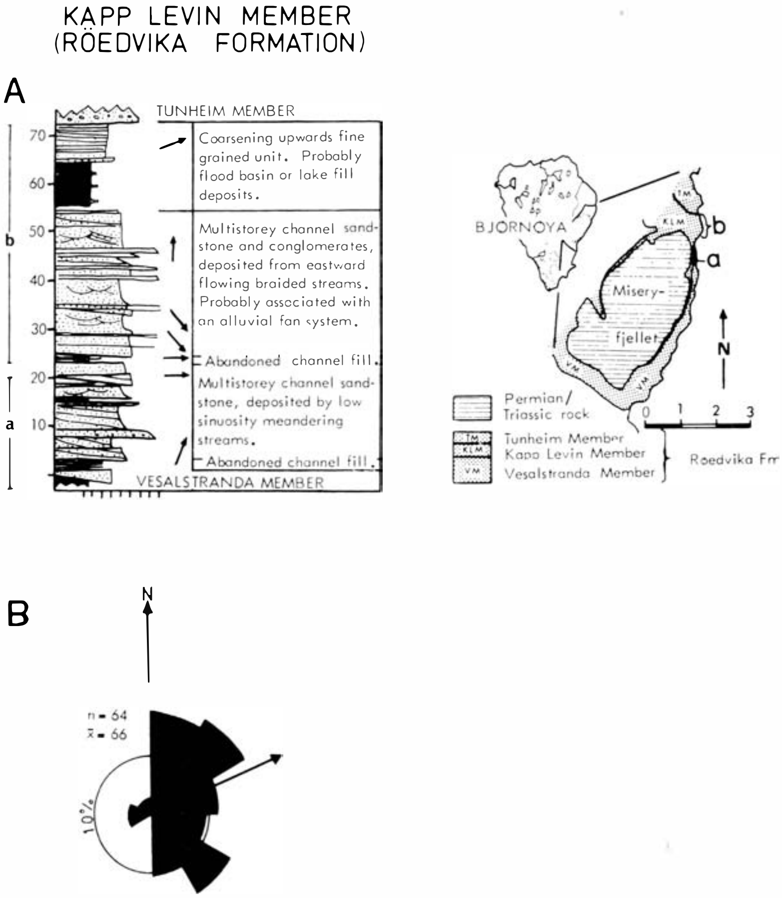

Fig. 5. *Type profile from Kapp Levin Member. The "rose diagram" in the lower part of the figure shows total paleocurrent distribution in Kapp Levin Member.*

occur between bedding planes. A few lenticular units of shale and interlayered thin sandstone are associated with the coarse sediments which dominate the member. The upper part of the member consists of a 15 metres thick fine-grained, laterally extensive unit (Figs. 9, 5).

Facies Association KA

This facies association dominates in the lower part of the member. It is typically composed of erosively based medium and coarse sandstones, with a slight tendency to upwards fining. (Fig. 6). Scattered clasts of intraformational mudstone were recorded locally in a few basal beds of the association. The most distinct feature is the occurrence of low angle, very large scale (up to 4 m set thickness) planar cross-stratification (ALLEN 1963). Such units may be overlain either by thin, low angle sets of sandstone (with or without mudstone drapes) or by similar thick, large-scale, cross-stratified sandstone units divided from each other by distinct erosion surfaces. Although the large-scale sets can

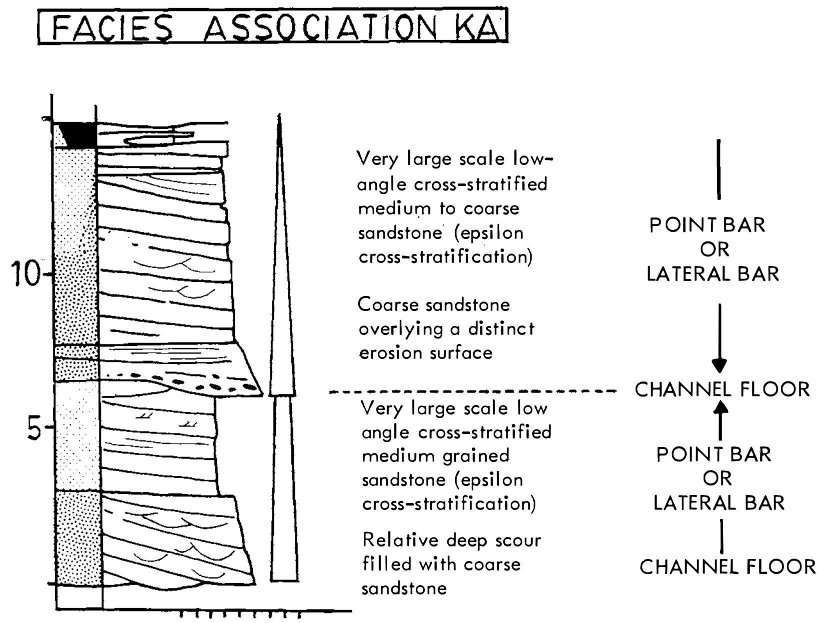

Fig. 6. *Two cyclic sequences of Facies Association KA. A common feature is the occurrence of very large-scale cross-stratification. The sequences show also slightly fining-upwards trends. The lower sequence has been considerably truncated by the overlying.*

persist for hundreds of metres laterally, there is commonly a marked lateral variation to match the vertical one.

Fine grained sediments (mudstone and siltstone) of relative great thickness are rarely found in this facies association, and the only few occurrences are laterally impersistent, and often bounded by erosion surfaces (see Facies Association KC).

Petrographically the sandstones very much resemble the fluvial sandstones of Vesalstranda Member, with subangular quartz grains and rock fragments of quartzitic sandstone as the dominating framework components.

Interpretation — The erosively based sandstones of this Facies Association show some points of resemblance with the channel sandstones of Facies Association A of Vesalstranda Member (GJELBERG 1978). The main differences occur with respect to the associated and overlying beds. The channel sandstones of Vesalstranda Member are overlain by thick, coal-bearing mudstone units (overbank deposits), while sandstones of this association are normally repeated in a multi-story manner with little or no fine-grained sediments preserved between. Very large-scale cross-stratification of the epsilon type was not recorded in Vesalstranda Member, but this may be rather a result of insufficient exposure.

The sediments of this facies association probably represent point bars or lateral bars of laterally migrating, low sinuosity stream channels, where the epsilon cross-stratification represents bar accretion (ALLEN 1970). If the stream

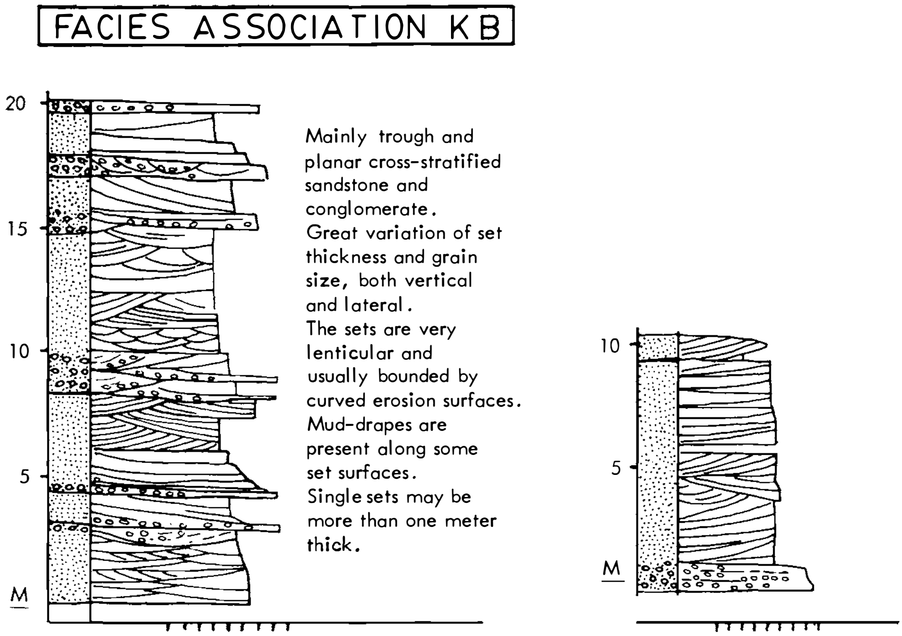

Fig. 7. *Two multistorey sandstone and conglomerate sequences of Facies Association KB. Probably deposited by braided river systems.*

was of low-sinuosity, it was not confined in a meander belt by channel-fills and was therefore free to sweep the entire flood plain (Allen 1965), resulting in a very low preservation potential for overbank sediments, and short duration of eventual flood basin area.

Alternatively this facies association may be interpreted as longitudinal or transverse bars of braided river systems. Such bars may produce sediments as described above as they migrate downstream. (Cant and Walker 1976).

Facies Association KB

Sequences of Facies Association KB (Fig. 7) occur mainly in the middle part of the member. Characteristic of these sediments is a rapid change of sedimentary structures and lithology both vertically and laterally. The lithology is mainly grey, poorly to moderately sorted medium to coarse sandstone and pebbly sandstone with occasional beds of conglomerates. Individual sets are usually bounded by curved erosion surfaces and are often very lenticular and of small lateral extent.

A wide range of primary structures was recorded. The dominant structures are, in order of importance:

1. Large-scale trough cross-stratification (including scour and fill).
2. Low angle — nearly horizontal stratification.
3. Medium and small-scale trough cross-stratification.
4. Large-scale planar cross-stratification.

Relatively thick sets of internally structureless sandstone and conglomerate are also present. Large troughs often appear as deep scours or channels, filled by cross-stratified sandstone and shales, with occasional concentrations of pebbles in the bottom. Thin, laterally impersistent drapes of mudstone are present between lenticular sandstone sets.

An upward decrease in grain size and an upward diminution in the size of sedimentary structures are present within single units, although a marked tendency for an alternation within the units between large and small scale structures and grain size more frequently was recorded.

Plant fossils are common and occur as impressions of relatively large trunks or as elongated leaves. Thin zones with concentrations of organic debris occur as drapes of coaly shale.

Interpretation — The frequency of erosion-surfaces, cross-stratified channels, scarcity of fine-grained sediments and the very rapid lithological and textural change both vertically and laterally suggest sedimentation which was characterized by large discharge fluctuation, rapid channel-filling and abandonment, and transport through considerable surface topography. All of these features are typical of braided stream activity (Steel 1974b). The very complex large-scale, lenticular bedding, reflects multi-story depositional events of complex channel systems, where both lateral and vertical accretion has taken place.

Very low-angle fine-grained sandstone units associated with the troughs probably represent adjacent overbank areas (McKee et al.1967). Mud drapes associated with channel fills reflect periods of slack water conditions where material desposited from suspension. Frequent occurrence of mud drapes in one single channel fill reflects composite infilling, with large and rather sudden changes in water discharge.

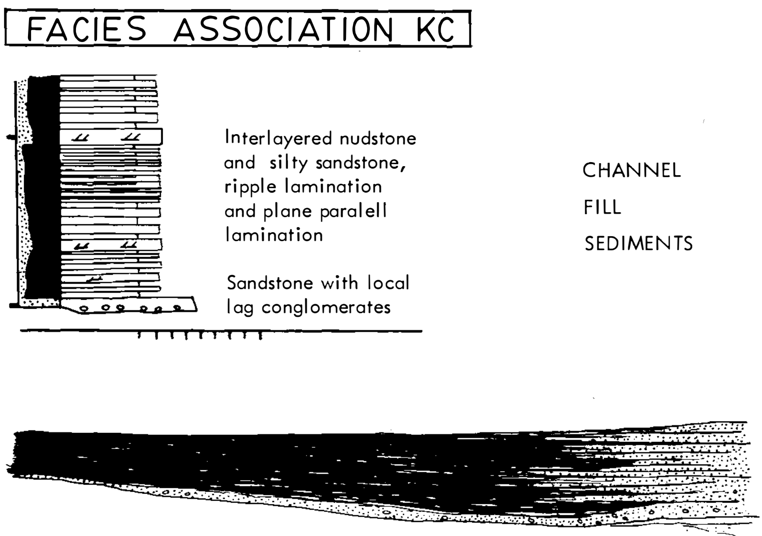

Fig. 8. *Vertical and lateral development of Facies Association KC.*

Facies Association KC

Facies Association KC consists of interlayered siltstone and mudstone (a few centimetres to about ten centimetres thick), which laterally grade into sandstone (Fig. 8). Plane parallel (horizontal) lamination and ripple lamination are the common sedimentary structures. At the base of the sequence shown in Fig. 8, a thin, laterally impersistent set of pebbly sandstone is located, overlying a curved erosion surface.

The lateral extension of this facies association is very restricted, and «channel-like» sedimentary bodies bounded mainly by erosion surfaces were recorded. Maximum thickness is about 2 metres. Plant fossils and zones of bedded clay-ironstone were recorded. Sediments of this Facies Association occur together with Facies Associations KA and KB.

Interpretation — This Facies Association represents vertically accreted sediments deposited mainly from suspension by slowly moving or stagnant waters. Due to the channellike geometry of the sedimentary bodies and the development of a basal lag conglomerate it is likely that these sediments represent some kind of abandoned channel fill, swale fill (Allen 1965) or slough fill (Bluck 1976). The sediments have been transported into the «protected» area during high flood stages. The interfingering sandstone, at the end of the unit, represents bedload sediments deposited nearer the active channel, while the more distal, more fine grained sediments (silt- and mudstone) were deposited from suspension. The siltstone layers represent the initial stage of deposition from each event of sediment influx, while the mudstone represent the waning or stagnating flow during falling stage and during periods of slack water between flooding.

Facies Association KD

The only occurrence of this facies association is in the upper part of the member, just below Rifleodden Conglomerate (Fig. 9).

Plane parallel laminated and blocky, grey and yellowish grey mudstone and siltstone with some ripple laminated intervals are the dominating lithologies in the lower eight metres of this facies association. A five metre thick horizontal or low-angle cross-stratified, very fine to fine sandstone sequence interlayered with thin mudstone strata and zones of clay-ironstone are located just above. This sequence constitutes the uppermost sediments of Kapp Levin Member.

The association has a relatively great lateral extension, and it is repeated with an approximate equal thickness more than a kilometre farther to the NW by block faulting.

Plant fossils are abundant.

Interpretation and discussion — The fine-grained portion of this facies association resembles, to some extent, the thick fine grained sequence of Vesalstranda Member, which represent mainly flood basin or lacustrine deposits. Braided

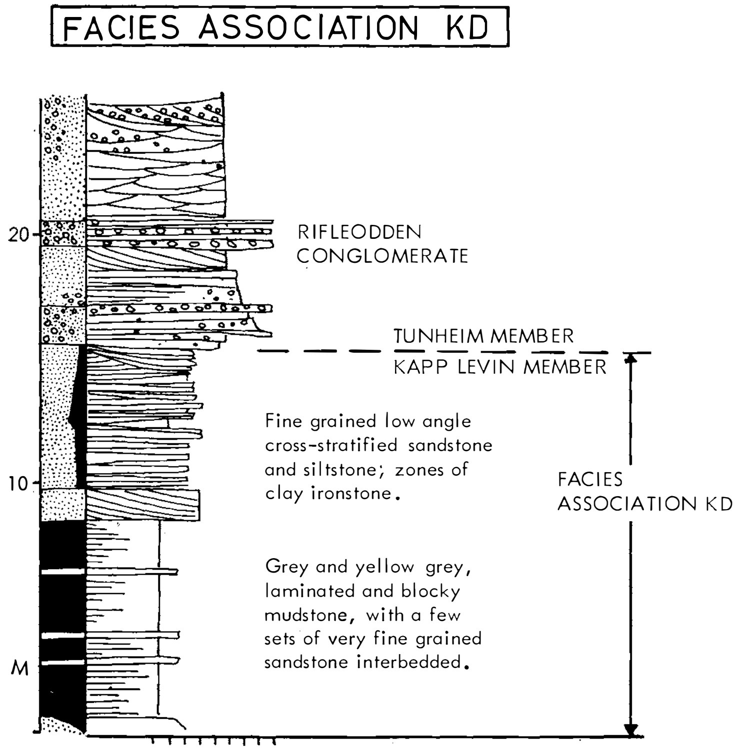

Fig. 9. *Vertical log of the only locality of Facies Association KD, with the accompanying Rifleodden Conglomerate.*

streams, however, are not characterised by having large floodbasin areas (MIALL 1977), although the abrupt change in regime (to a floodbasin) may have been caused by a sudden change in river position, for example as a consequence of avulsion (ALLEN 1965) or river capture. Alternatively, the fine sediments may be more laterally extensive representing sedimentation in a more permanent, widespread water body. The sudden appearance of such a water body may have resulted from tectonic movements along a near-by active fault zone, producing a sudden lowering of base level in the area. This possibility is noted here because of nearby N-S faults known to have been active during deposition of later strata, as discussed below.

The entire sedimentary sequence (Fig. 9), including the coarse pebbly sandstone and conglomerate above (Rifleodden Conglomerate) shows a well defined coarsening upward sequence which probably reflects deltaic outbuilding into a standing body of water, with the mudstones as the distal lacustrine deposits, the overlying sandstones as the delta front sediments and the overlying Rifleodden Conglomerate as the accompanying river channel system, responsible for the transport of sediment into the basin. Whether this sequence represents a marine or lacustrine delta is not clear, but the abundance of plant fossils, the absence of marine fossils and trace fossils and the occurrence of laminated clay ironstone (siderite) favours a lacustrine delta interpretation.

Sedimentary history and paleogeography

Kapp Levin Member represents a thick sandstone sequence deposited by low sinuosity to meandering streams in the lower part, and by more typical braided river systems in the middle and upper parts. The lower part also grades downwards into the high sinuosity stream sediments of the underlying Vesalstranda Member. This overall change of depositional environment from Vesalstranda Member to the Kapp Levin Member, with a clear influx of coarser sediments through time, is probably a result of increased paleoslope, possibly related to increased dominance of lateral fill (as opposed to axial fill) at the latest slopes. The top of the member marks an abrupt change in depositional environment, where a relatively thick sequence of fine-grained sediments accumulated in a standing water body.

Palaeocurrent directions obtained from planar cross-strata and trough axes vary considerably, and a significant trend is difficult to obtain, as measurements towards all directions but south-west were recorded. No significant changes were recorded vertically in the succession. The diagram shown in Fig. 5 is based upon average paleocurrent directions within approximately equal intervals of the member. According to this diagram the upland source area was most likely located towards the west or south-west of the section examined.

4. TUNHEIM MEMBER

The Tunheim Member is best and most accessibly exposed on the north-east coast of Bjørnøya, between Kapp Olsen in the north and Rifleodden in the south (Fig. 1), with an estimated thickness of 80 m. The uppermost part of the member is, however, not exposed, so that a complete section is not available. Fig. 10 shows 9 profiles from different intervals within the member, with a suggested correlation based mainly upon the A-coal seam of HORN and ORVIN (1928).

Tunheim Member consists mainly of grey sandstones and shales with a few relatively thick coal-seams in its middle portion (the Tunheim series of HORN and ORVIN 1928). Conglomerates are locally developed in the lower part of the member.

The coal mining activity on Bjørnøya (from 1916 to 1925) was based on exploitation of the A-coal seam of HORN and ORVIN (1928). The latter authors also dealt in detail with coal properties.

Strata below the A-coal seam

In the area between Shivebukta and Framnes (Fig. 10) there is a 20 to 30 metres thick sandstone and conglomerate (Rifleodden Conglomerate) sequence whose top is marked by mud- and siltstone containing the A-coal seam (Fig. 10). This sequence is very complex in places, with many very large-scale channels, filled in a complex manner. An upward decrease in grain size and in the scale of sedimentary structures is present within single channel fill units, although there is also a marked local tendency for an alternation between

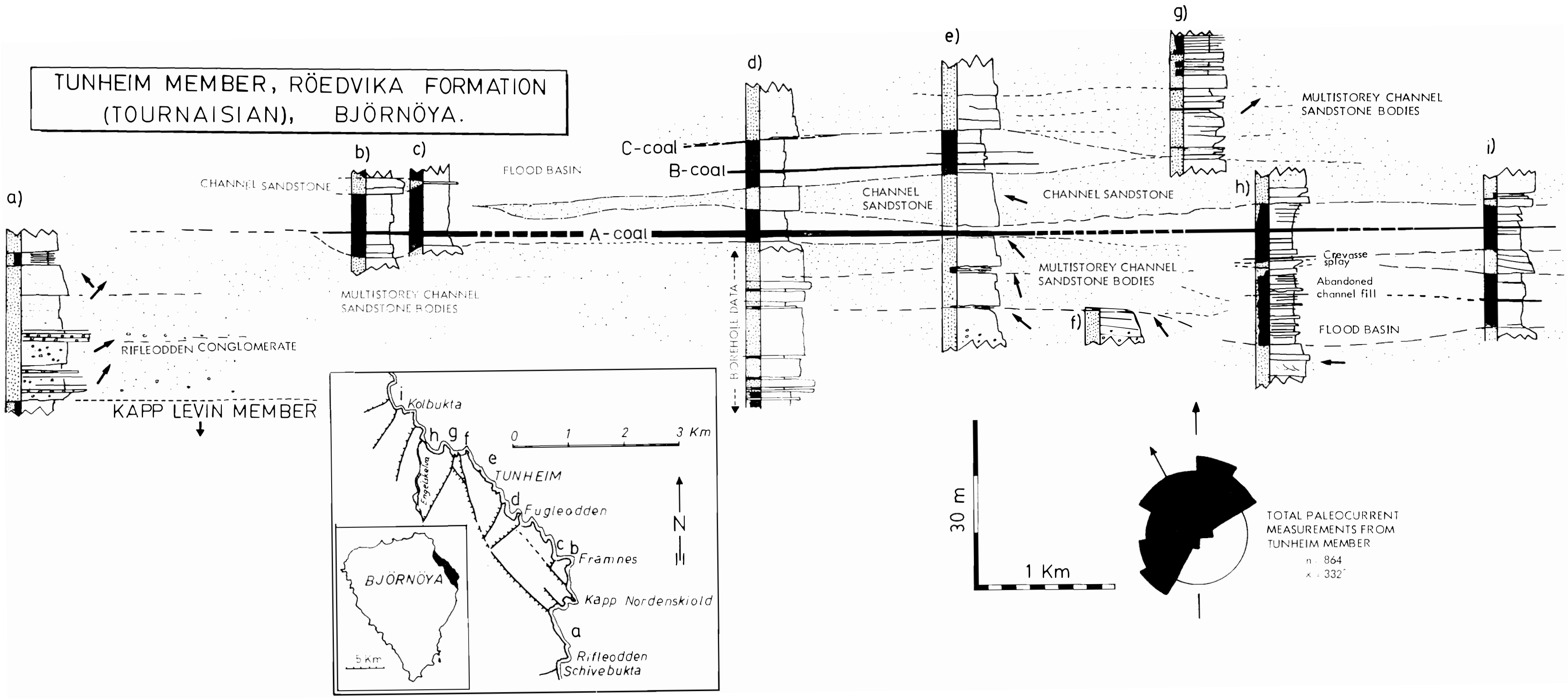

Fig. 10. *Generalized vertical logs from Tunheim Member, Röedvika Formation. The lateral correlation is based on the A-coal seam. The "rose diagram" below shows the total paleocurrent measurements obtained from the Member.*

large and small-scale structures and grain size. The channel-fill sediments are dominated by large-scale trough cross-stratification and planar cross-stratification (probably produced by migrating dunes and sand waves) with subsidiary very low angle, nearly horizontal stratification. As a whole this lower 20—30 meters of strata contain the same sedimentary facies associations as discussed for KA and KB of Kapp Levin Member and it is likely that this part of the member represents channel and bar sediments (now multi-story) deposited by rapid shifting low sinuosity meandering streams and braided streams.

In the area from just west of Kapp Bergesen to Tunheim there is another sandstone succession and a vertical log from here is shown in Figure 10 (profile e, below the A-coal seam). This succession is (using the A-seam as a correlation horizon) a lateral equivalent to the sequence exposed in the area between Shivebukta and Framneset. The two successions are in considerable contrast, however, since the succession just north-west of Tunheim shows three, more or less well defined fining-upwards sequences, bounded by sharp erosion surfaces below, and finely stratified very fine sandstone and mudstone above, (the base of the lowermost fining-upwards sequence of this succession is, however, not exposed). At one location, between Tunheim and Kapp Bergesen, a thin coal lens was recorded, just below the base of the uppermost fining-upwards sequence of this succession. This coal lens represents a remnant of a pre-existing, more extensive peat layer, which has been eroded away almost completely. Overlying the three fining-upward cycles, there is a fine-grained mudstone/siltstone unit containing the A-coal seam.

The fining-upward units described above represent sedimentary sequences similar to those of Facies Association A (GJELBERG 1978) of Vesalstranda Member, and consequently represent point bar sandstones of meandering river channels.

The lateral distance between the two sandstone successions of between Shivebukta/Framneset, and Kapp Bergesen/Tunheim is only a few kilometres. Another kilometre towards the north-west from Kapp Bergesen, at Austervåg, a farther contrasting lithological sequence occurs below the A-coal seam (see Fig. 10, profile h). In this area a 25 metre thick succession of mudstone and siltstone, interbedded with relatively thin sandstone units, occurs (Fig. 10). These fine-grained sediments overlie a fining-upwards sequence of the point bar type. The 25 m sequence is very similar to the thick flood basin sediments described from Vesalstranda Member (GJELBERG 1978). The thin, often sheet-like sandstone strata interbedded in the shale probably represent crevasse splays, deposited as discrete units during periods of high flood stage. A few sandstone units within the fine-grained sediments show well-defined coarsening upwards trends probably representing deposits similar to those of Facies Association D of Vesalstranda Member (lake or pond infill) (GJELBERG 1978). The lake-fill units which show a channel-like geometry probably represent infill of abandoned stream channels. Small syn-depositional faults are present in this succession (Fig. 11). One of the most puzzling aspects of the fine-grained sediments underlying the A-coal seam here is their dramatic variation in thickness, laterally towards the north-west, from about one metre thick in the

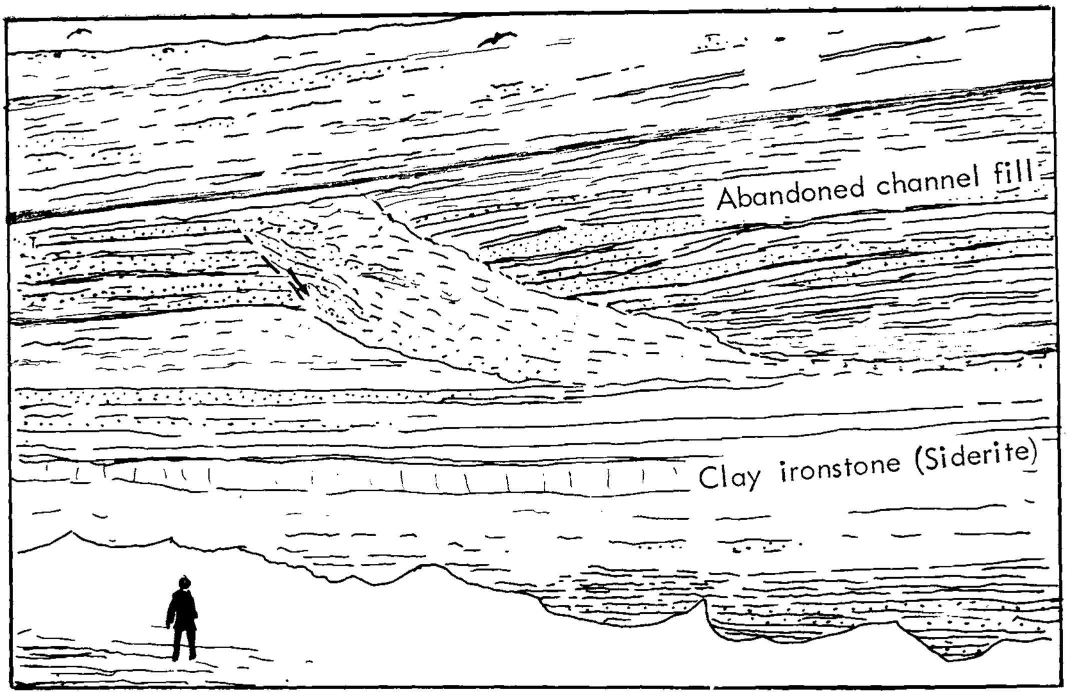

Fig. 11. *Part of the thick flood basin sequence exposed in Austervåg. Note syn-depositional faults probably developed on the margin of a pond or abandoned channel.*

area around Tunheim to 25 metres in Austervåg. Unfortunately, the A-seam is not exposed in the area between Tunheim and Austervåg, so the reason for this variation is not clear, but a general wedging out of the sandstone sequences seems likely.

The very complex sandstone and conglomerate sequence, exposed in the area between Shivebukta and Framnes is thought to represent the most active part of a meandering belt, where stream channels shifted rather quickly in their positions, resulting in a complex, multi-story sedimentary sequence. The fining-upwards sandstone bodies exposed in the area between Tunheim and Kapp Bergesen may represent meandering channels sweeping into more marginal areas of the main meander belt. Finally, the thick flood basin sequence in Austervåg probably reflects a more stable flood basin area, even more distant from the main meander belt, where active stream channels had only minor influence on the sedimentation.

Strata above the A-coal seam

As already noted, the A-coal seam occurs in a mudstone/siltstone unit overlying a fining-upward sandstone sequence. Above this unit occurs another sandstone sequence which varies considerably in thickness. In the Tunheim area it constitutes a well defined, 10 metres thick fining-upward sequence (Fig. 10), while to the south-east, towards Framnes, it completely wedges out (Fig. 10). To the north-west of Tunheim it becomes much thicker, and much

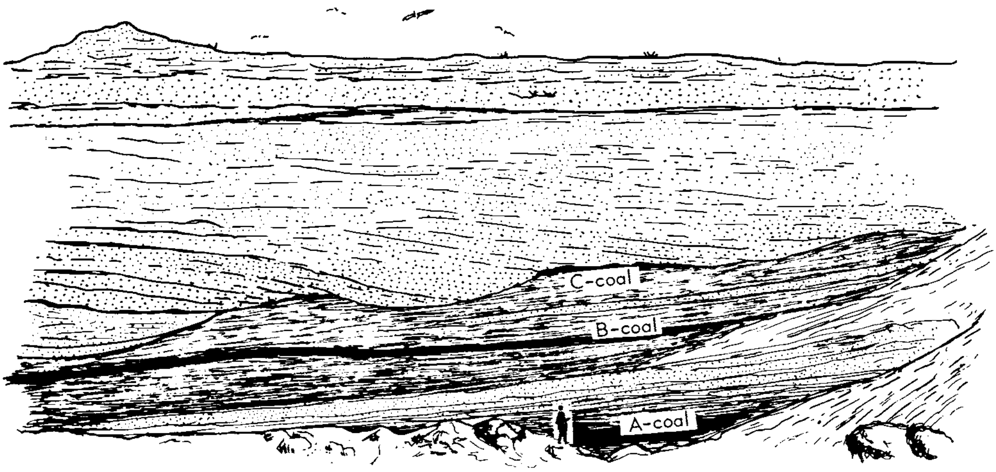

Fig. 12. *Occurrence of A-, B-, and C-coal in a location between Tunheim and Fugleodden. Note how the C-coal has been eroded by the succeeding sandstone sequence. Also note the very low-angle gigantic cross-stratification at the base of this sandstone.*

more complex in character (see Fig. 10). In the mudstone/siltstone unit located above this sandstone sequence occur the B- and C-coal seams of Horn and Orvin (1928). These coal seams, exposed in the area between Tunheim and Fugleodden are much thinner and more impersistent than the A-seam, and may be laterally eroded by succeeding fining-upwards sandstone beds. This is especially the case with the C-coal (see Fig. 12).

The sandstone sequence overlying these coal bearing intervals (overlying the C-coal), is more than 35 metres thick at Fugleodden, but because of inaccessibility, no complete vertical log was obtained. The sequence appears to be of complex character, even though in its lower part it shows a typical fining-upwards, epsilon-type cross-stratified unit (Fig. 12).

Well-defined fining-upwards sandstone sequences (similar to those of Facies Association A of Vesalstranda Member) are very common in Tunheim Member (as stressed by Worsley and Edwards (1976)). Large-scale trough and planar cross-stratification dominates in the lower and middle parts of individual sequences, while nearly horizontal stratification dominates in the upper part. From vertical sections, such trough cross-stratified units often appear to be strongly festoon-shaped (with a general decrease of set thickness upwards). In areas where sandstone surfaces have been eroded out nearly parallel to the original bedding, the curved internal laminations of the trough-like structures are easy to observe, and numerous paleocurrent measurements have been obtained. It is most likely that this type of cross-strata originated as a result of migrating undulatory, lingoid and lunate megaripples and dunes.

Another characteristic feature of the fining-upwards sandstone sequences is the frequent occurrence of giant cross-stratification or accretion units (Figs. 12, 13) with smaller scale sedimentary structures superimposed. The paleocurrent directions obtained from the second order structures are almost exclusively orientated normal to, or approximately normal to the dip direction

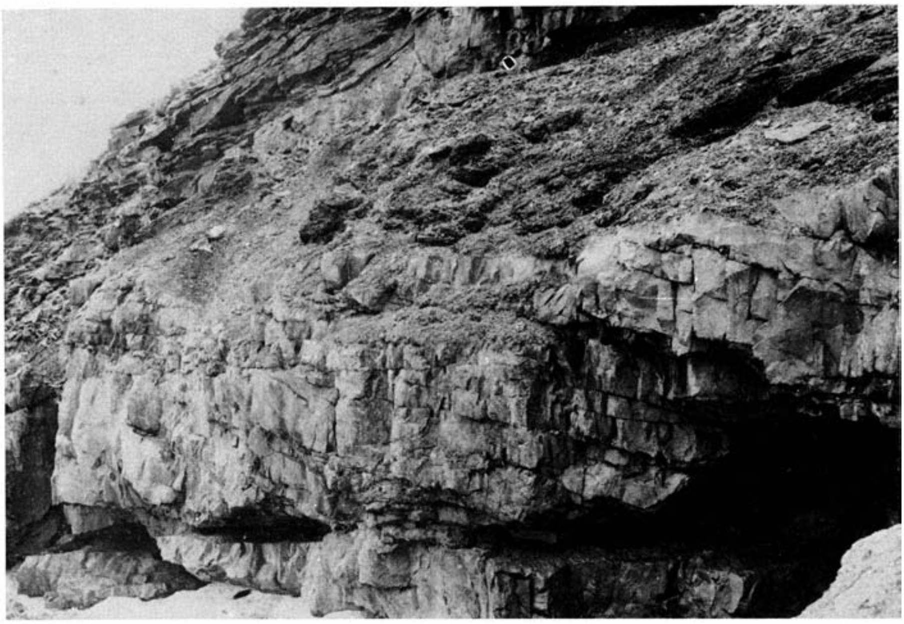

Fig. 13. *Fining-upwards sandstone sequence of Tunheim Member. Note the gigantic cross-stratification developed in the lower part (? Epsilon cross-stratification).*

of the first order structure. The giant cross-stratification is usually located in the lower part of fining-upwards sequences (Figs. 12, 13), and most likely represents the epsilon type (or point bar type) of cross-stratification. Many of the small peninsulas along the north-eastern coast of Bjørnøya are made up of such gigantic cross-stratified sandstone, where dip direction of the cross-strata are orientated seawards normal to the coastline. This persistent direction (seawards) of the cross-strata is puzzling (point bar surfaces ought to be made more variable in direction), but may be due to preferential preservation (dissipation of storm wave erosive power would tend to be maximum where waves break upslope) rather than an original unidirection arrangement of point bars.

Petrography

The white/grey poorly to moderately sorted sandstones of Tunheim Member resemble the sandstones of Kapp Levin Member. They consist mainly of quartz and rock fragments of quartzite. Pyrite occurs locally as relatively large concretions.

The clast composition of Rifleodden Conglomerate, in the base of the member, is almost exclusively white and pink quartzite and vein quartz. It is of interest that no "quartzites" exposed on the island today show similar high degree of metamorphism (see also HORN and ORVIN 1928, p. 22). Silica and ferrigenous cement are relatively common in the sandstones. In the shale and siltstone sequences, clay-ironstone is relatively common. In Austervåg, thick siltstone beds, containing numerous small, spherical sideritic concretions, oc-

Fig. 14. *In situ large plant root fossil, from a location just south of Tunheim.*

cur. The small concretions (mm) are so regularly developed that they give the rock a characteristic "oolitic" appearance. Stylolite-like features are present in sandstone sequences.

Plant fossils are very abundant in the Tunheim Member, and occur both as impressions of trunks of various sizes and as leaf imprints. In situ, silicified, plant roots, of relatively large dimensions, are preserved locally in shales (Fig. 14). The fossil flora from Bjørnøya has been treated in detail by earlier investigators (eg. NATHORST 1900, 1902; SCHWEITZER 1967).

Sedimentary history and paleogeography

As already suggested above, most of the sedimentary sequences of Tunheim Member, represent a flood-plain depositional setting, dominated by meandering streams. Fine-grained sediment (mainly mud and silt) accumulated in flood-basin areas, which most of the time were densely vegetated. The conditions neccessary for peat to accumulate (eg. high water table, little influx of clastic sediments, dense vegetation, etc.) have been optimum at times.

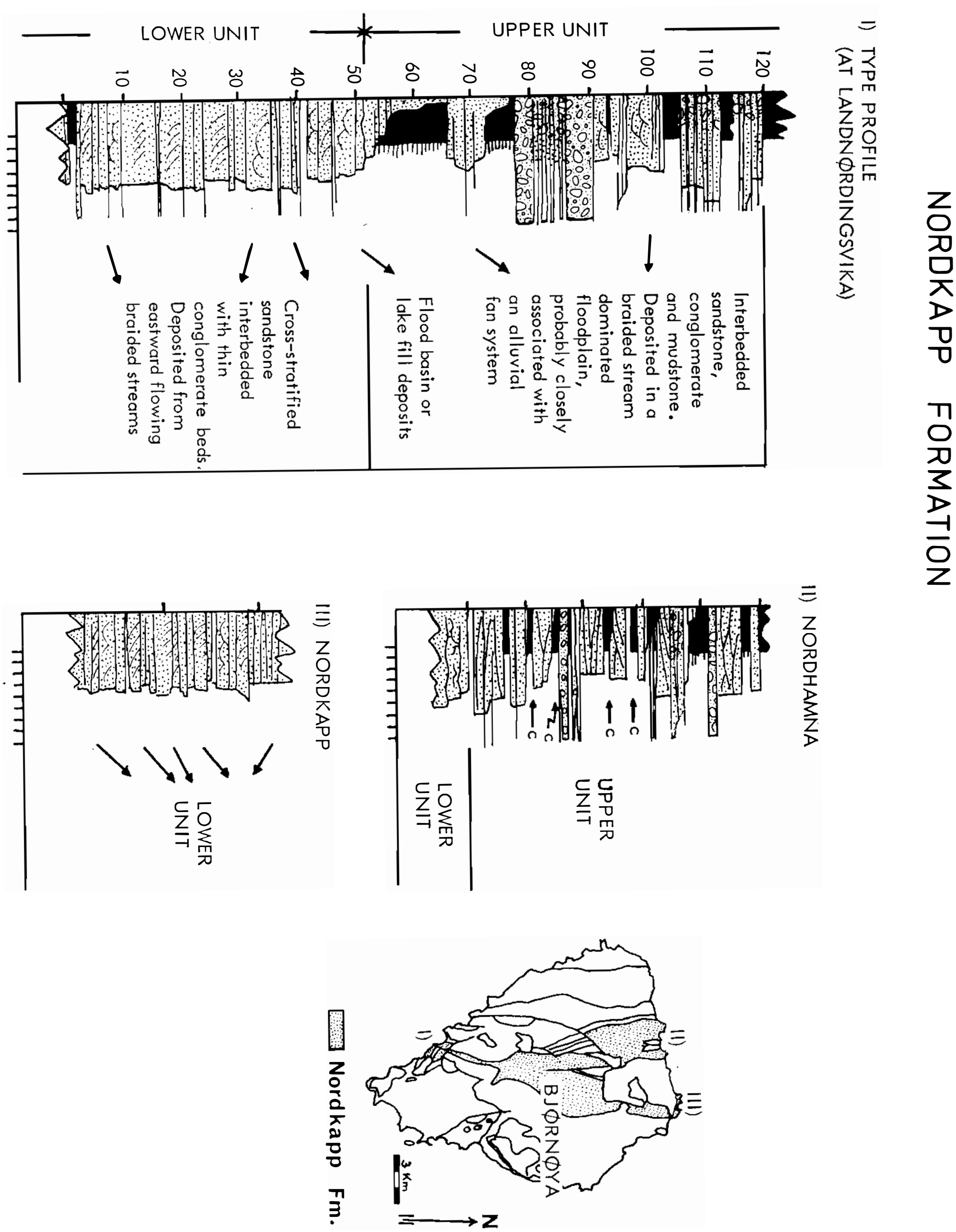

Fig. 15. *Generalized vertical logs from Nordkapp Formation.*

Profile I: from the exposures at Landnørdingsvika (type profile).
Profile II: from the exposures at Nordhamna on the north coast.
Profile III: from the exposures at Nordkapp on the north coast.

Rifleodden Conglomerate, in the lowermost part of the member constitutes the coarsest sediments of the entire succession. It is likely that these sediments represent a more proximal fluvial depositional environment (high discharge, braided streams) and are more nearly related to the underlying than to the overlying strata.

864 paleocurrent measurements based mainly on trough and planar cross-stratification, were obtained from the member. Paleocurrent direction varies considerably both vertically and laterally within the member. Fig. 10 (lower part) shows the mean vector azimuth to be 332° towards north-west. However, measurements towards all directions but the south-east have been recorded. Rifleodden Conglomerate shows an average transport direction towards north-east (Fig. 10), which corresponds fairly well with the mean vector azimuth of the paleocurrent measurements of the underlying Kapp Levin Member.

According to the data given above, the following paleogeographic conditions may be suggested: a north-westward orientated meander belt dominated the area (as also suggested for Vesalstranda Member). This implies a sedimentary basin w th a paleoslope towards north-west. However, the picture is much more complicated, as the basin at the same time received sediments from a source area in the west or south-west. Most sediments of Kapp Levin Member and probably the lowermost part of Tunheim Member (Rifleodden Conglomerate) originate from this direction. As suggested above, this source area may have been periodically important during phases of uplift. The fine-grained sequence underlying Rifleodden Conglomerate probably reflects a sudden lowering of base level, the immediate result of faulting. The overlying conglomerate, in turn, reflects the increased topography (and hence increased discharge) as a consequence of the faulting. Changing climatic conditions may also explain these changes in deposition.

The sediments of Tunheim Member, reflect mainly the same paleoclimatic conditions as during the deposition of Vesalstranda Member: relatively warm, moist climate.

As indicated above, all coal seams of Tunheim Member occur within flood basin sediments overlying fining-upwards channel sandstone sequences (i.e. limnic coal basins).

III. Nordkapp Formation

1. INTRODUCTION

The upper coarse sandstone unit of the Ursa Sandstone of earlier investigators (Horn and Orvin 1928) was renamed as the Nordkapp Formation by Cutbill and Challinor (1965). It is the uppermost coal-bearing succession on Bjørnøya and has consequently been closely examined by earlier investigators (Horn and Orvin 1928).

The best exposures of Nordkapp Formation occur in Landnørdingsvika on the south-west coast of Bjørnøya (Fig. 15). In this area a continuous sequence of the uppermost 120 metres of the formation is exposed. Although the base of the formation is unexposed, the profile measured in this area represents the best exposures of the formation, and will be referred to here as the *type profile*. The exposures along the north coast are locally very good and accessible, but a continual vertical log is very difficult to obtain due to the many faults intersecting this area. This is also the case for the area around Nordkapp, from which the formation has been named (CUTBILL and CHALLINOR 1965).

The contact between Nordkapp Formation and the underlying Tunheim Member is not exposed at any accessible locality on Bjørnøya. The contact between Nordkapp Formation and the overlying Landnørdingsvika Formation is exposed both in Landnørdingsvika (in the south) and in Kobbebukta on the north coast. In Landnørdingsvika, WORSLEY and EDWARDS (1976) placed the boundary between the two formations at the appearance of the red mudstones characteristic for the lower part of Landnørdingsvika Formation. Here a great lithological dissimilarity exists between the two formations, and WORSLEY and EDWARDS (1976) suggested an appreciable break in deposition. However, sedimentological studies from the north coast, and from borehole data, suggest that the transition from the grey, coarse-grained lithology in the upper part of Nordkapp Formation to the red siltstone dominating the lower part of Landnørdingsvika Formation is rather more gradual, without any obvious break in sedimentation. This will be discussed more in detail below.

As suggested by HORN and ORVIN (1928) and WORSLEY and EDWARDS (1976), the thickness of the formation increases northward, to more than 230 m in a borehole at the south end of Hausvatnet (HORN and ORVIN 1928). The variation in thickness may, however, be a little less than suggested by HORN and ORVIN (1928), who measured less than 110 m at Ellasjøen. The present studies show that the thickness is more than 120 m in this area.

ANTEVS and NATHORST (1917) dated the upper coarse sandstone part of the Ursa Sandstone (Nordkapp Formation) as Lower Carboniferous. Micro-flora from the exposures at Nordkapp contain elements of the *aurita* assemblage of Spitsbergen; it was assigned to Viséan by PLAYFORD (1962, 1963) and to the Namurian by CUTBILL and CHALLINOR (1965). However, KAISER (1970) reassigned this part of the formation to the Viséan. WORSLEY and EDWARDS (1976) suggested that most of the Formation belongs to the Viséan, but they also indicated that the lower part of the Formation spans the Tournaisian/Viséan boundary, because of a coal seam of Upper Tournaisan age, which outcrops south of Ellasjøen and probably belongs to this Formation and not (as suggested by KAISER (1970)) to the Røedvika Formation.

Because the uppermost part of the formation contains much more conglomerate and mudstone than the rest of the formation, it has been found convenient to divide it into two units.

Composition of the sandstones does not differ dramatically for the two units, as quartz grains and rock fragments of quartzite are the dominating components in both units and often account for more than 90% of the rock. Chert, as very small clasts, is much more common in Nordkapp Formation than in the underlying Røedvika Formation, and in some conglomerate beds (debris flow, and streamflood conglomerates) it constitutes more than 30%

of the clast composition (Fig. 19). Concentrations of clay minerals (mainly illite and kaolinite) which occur as "clasts" both in conglomerates and sandstones, are common in certain zones both in the lower and upper units. This probably originates from weathering of relatively unstable minerals (e.g. feldspar). Heavy minerals of pyrite and magnetite were recorded. Rutile and mica occur as accessories. Ferruginous cement is common.

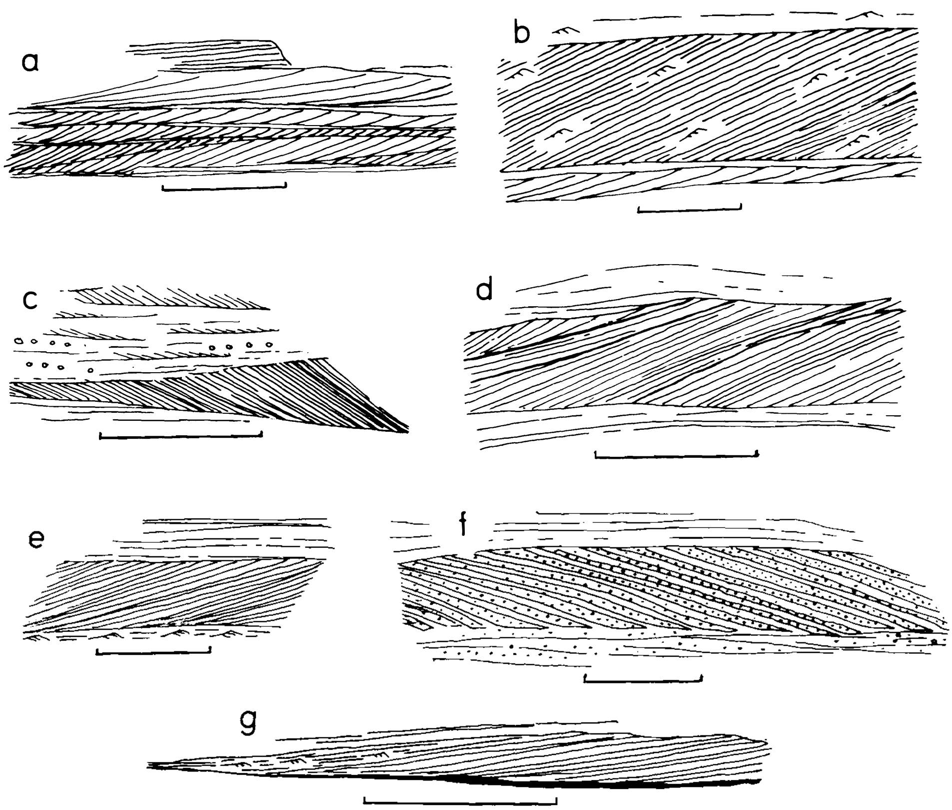

Fig. 16. *Various types of planar cross-stratifications recorded from Nordkapp Formation, lower unit, (scale is 1 m):*

a. *Grouped sets of planar cross-stratification. Probably formed by migration of lingoid bars and sandwaves.*

b. *Tabular cross-stratification with angular basal contact (weak separation eddy). Small-scale current ripples superimposed oblique to the foresets.*

c. *Prograding bar with well developed foresets and back bar sediments. Straight foresets with angular lower contact suggest formation by current with weak separation eddy. The increased set thickness may be a result of increased water-depth during deposition.*

d. *Planar cross-stratification showing reactivation surfaces. The reactivation surfaces indicate several episodes of bar progradation.*

e. *Planar cross-stratification with tangential lower contact. Ripples in base are probably a result of backflow. The very tangential contact also suggests formation by current with a strong separation eddy.*

f. *Tabular cross-stratification with rhythmic change between foresets of sand and granule conglomerate a result of rapid change of discharge.*

g. *Low angle cross-stratification with tangential lower contact. The lower parts of the foresets are ripple-laminated.*

Plant fossils were recorded frequently from the exposures on the north coast, where they occur mainly as impressions of tree trunks.

Most of the lithofacies associations of this Formation are basically similar to facies associations already described from Røedvika Formation. The fundamental description of those associations is therefore not repeated, but cross-reference to previous descriptions is made. Because of this only a generalized description is outlined below, together with an effort to highlight particular unusual or interesting aspects of this formation.

2. LOWER UNIT — DESCRIPTION AND INTERPRETATION

This unit is exposed in Landnørdingsvika on the south-west coast, and on the north coast around Nordkapp, Herwighamna, Gravodden and Kapp Kjellstrøm (Fig. 1).

As indicated above this part of the formation consists mainly of uniformly developed sandstone with occasional beds of pebbly sandstone and thin conglomerate. Beds of mudstone and siltstone are scarce (1.6%). Beds are usually very lenticular and often bounded by curved erosion surfaces. Large-scale, high angle planar cross-stratification dominates and are frequently very regularly developed and relatively laterally extensive. Various types of planar cross-stratification documented are shown in Figure 16. Trough cross-stratification and low angle, nearly horizontal stratification are also common. Ripple laminated intervals are present locally. Soft sediment deformation structures occur frequently, some of which may be of considerable size (see Fig. 17).

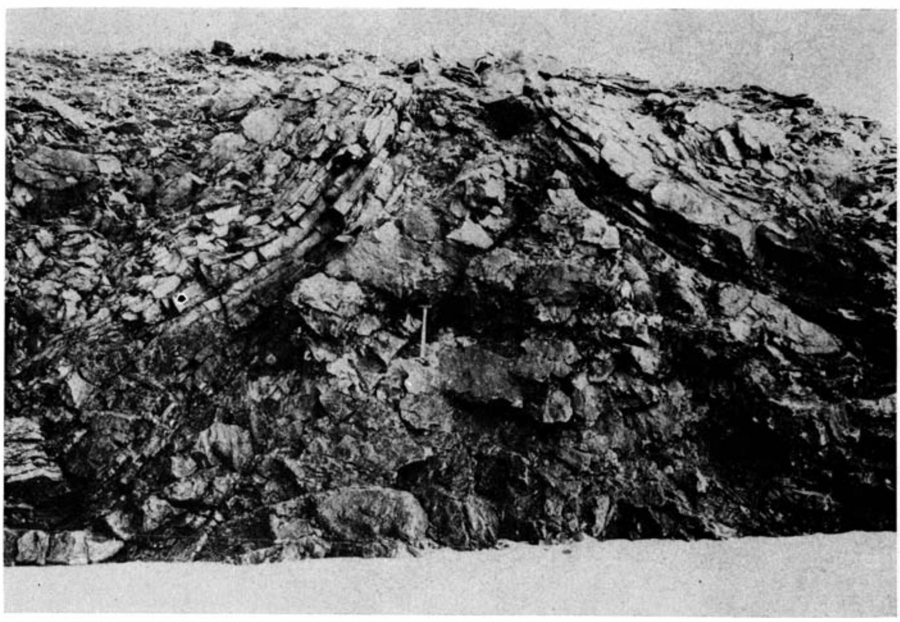

Fig. 17. *Large-scale deformation structures in Nordkapp Formation. From the exposures just west of Gravodden. The core of the anticline is completely massive, while primary sedimentary structures are still distinguishable on the limbs.*

The sediments of this member generally represent the same lithofacies association as those of Facies Association KB of Kapp Levin Member. The following differences are important here, however:

a) The sandstone/conglomerate ratio is much higher here.
b) Planar cross-stratification is much more common here than for Facies Association KB of Kapp Levin Member, where large-scale trough cross-stratification and channel scour and fill dominate.

On the basis of vertical evolution of sedimentary sequences, grain size and sedimentary structures, it is likely that most of the sediments of the lower unit of Nordkapp Formation represent MIALL's (1977) Platte type braided stream system. The sediments of Facies Association KB, probably represent a braided river system more like MIALL's (1977) "Donjek type".

Because of the abundance of planar cross-stratification in this member more than 300 paleocurrent measurements were recorded from various localities. Figure 18 shows the paleocurrents obtained from the north coast, at Landnørdingsvika and at Kapp Harry. The mean vector azimuth is 63° towards east.

According to the above data it is suggested that there was an elevated area in west which acted as upland area for a persistent, eastward flowing braided stream system.

3. UPPER UNIT — DESCRIPTION AND INTERPRETATION

A 65 metres thick sequence of this unit is exposed in Landnørdingsvika, while it is about 40 metres thick in Nordhamna (Fig. 15, profile I), and less than 20 metres in Kobbebukta.

Sedimentary sequences similar to those described from Facies Association KB (Kapp Levin Member) are most commonly developed in this unit. A very complex and lenticular bedding type dominates. Large-scale, trough cross-stratification, channel scour and fill, low angle, nearly horizontal stratification and large-scale planar cross-stratification are the dominating elements.

Sandstone, conglomerates and siltstone/mudstone are the dominating lithologies and in Landnørdingsvika conglomerates and siltstone/mudstone account for 24% and 19% of the succession respectively. The siltstone/mudstone horizons locally contain a lot of organic material and thin coals and coaly shales are developed (Fig. 15, profile I).

Using the same arguments as for Facies Association KB (of Kapp Levin Member), the sandstone and conglomerates of this unit most likely represent braided river channel systems with sedimentation at different topographic levels within the channel system, or successive events of vertical aggradation followed by channel switching (see also MIALL 1977).

The lens-shaped fine-grained mudstone/siltstone units associated with the coarse-grained (sandstone/conglomerate) sediments may represent sediments similar to those described from Facies Association KC (Kapp Levin Member), and hence reflect abandoned channel fill, swale fill or slough fill sediments

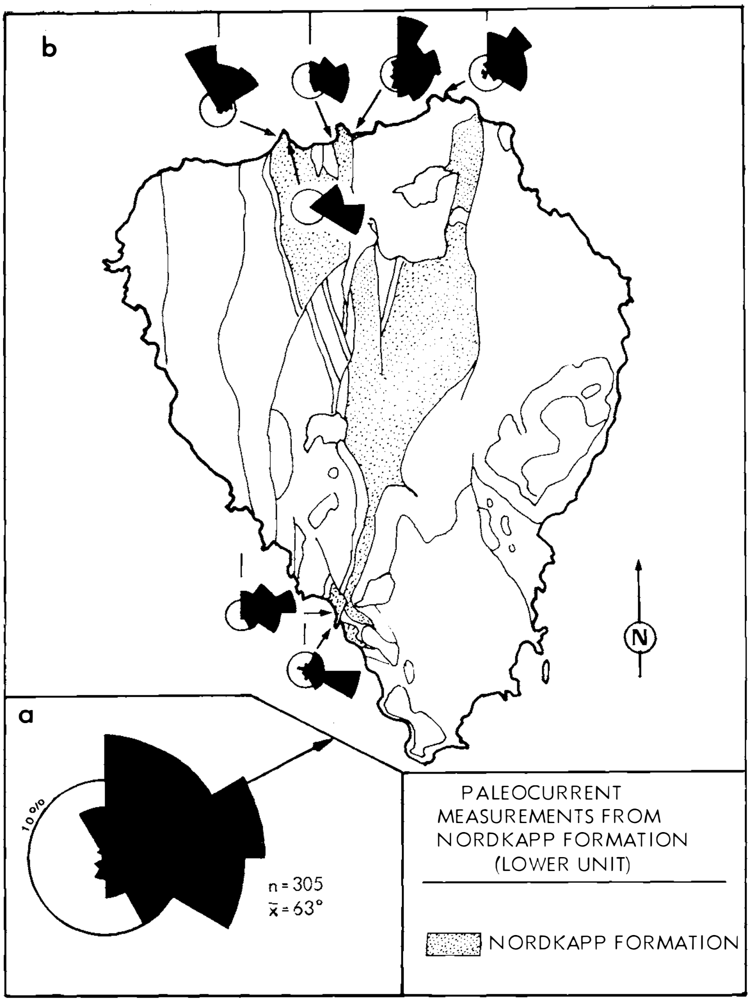

Fig. 18. *Paleocurrent data from Nordkapp Formation, lower unit.*

a. Total paleocurrent measurements obtained from this unit.

b. Paleocurrent directions from exposures on the north coast, at Landnørdingsvika and at Kapp Harry.

deposited from suspension. However, these sediments may also represent distal flood basin sediments where conditions necessary for coal to accumulate have been optimum.

Fine-grained sandstone/mudstone sequence at the base of the upper unit

At Landnørdingsvika the boundary between the upper and lower units may be placed at a very distinct, 10 metres thick sequence of fine-grained sediments, sharply overlying the uniformly developed sandstone succession of the lower unit. It consists of fine-grained, trough cross-stratified sandstone interlayered with thin mudstone strata in the lower part which grades upward into flat stratified sandstone interlayered with siltstone and mudstone (Fig. 15, profile 1). Plane parallel lamination is common in the upper part, and plant fossils are present as elongated leaves between laminae. Overlying this fine-grained unit occurs a 7 m thick sandstone sequence, coarsening upwards in the lower part and fining upwards in the upper part. Somewhat similar developments to those found in Landnørdingsvika also appear in borehole sections from various localities in the interior of the island (e.g. south end of Laksevatnet and south end of Hausvatnet) and it is probable that these represent lateral equivalents. In this case the unit is very laterally persistent (more than 10 km). It is likely that this unit, which marks the transition from lower to upper members, reflects a rather dramatic change in deposition. This suggestion is supported by the very distinct boundary between the two units exposed on the west side of Kapp Kjellstrøm and it may well reflect a break in deposition.

Sediments deposited from suspension with intercalations of bedload sediments (ripple lamination and plane lamination of lower flow regime) dominate in the upper part of the sequence. In the lower part, bedload sediments dominate.

It is suggested here that this unit represents vertical accretion of fluvial sediments developed somewhat lateral to active stream channels, probably in a flood basin or a lake. Most of the bedload sediments were probably brought into the basin during flood events. The interstratified mudstone and siltstone is thought to have been deposited from suspension during periods of slack water conditions.

Prominent conglomerate sequences in the upper unit

The prominent conglomerate sequences of this unit in Landnørdingsvika (Fig. 15), differ considerably from the conglomerates described in previous sections. These conglomerates are characterized by sheetlike sets of internally structureless, unsorted conglomerates, mainly matrix-supported, but with well-sorted, almost matrix-free intervals. Some sets of large-scale, very low-angle planar cross-stratification were recorded. Individual conglomerate sets are often overlain by thin sheet-like, cross-stratified and massive sandstone sets. However, units of superimposed conglomerate sets, without intercalation of sandstone are also common. Basal erosion surfaces are scarce, and there is a positive correlation between maximum particle size (MPS) and bed thickness (BTh) (Fig. 19A).

Figure 19B shows clast orientation data from 350 long-axis (A-axis), and medium axis (B-axis) orientation measurements from different intervals within the conglomerates. No obvius B-axis orientation occurs, but long-axis are mainly orientated in north-south direction. Imbrication is poor.

Matrix of this conglomerate is highly unsorted and contains sediments of all grain sizes from mud to granules. Clast composition data of the conglomerates are shown in Figure 19. Clasts of bright quartzite, red and grey quartzitic sandstone and chert dominate. No carbonate clasts were recorded. (This differs considerably from the composition of the conglomerates of the overlying Landnørdingsvika Formation).

Many conglomerate beds show basically the characteristics of both ancient and recent debris-flows, while other beds resemble streamflood conglomerates.

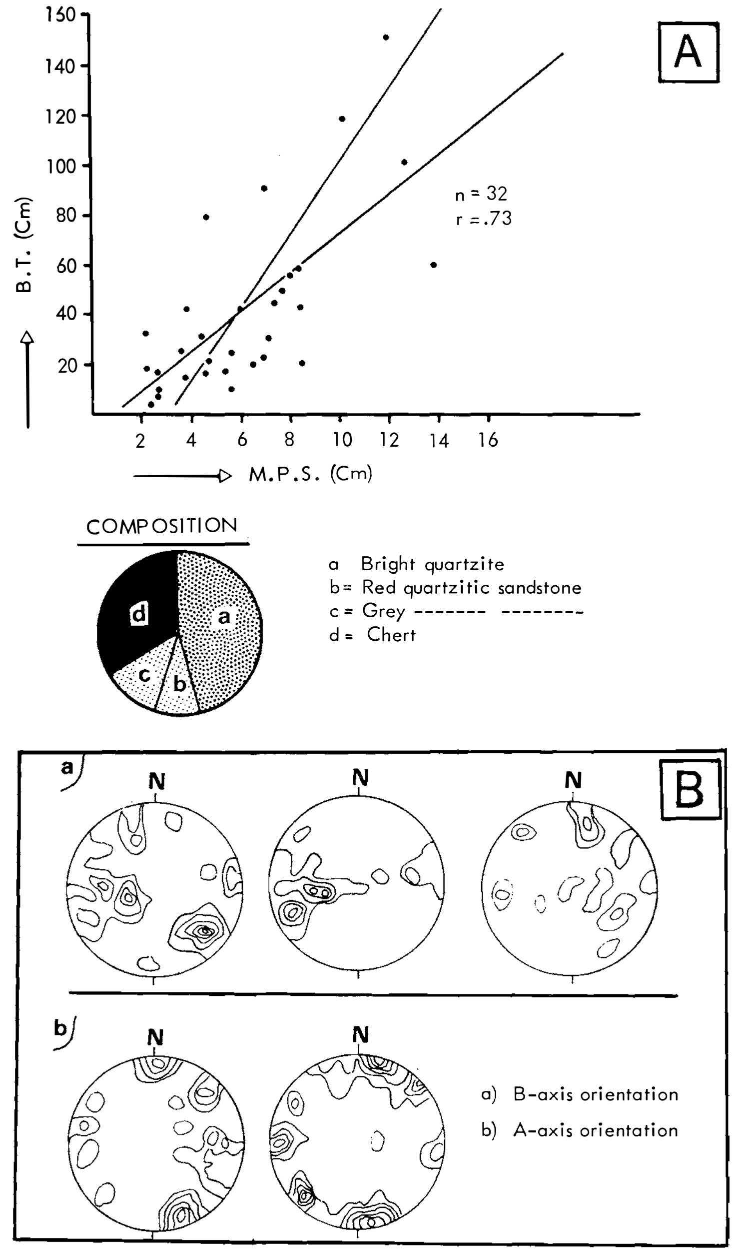

Fig. 19. *A. Plots of maximum particle size (M.P.S.) with respect to bed thickness (B.T.) from the most prominent conglomerate beds in Nordkapp Formation, upper unit. Note the correlation. Figure also shows clast composition.*

B. Clast orientation from the most prominent conglomerate beds of Nordkapp Formation, upper unit. a) B-axis orientation; b) A-axis orientation.

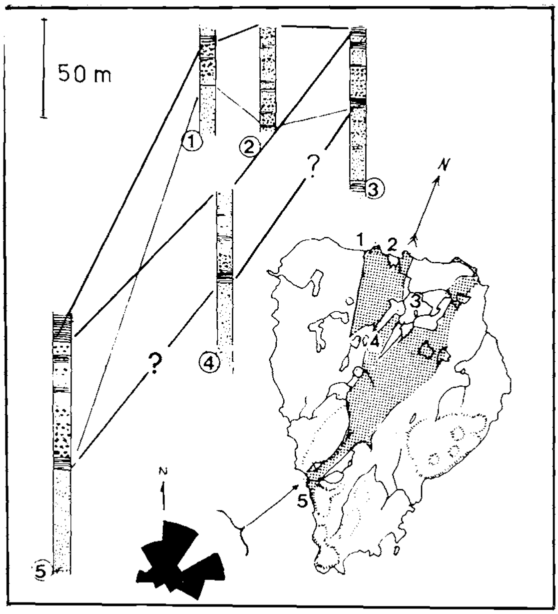

Fig. 20. *Thickness variation of the upper conglomerate unit of Nordkapp Formation. Figure also shows paleocurrent measurements from the south-west coast.*

Thickness of the upper unit

The thickness of this upper unit varies as shown in Figure 20, with an increase towards east.

From the exposures on the north coast very few paleocurrent data were obtained.

4. ENVIRONMENT OF DEPOSITION

According to the above interpretation this Formation represents a braided river system somewhat similar to that suggested for Kapp Levin Member. Flow direction probably was towards north or north-east (se Fig 41). It is suggested here that the sediments of this succession represent distal parts of a more complex alluvial fan system, with a source area in the south or southwest on which deposition by debris flow processes also were present. The interfingering of debris flow sediments reflects more extensive lateral migration of these sediments probably as a result of increased topography, as a result of tectonic movements, or change in climatic conditions.

Because of the frequent occurrence of primary deformation structures (probably as a result of liquifaction caused by seismic shocks) it is suggested that a near-by active faultline or zone influenced sedimentation through time. This suggested tectonic activity may have caused an elevated source area to the west and southwest. This is consistent with the sedimentological evolution of the overlying Landnørdingsvika Formation, discussed below.

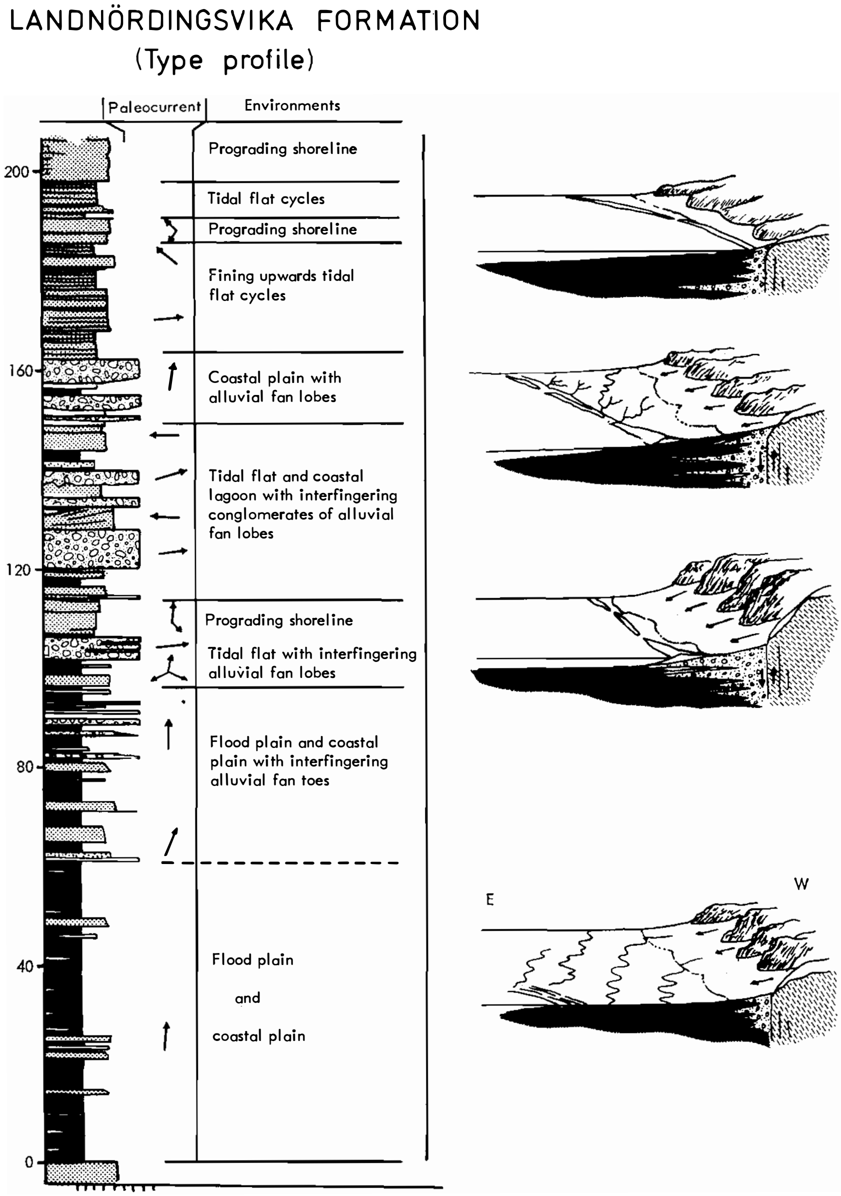

Fig. 21. *Generalized vertical log of the type profile of Landnørdingsvika Formation. Interpretation according to depositional environment and paleogeography.*

IV. Landnørdingsvika Formation

1. INTRODUCTION

A complete section from this formation (205 meters thick) is exposed at Landnørdingsvika on the south-west coast (Fig. 21). The name landnørdingsvika Formation was first used by Krasil'ščikov and Livšic (1974), and it replaced "Red Conglomerate Series" of earlier workers (eg. Andersson 1900; Holtedahl 1920; Horn and Orvin 1928).

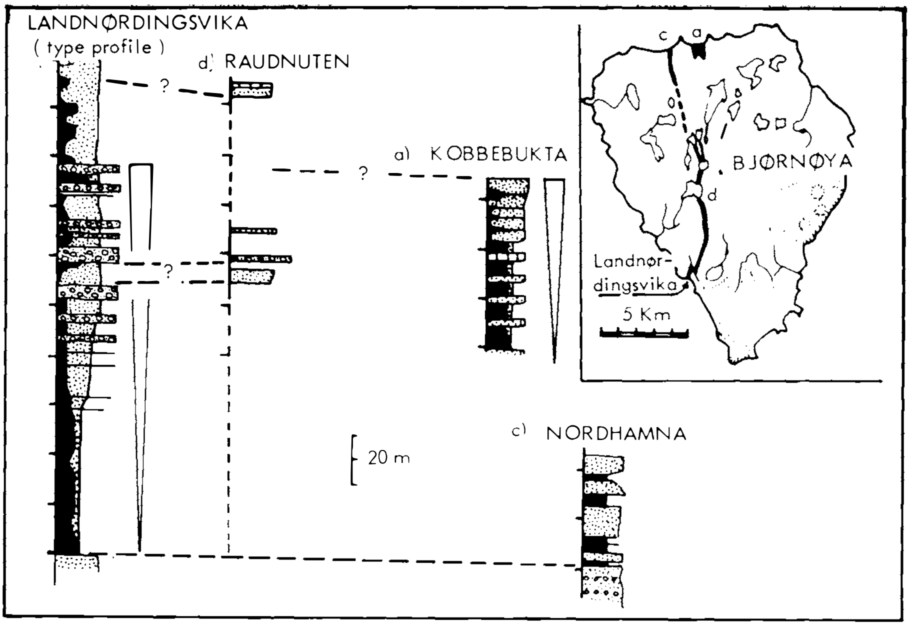

Fig. 22. *Suggested correlation between different profiles of Landnørdingsvika Formation.*

In Landnørdingsvika the base of the formation is placed at the appearance of red mudstones. WORSLEY and EDWARDS (1976) placed the upper boundary at the top of the last prominent conglomerate bed.

Outcrops of the formation are shown in Fig. 1, but only the exposures on the coastline are good enough to give any reliable data, as most of the inland area is covered by scree. In addition to the type profile at Landnørdingsvika three other vertical logs were obtained, but none of them represent a complete section through the formation. Their location, and suggested correlation with the type profile is shown in Fig. 22.

Profile a in Fig. 23 was obtained from a 70 meters thick succession in Nordhamna on the north coast.

This succession was assigned to the overlying Ambigua Limestone by HORN and ORVIN (1928), but it has been suggested by WORSLEY and EDWARDS (1976) that it should be assigned to the Landnørdingsvika Formation. On the basis of facies evolution and lithology it is suggested here that this succession may be equivalent to the upper-middle part of the formation at Landnørdingsvika (Fig. 22). Profile c) in Fig. 22, obtained from Kobbebukta on the north coast, represents the lowermost 50 meters of the formation, as a transition to the underlying Nordkapp Formation is exposed in this area. It is emphasised that there exists no sharp boundary between these two formations as there is a gradual passage from the coarse-grained, braided stream deposits of the Nordkapp Formation to the finer grained, red sediments of Landnørdingsvika Formation. This differs much from the relatively sharp contact between the two formations found on the south-west coast. Profile d) in Fig. 22 was logged at Raudnuten just south of Røyevatn and represents the only useful

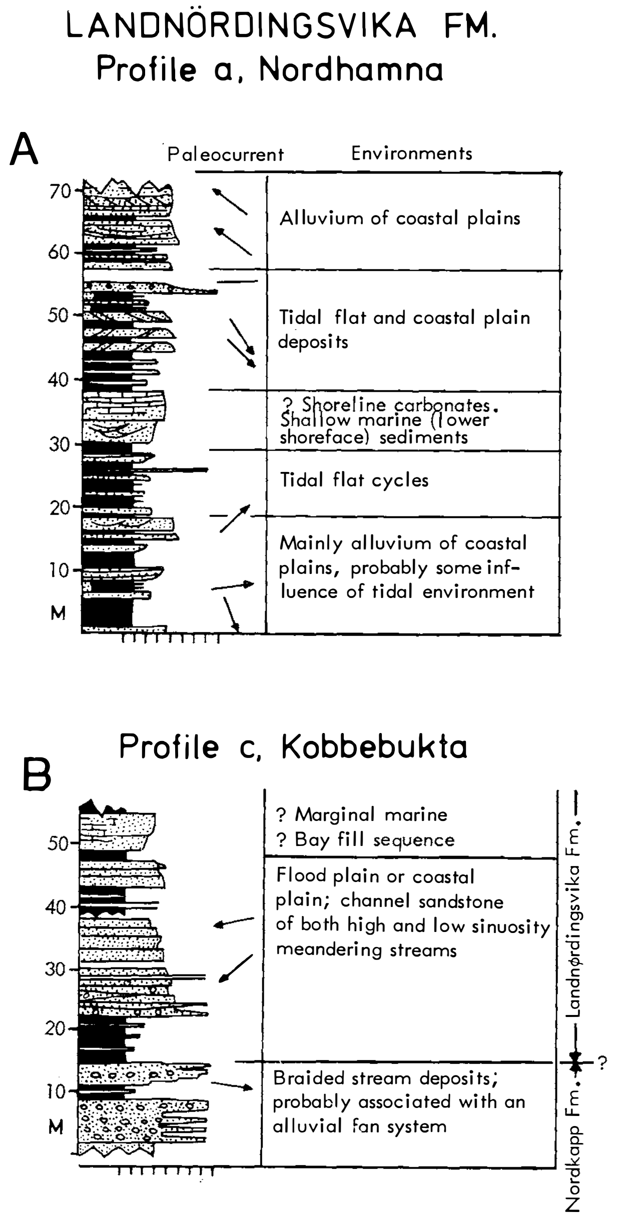

Fig. 23. *A. Generalized vertical log of Landnørdingsvika Formation. From the exposures in Nordhamna on the north coast.*
B. Generalized vertical log of lower part of Landnørdingsvika Formation and upper part of Nordkapp Formation. From the exposures in Kobbebukta on the north coast.

exposures from the central part of the island, though they are very incomplete (Fig. 22).

The gradational upper contact to the overlying Moscovian Kapp Kåre Formation implies at least a slightly older age for the Landnørdingsvika Formation. Fossils found in the upper part of the formation support this suggestion

(Worsley and Edwards 1976). This, in turn, suggests an appreciable break in deposition between the Nordkapp and Landnørdingsvika Formations (Worsley and Edwards 1976), as the Nordkapp Formation has been assigned to Viséan. Worsley and Edwards (1976) used the great dissimilarity between the two formations on the south-west coast to support this suggestion.

As noted above, however, no obvious sign of such a break in deposition is present on the north coast, where a gradual transition and interfingering between the grey sandstone, mudstone and conglomerates of Nordkapp Formation to the red mudstone and interbedded drab sandstone of Landnørdingsvika Formation occur. A similar gradual transition is reflected in a borehole section from the outlet of Laksevatnet (Horn and Orvin 1928). No distinct boundary exists between the red and grey lithologies, suggesting a continual sedimentary sequence without any extensive break in sedimentation as suggested by Worsley and Edwards (1976). It is suggested here, however, that there is an important break in sedimentation within the upper part of Nordkapp Formation, as seen from the sharp boundary between lower and upper units. This may imply that the formation spans over a longer interval of time than earlier assumed.

The type profile in Landnørdingsvika shows the following general lithological development:

The lower part of the formation consists mainly of red, blocky mudstones with occasional, erosively based, drab sandstone beds. Cornstones are sparsely developed in the mudstones. Red conglomerates gradually appear at about 50 metres above base; and become very important in the middle part of the formation, where they are associated with drab sandstone, and red mudstone beds. In the upper-middle part, the conglomerate beds become lenticular

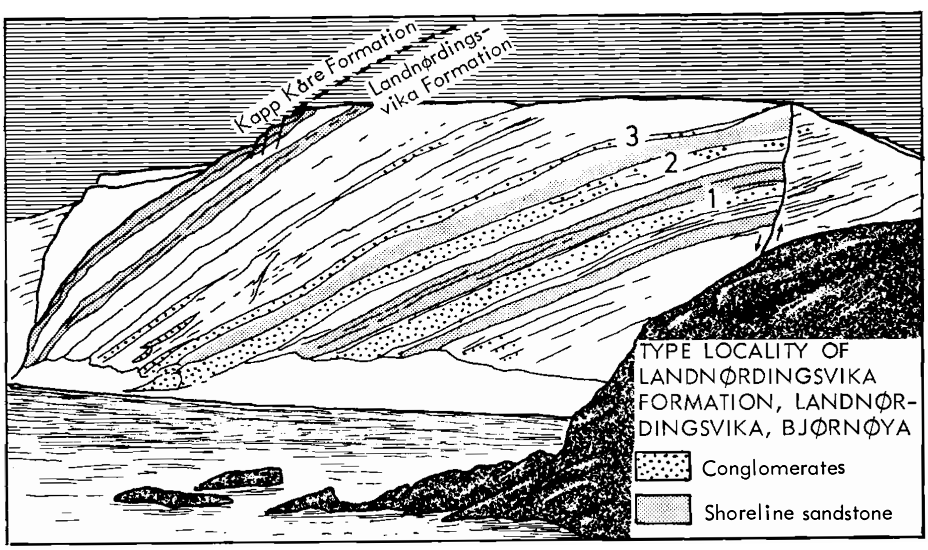

Fig. 24. *Type locality of Landnørdingsvika Formation, Landnørdingsvika, on the south-west coast of Bjørnøya. The cliff is 95 m high. The most prominent conglomerate lobes are marked with the numbers 1—3.*

and finally disappear (Fig. 24). The upper part of the formation consists mainly of fining-upwards drab sandstone beds overlain by red mudstone. A few prominent calcareous sandstone beds contain typical marine fossils.

The lithology on the north coast differs from that in Landnørdingsvika, as the thick conglomerate sequences are completely absent. The northern development probably represents a more distal facies development.

2. FACIES ANALYSIS

Facies Association I.A — (Flood plain/coastal plain)

This facies association occurs mainly in the lower part of the formation. In Landnørdingsvika, where the boundary between Nordkapp Formation and Landnørdingsvika Formation is exposed, sediments assigned to this facies association occur at the lowest 70 m of the succession, lying abruptly over the much coarser and lithologically very different sediments of Nordkapp Formation. At Kobbebukta, however, on the north coast, where also the lower part of the formation is exposed, sediments of this association are less dominant (Fig. 23).

In general, this facies association consists of red, usually massive, mudstone units interbedded with drab, fining upwards sandstone units.

Coarse units — The relatively thick (1—3 m) sandstone units which are interbedded with the mudstones are very fine- to medium-grained and each unit shows a slight upwards fining tendency, with a sharp, often erosional base (Fig. 25). Lag conglomerates, composed of intraformational (mud clasts) and extraformational pebbles are developed immediately above some of the basal scours. Generally these sandy units pass upward gradually into the overlying mudrock; this upper boundary of the coarse unit appears to be relatively sharp for some of the sandstone sequences. Where their internal sedimentary structures can be observed they show unidirectional planar and trough cross-stratification in places merging laterally and vertically into small-scale cross-lamination and plane horizontal lamination. Along the base of units, small scour and fill structures are developed, and in a few cases relatively deep channel scouring, up to 1.5 m, occurs. Large-scale (sets up to 2 m) cross-stratification of the epsilon type (Allen 1963) with superimposed ripple-lamination and cross-stratification was seen in a few sequences. These sandstones are moderately sorted, with a low matrix control and a carbonate cement which fills the grain framework. No fossils fauna or plants fossils were observed in this facies association.

Fine grained units — This type of unit is always closely associated with the sandstone units in as much as it usually constitutes the uppermost part of a complete fining-upward cycle. The bulk of this subdivision consists of reddish mudstone, with very thin, very fine-grained, often ripple laminated sandstone strata interbedded. The red mudstones are usually massive, and the original ripple lamination can only be seen in some scattered locations. No fossils fauna

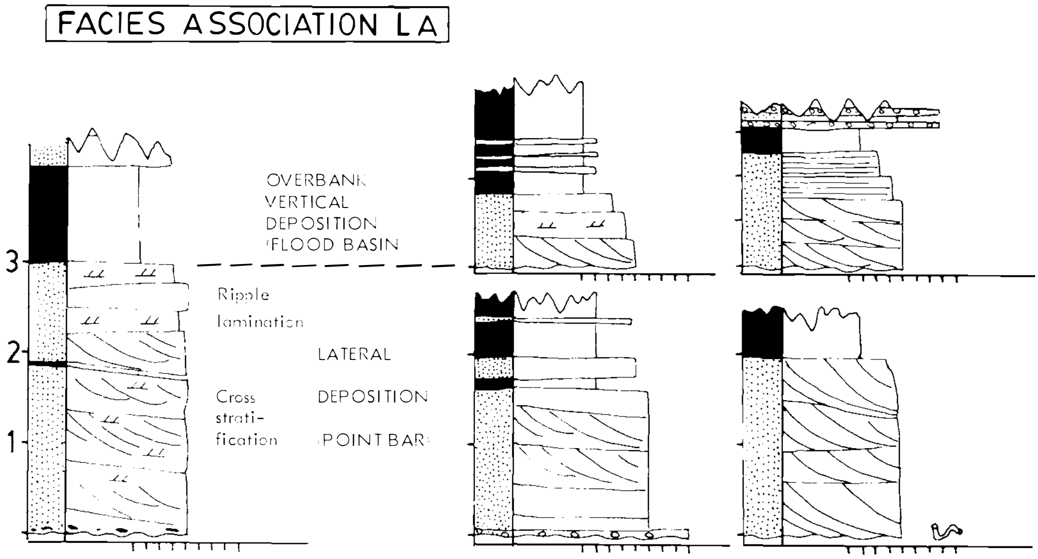

Fig. 25. *Detailed vertical logs from Facies Association LA (Landnørdingsvika Formation).*

or plant fossils were recorded, even though the massive character of the mudstone beds is probably a result of bioturbation. Cornstone horizons, probably ancient caliche (Steel 1974a), are sparsely developed. It is worth noting that most of the caliche horizons represent a rather immature stage of development (mainly 1 and 2 of Steel's classification 1974a). This fine-grained subdivision is obviously the most important part of the facies association quantitatively, with individual units more than 10 m in thickness.

Interpretation — It is most likely that this facies association originated as meandering stream deposits with the fine-grained units representing deposits from overbank flooding, and the sandstone bodies representing mainly point bar deposits from fluvial channels.

The most obvious differences between the fining-upwards sequence here and in Røedvika Formation (Gjelberg 1978) occur in the fine-grained units: a distinct red colour dominates the sediment in Landnørdingsvika Formation, while the corresponding sediments in Røedvika Formation are grey, yellow-grey and black. Coal seams are completely absent in Landnørdingsvika Formation, and calcareous soil horizons are developed instead. In addition the sandstone units of the fining-upwards sequences here (point bar deposits) are somewhat thinner than those described from Vesalstranda Member.

The fine-grained "mudstone" unit represents the result of vertical accretion of flood basin deposits. The thin ripple laminated sandstone strata interbedded in the silt-mudstone represent the more severe overbank flooding, where stream capacity has been great enough to carry sand material into the flood basin areas.

The flood basin sediments are very thick compared with the associated channel sand deposits. This probably resulted from the high sinuosity of the river channels, where streams became more or less fixed in their position so that long periods were available for flood basin sedimentation (ALLEN 1965, p. 126). In addition, it is likely that thick mudstone units are multistorey, resultant from more than one stream channel system.

It is probable that the sediments of this facies association represent a coastal plain alluvial environment, due to the closely associated marginal marine deposits.

Facies Association I.B (Red conglomerates)

This facies association consists of relatively thick, red conglomerate sequences and associated red sandstone/mudstone units. It is exposed only in Landnørdingsvika (type profile) and at Raudnuten (Fig. 22). Sediments of this facies association are completely absent on the north coast, while in Landnørdingsvika they occur mainly in the middle part of the profile (Fig. 21).

Description — Most of the conglomerates have relatively sheetlike extension (more than 250 m) (Fig. 24), but in some cases the lateral extension may also be very restricted. This is especially the case in the uppermost exposures, where a channel-like geometry dominates (Fig. 24). The thickness of the different conglomerate sequence never exceeds 10 metres. Detailed vertical logs through two of the most prominent conglomerate profiles are shown in Fig. 26. With respect to sedimentary structures and textures these conglomerates may be divided into the following three types:

a) Unsorted, internally structureless, matrix-supported and clast-supported conglomerates which are often overlain by thin massive sandstone strata. This is the most common conglomerate type, and usually forms the thickest sets (up to 0.8 m). However, set thickness varies considerably, and thin sets (10—15 cm) are common. Locally, relative thick units of conglomerate are entirely built up of such thin sets super-imposed on each other, giving the unit a distinct, flat stratification.

b) Well-sorted, thin sets of openwork clast-supported conglomerate.

c) Planar cross-stratified conglomerates of both well sorted (matrixfree) and more unsorted character.

These three conglomerate types are usually closely associated with each other, but appear to have no preferential vertical occurrence with respect to each other.

The matrix of these conglomerates consists mainly of red, carbonate-rich mudstone and sandstone of an extremely unsorted character. The matrix content varies considerably, and certain sets are openwork, i.e. almost completely free from finegrained matrix. In such typical openwork conglomerates carbonate cement fills the grain framework. The composition of the coarse fraction (more than 1 cm) is shown in Fig. 27. The content of carbonate fragments obtained from composition measurements from different conglomerate lobes,

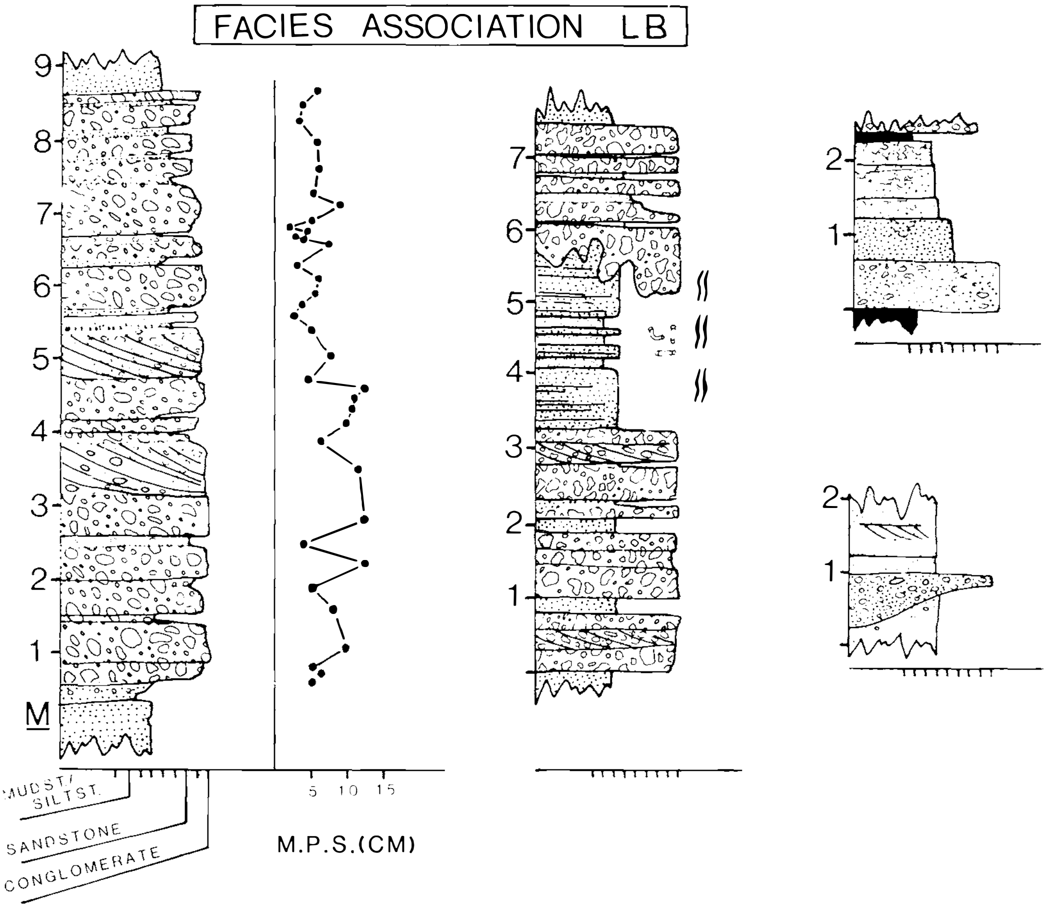

Fig. 26. *Detailed vertical log from some conglomerate lobes of Facies Association LB. The two profiles to the right represent alluvial fan toe deposits.*

shows a slight increase upwards in the formation from 27.5% in the lowermost prominent lobe to 36.3% in the uppermost while the content of chert fragments decreases.

The pebbles/cobbles of the conglomerates are mainly rounded, however, angular fragments also occur. Fig. 27 shows maximum particle size/bed thickness diagrams for the conglomerates of various lobes. They show that there exists a partial positive correlation between the two parameters, (i.e. an increase in set thickness with an increase in maximum particle size).

No sign of plant fossil or fossil fauna occurs within the conglomerates.

The most common deposits associated with the conglomerates are:

Facies association	LA	(flood plain and coastal plain).
,, ,,	LC1 and LC2	(tidal flat and tidal lagoon).
,, ,,	LD	(prograding shoreline).

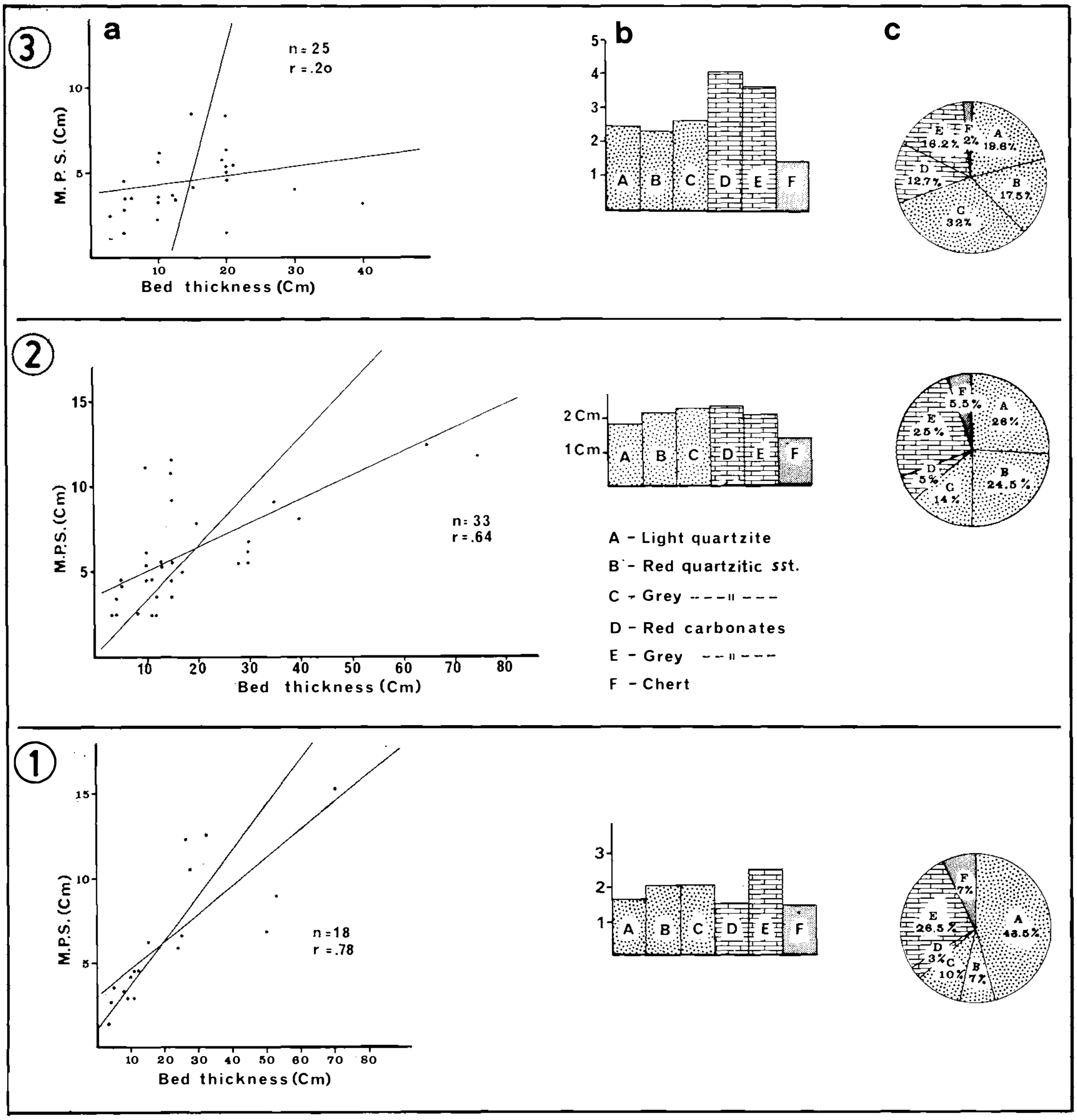

Fig. 27. *Plots of bed thickness against maximum particle size (M.P.S.) from three conglomerate lobes of Facies Association LB; clast composition for the respective conglomerate lobes are also shown, together with average size of different clast types (see Fig. 24 for location of lobe 1, 2, and 3).*

Interpretation and discussion — Many features characteristic of some of these conglomerates suggest that they were deposited from high sediment concentration, mass flows, notably the thick, poorly sorted, internal structureless types. Facts supporting this suggestion are:

a) *The sheetlike geometry of the deposits.* (STEEL and WILSON 1975).
b) *The lack of significant erosion.* (BLUCK 1967). The few erosion surfaces observed are usually flat lying or trough formed, some having almost vertical

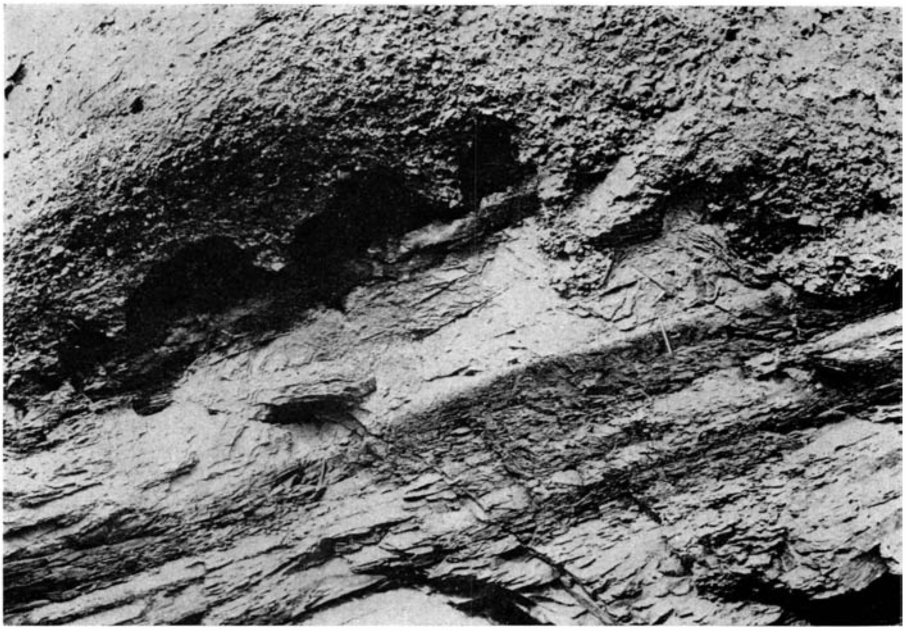

Fig. 28. *Steep erosion surface (almost vertical in places), overlain by debris-flow conglomerates, cutting through stratified silty sandstone. Loading have probably enforced the uneven character of this surface.*

sides (Fig. 28). Those observations are similar to those of BLUCK (1967), with respect to Scottish Devonian sediments interpreted as alluvial fan sheet flood deposits.

C *The unsorted nature of the conglomerates.* (STEEL and WILSON 1975; BULL 1972).

d) *Elongated fragments aligned roughly parallel to flow boundaries* are indicative of laminar flow.

The cross-bedded conglomerates (type c), occurring randomly in most of the conglomerate lobes, also show relatively good sorting in most intervals. The development of cross-stratification presumably resulted from fluviatile processes. This suggestion is consistent with the occurrence here also of "winnowed" intervals (foresets) almost completely free from matrix associated with such structures. The cross-stratified units are, however, not very persistent laterally, and they usually wedge out over relatively short distances. This conglomerate type shows similarities with the stream flood conglomerates of BLUCK (1967).

The sandstone members usually overlying the debris flow conglomerates are interpreted in terms of the high stage of flood-water known to follow debris flows on recent deposits. This flood-water may have winnowed out some sand from the gravel.

It is suggested here that the conglomerates were mainly deposited by debris flows. However, during certain periods there was a sufficiently high water/sediment ratio to create turbulent flows, resulting in reworking of previously deposited debris-flow deposits and the deposition of other water-laid sediments.

This first occurrence of alluvial fan conglomerates in Landnørdingsvika Formation differs from the middle and uppermost conglomerate occurrences in as much as it has a much smaller particle size, much thinner bed thickness and much higher sandstone conglomerate ratio — (usually thicker sandstone sets). Calcareous soil horizons (caliche) were recorded from a few such associated sandstone units. It is likely that this lowest conglomerate occurrence represents the distal part of an alluvial fan (fan toe sediments).

The thick sandstone units associated with these conglomerates were probably deposited by the high stage of flood-water known to follow debris flows. Through time thick units of such sand accumulated in front of the alluvial toe. It should also be noted that some of the sandstone beds interbedded with the red mudstones in the lower part of this formation (see also Facies Association LA) may represent similar deposits.

It is suggested here that each conglomerate sequence in Landnørdingsvika Formation, represents an individual lobe of a larger alluvial fan system. It is also probable that the exposures in Landnørdingsvika represent the most distal parts of the fans. This also explains the high portion of rounded clasts in the conglomerates, as the roundness of coarse grains increases with increasing distance from the apex. This is especially the case in fans where reworking by fluvial processes is common.

Paleocurrent data, such as channel axes, cross-stratification and imbrication indicate a transport direction which varies between north and east. The source areas were therefore located just west or south-west of the present position of Bjørnøya (this will be discussed more thoroughly below).

Facies Association LC1 (Tidal flat)

This facies association is common in the middle and upper parts of the formation. It consists mainly of clastic sediments from coarse sandstone to mudstone, usually arranged in fining-upwards sequences, from 2 to 6 metres thick. A representative selection of such sequences, illustrating their essential organization and character, is shown in Fig. 29.

Description of the basic sequence. Basal sandstone unit. — The basal sandstone unit, which is usually of grey, green or pink colour, varies from coarse to very fine in grain size. The dominating sedimentary structures are trough cross-stratification, planar cross-stratification of different scales and ripple lamination. A notable and distinctive feature is that many of the individual sets are draped by thin clay laminae. Plane horizontal or very low angle cross-lamination also occurs. The unit also contains more or less well-developed reactivation surfaces, and herringbone cross-stratification.

Low-angle, large-scale cross-stratification up to 1 metre thick, probably made by lateral migration of small meandering channels (epsilon cross-stratification) also occurs (Fig. 30). Channels up to one metre deep cut through the sandstone, and are usually filled with medium to very fine sandstone with claystone drapes. The channel bases are marked by erosion surfaces, often

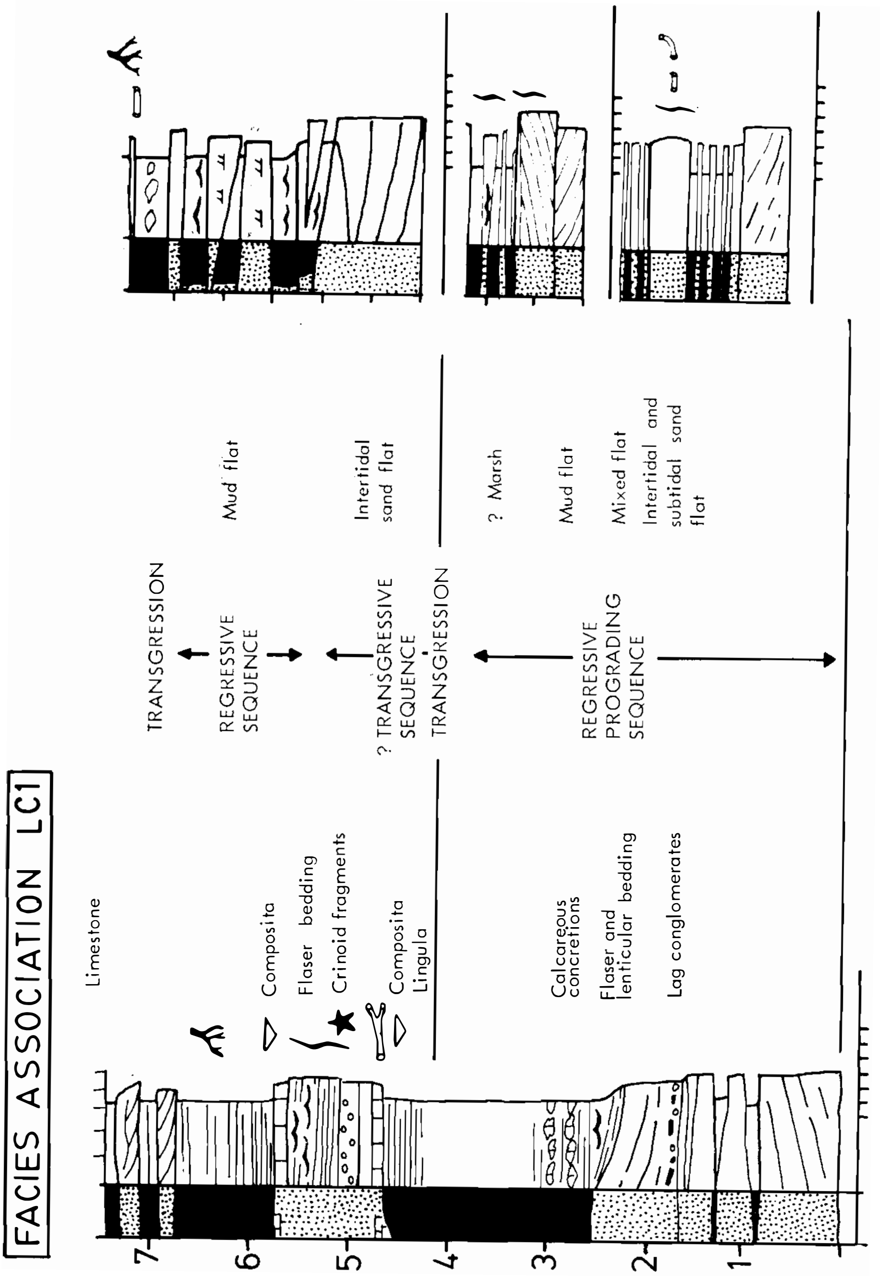

Fig. 29. Detailed vertical logs to illustrate examples of Facies Association LC 1.

overlain by mudclast conglomerates. These are succeded by ripple laminated and cross-stratified sandstones.

Fossil fragments and faceal pellets are common in certain zones.

Middle and upper sandstone/mudstone unit — The upper and middle parts of a typical sequence in this facies association consist mainly of green/grey sandstone and red siltstone/mudstone, often in rapid alternation. Flaser, wavy and lenticular bedding are relatively common in this unit, and dominate certain intervals of it.

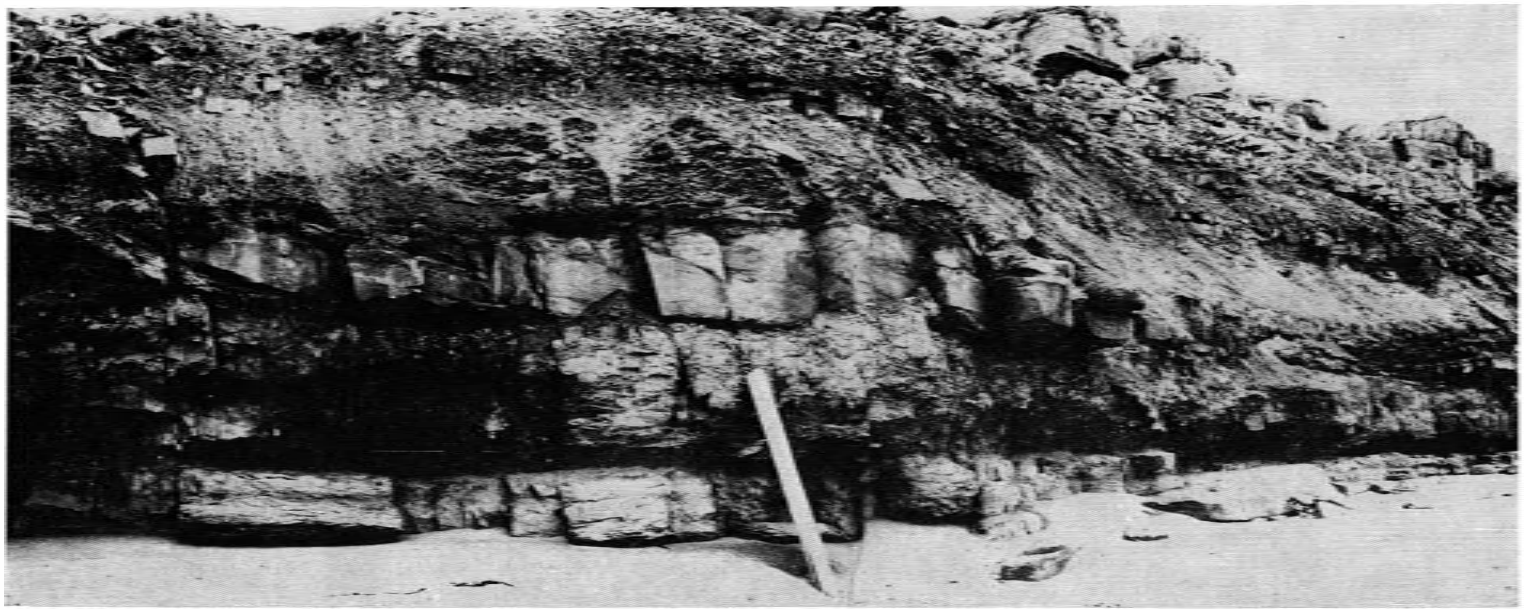

Fig. 30. *Large-scale cross-stratification probably produced by lateral migration of tidal channel (longitudinal cross-stratification). Note how the cross-stratified sandstone terminates into a mud-filled channel (to the right). From Nordhamna. The trunk is about 2 m long.*

Fig. 31. *Sand filled tidal channel, inter-sectioning coarsely interlayered (sand and mudstone) sediments of the intertidal zone.*

Thick sets of massive sandstone, siltstone and mudstone occur frequently. In some cases it is clear that the massive character of the sets is a result of bioturbation. The uppermost part of this unit consists of much more mudstone than the lower and middle parts, and massive mudstone beds more than one metre thick have been recorded. Coarsely interlayered sets of sandstone and mudstone are relatively common in the upper and middle parts of this facies association.

Sandstone- and mudstone-filled channels, up to one metre thick, cut through this upper fine-grained unit of the facies association in a few locations (e.g. Fig. 31). These channels often exhibit a similar range of structures to those from the basal sand unit.

Mudcracks occur in the upper part of the facies association, however, not very frequently. A few examples of plant root fossils in situ (stigmaria), were also recorded from the upper fine-grained part of this facies association. They are located only in massive red mudstone beds, where they occur as distinct, elongate bodies up to 10 centimetres thick. The plant tissues are mineralized mainly by carbonates. No coal horizons were recorded. Horizons of calcareous nodules are present in the upper red mudstone beds, where they probably were developed as soil profiles (caliche).

Many fragments of brachiopods, molluscs and foraminifera occur in various sequences. Crinoid fragments are concentrated in a few zones. Trace fossils are also very common. Simple vertical cylindrical burrows, in the range 0.5—1.5 cm diametres, probably of the skolithos assemblage, were recorded. Large, mainly horizontal trace fossils, occur in the lower sandstone units. These traces are up to 3 cm thick, and somewhat irregularly developed, often branching. They are commonly traceable for 30 centimetres or more (? Thalassinoides). One species, probably of the cruziana assemblage, was also recorded in one of the lower sandstone units.

Sequences of this facies association occur commonly in the profile and are therefore closely associated with most of the other facies associations of Landnørdingsvika Formation.

Interpretation and discussion — This facies association shows some similarities both in grain size and vertical organization with Facies Association LA. The fining-upwards trend, from sandstone to red mudstone, with a sharp, often erosive base, is common for both associations. There are some important contrasts, however, particularly with respect to sedimentary structures and bioactivity.

Most of the sequences assigned to this facies association show many similarities with both modern and ancient silicaclastic prograding tidal flat sequences (see case histories of GINSBURG 1975). Even though individual structures of those mentioned above are not diagnostic for tidal flat environment alone, they may be useful as tidal indicators where they occur together.

The uppermost, massive, red mudstone beds which sometimes show plant roots represent the supratidal portion of the sequence (salt marsh). The middle part of this facies association, usually containing wavy, flaser and lenticular bedding together with coarsely interlayered bedding, probably represent a mud flat and mixed intertidal flat assemblage. The few shallow channels dissecting this flat are probably a result of tidal currents. The large-scale cross-stratification shown in Fig. 30 is a result of lateral migration of such channels (longitudinal cross-stratification). Reworking of tidal flats by lateral, migration of tidal channels or gullies is known to be a common phenomena (REINECK 1958).

The basal sand unit reflects deposition under more turbulent conditions than those of the upper sand/mudstone unit. This is indicated by the frequent occurrence of cross-stratification often with basal scouring. This unit probably represents sediments deposited in a lower sand flat or upper shoreface environment.

The coarsely interlayered bedding common in the middle and upper part of this facies association (consisting of rhythmic alternation between sandstone/siltstone and mudstone) is not yet clearly understood. Nevertheless it is quite likely that the sand layers have been deposited during current and wave activity. Most mud is deposited during periods of slack water. The high energy condition responsible for the deposition of sandstone strata may be a result of storm activity. Such interbedding is not uncommon in storm-generated sequences on tidal flats (REINECK and SINGH 1973, p. 107).

The sediments trapped on tidal flat causes a net addition to the sediment budget of this environmental unit. If the rate of accumulation of sediment of the tidal flat is greater than the rate of relative sea-level rise, the tidal flat will tend to prograde seawards. If the relative sea-level rise is faster than the rate of sedimentation the tidal flat environment will tend to prograde land-

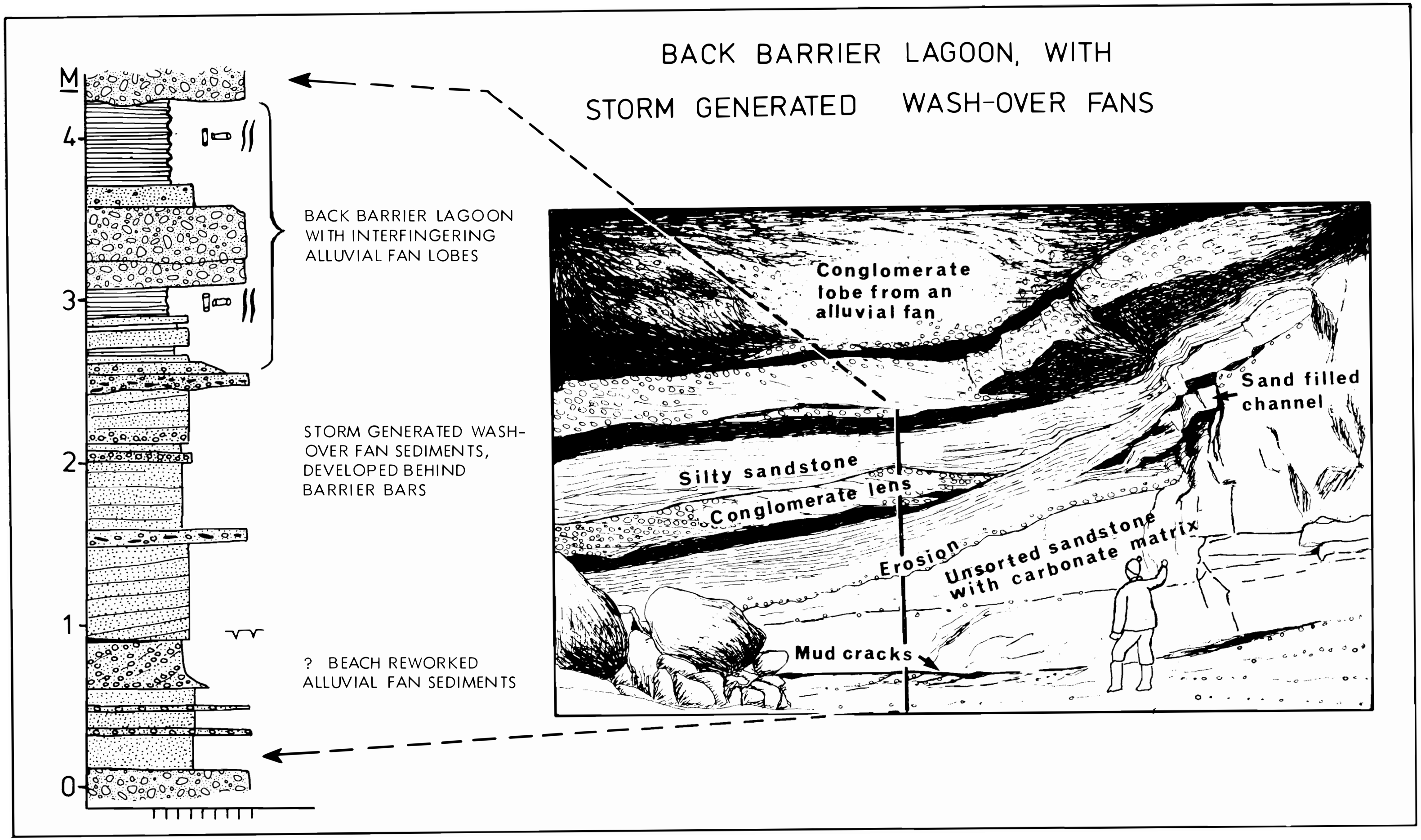

Fig. 32. *Sequence illustrating the occurrence of washover fan sediments in Landnørdingsvika Formation.*

wards, and a crude coarsening upward sequence may result. In this latter case relatively little tidal flat sediment is likely to accumulate (LUCIA 1972). This may explain the few diagnostic transgressive sequences observed in the formation.

Facies Association LC2 — (Back barrier lagoon with washover fans)

Detailed vertical logs from this facies association are shown in Fig. 32. The sequence shows how this facies association occurs together with sediments from associated depositional environments. It overlies a thick conglomerate sequence, interpreted as an alluvial fan lobe. It is suggested that the top of this conglomerate sequence has been strongly reworked, and a unit of interlayered sandstone and conglomerate of much the same type as described in Facies Association LD (interpreted as wave-reworked shoreface conglomerates) has resulted. This reworked, conglomeratic unit is about one metre thick. The occurrence here of extremely well rounded pebbles (often spherical), in contrast to less well rounded clast below, reflects the influence of high physical energy. This unit may well represent the initial stage of a gradual outbuilding of a prograding barrier bar. The succeeding 1.5 metres consists of unsorted sandstone with occasional pebbles. The bedding is slightly inclined towards the west. A few distinct erosion surfaces, overlain by lag deposits of both extraformational and intraformation pebbles, were recorded. Overlying this unsorted sandstone unit occurs a unit of coarsely interlayered grey/green sandstone and red/brown siltstone extensively bioturbated. This unit shows many similarities with the interlayered bedding described in the previous section.

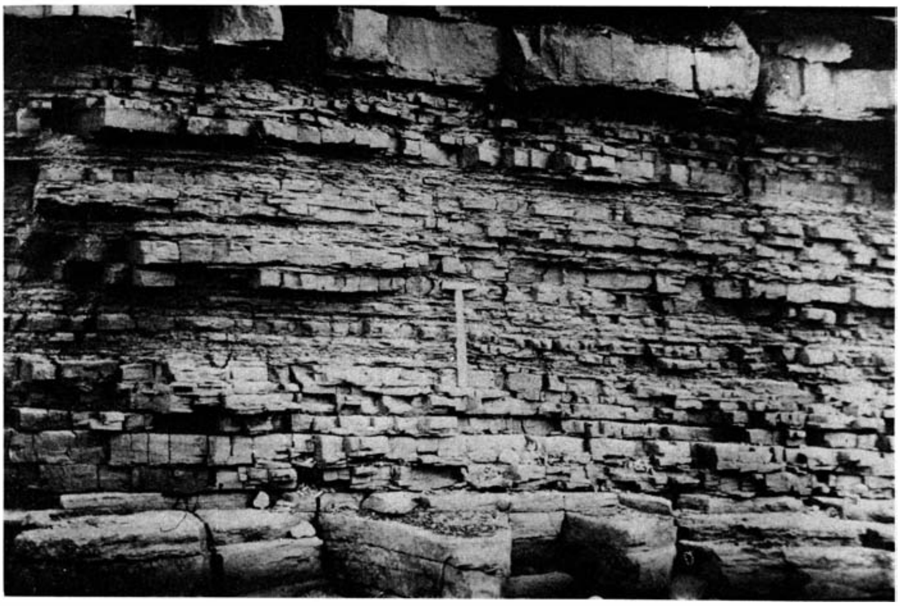

Fig. 33. *Tidal or coastal lagoon deposits. Sand strata may be storm generated. From the exposures in Nordhamna on the north coast of Bjørnøya.*

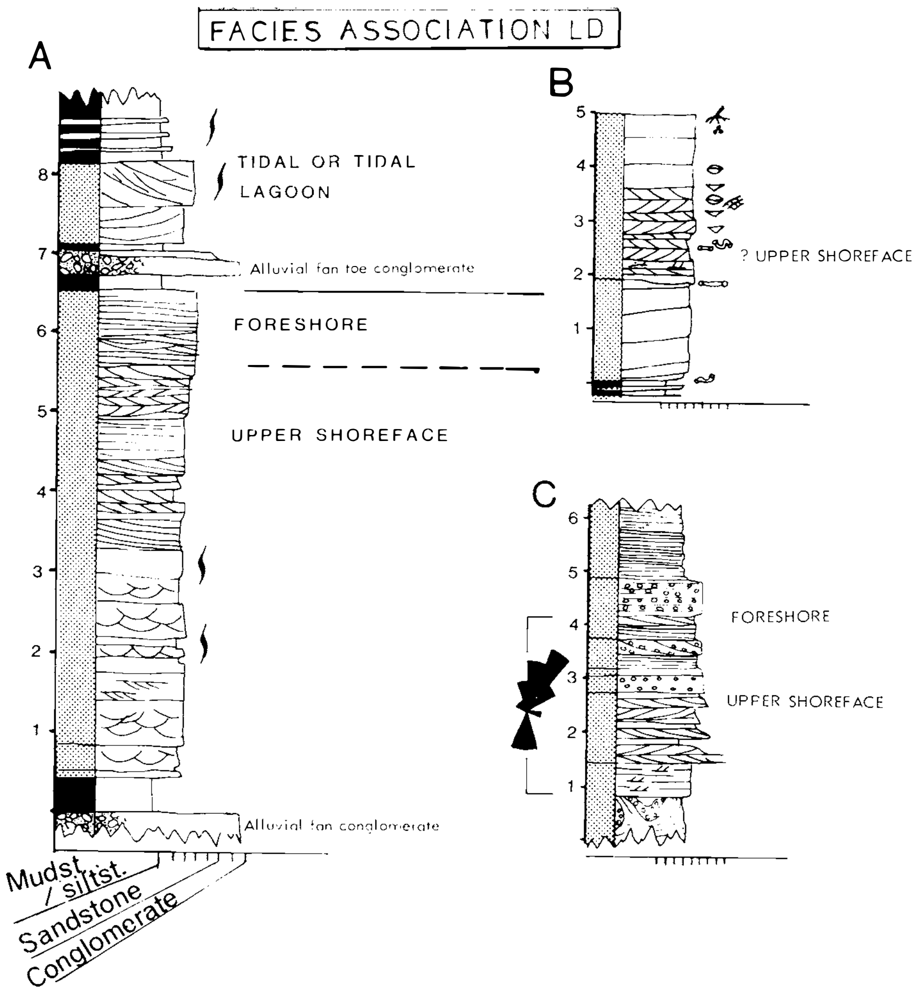

Fig. 34. *Detailed vertical logs from Facies Association LD.*

A conglomerate lobe of the alluvial fan toe type (described in Facies Association LB) is interfingering with this unit.

Further details of this facies association are clear in Fig. 32.

The sequence shown in Fig. 33 shows some of the same properties as the sequence described above, and should be assigned to the same facies association.

Interpretation — A suggested environmental interpretation of this sequence is given in Fig. 32. The facies association has been interpreted in terms of a back bar (? lagoon) situation, with storm derived washover fan sediments. This interpretation is based both upon the nature of the sediments themselves, and (perhaps the most important) the associated sediments. The very clear exposures make it possible to see the lateral evolution of different facies.

The most important washover-fans today are generated by heavy storms and hurricanes (Reineck and Singh 1973, p. 298). During such events much

Fig. 35. *Herringbone cross-stratification in the middle part of Facies Association LD (heavy minerals are concentrated along laminae).*

sediment is eroded from the coastal sand. The occurrence of very distinct erosion surfaces in the Landnørdingsvika proximal washover fan, probably reflects the high physical energy and the erosive power of the storms. During calm periods fine-grained material (mud) was deposited, as seen from the high portion of intraformational "mudflakes" overlying the erosion surfaces. One thin lens of mudstone is preserved in the lower part of the fan. Subaerial exposure is indicated by well developed mudracks.

The same interpretation for the sequence shown in Fig. 33 is proposed (storm derived sediments deposited in a shallow lagoon or pond of tidal flat or coastal plain).

Facies Association LD — (Prograding shoreface)

Figure 34 shows detailed vertical logs from three sequences of this facies association, located in the middle and upper parts of Landnørdingsvika Formation. It consists mainly of grey quartzitic sandstone, pebbly sandstone and conglomerates. The sequences show slight coarsening upward trends (Fig. 34). The lower part of Facies Association LD consists mainly of trough cross-stratified sandstone, with some intervals of planar cross-stratification (an exception here is sequence C (Fig. 34) which is massive in the lower part, with gigantic cross-stratification developed locally). In the middle part, planar cross-stratification of both high and low angle types dominate, together with sets of nearly horizontal lamination which are often wedge shaped and truncated. Some of the high-angle, cross-stratified sets are orientated in approximately opposite direction, and good examples of herringbone cross-stratification have

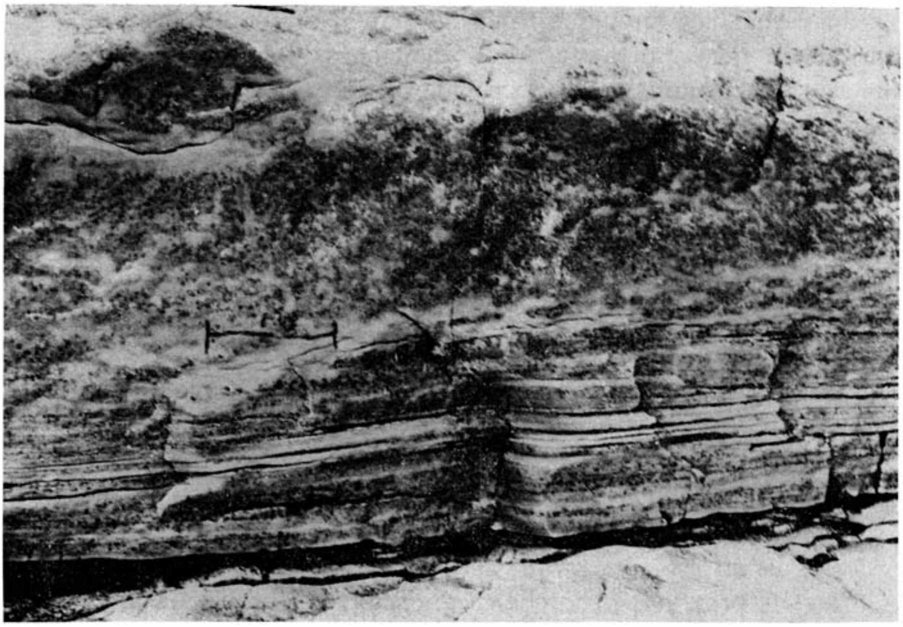

Fig. 36. *Plane parallel, horizontal laminated (or very low angle cross-stratified) sandstone in the upper part of Facies Association LD. Note the massive unit on the top of the laminated unit, and its very diffuse lower boundary.*

been recorded (Figs. 34, 35). The herringbone cross-stratified unit is generally located in the middle part of the sequences (Fig. 34). Bedding at the top is nearly parallel, even laminated well sorted sandstone and conglomerates. The laminae lie mostly parallel to set contacts, and most of the sets have very low-angle dip, which may be nearly horizontal in places. The top of the sequences are locally very massive. The massive part usually grades into the laminated sediments below (see Fig. 36).

Plant fossils and a fossil fauna have been recorded from only one of the sequences (Fig. 34B). Brachiopods occur in the middle part of this sequence, molluscs in the upper part and plant and root fossils at the top of the same sequence. Except for this, only a few impressions which probably originate from brachiopods or bivalves were recorded. Tubes of burrowing organisms occur in a few zones, which tend to be massive, probably a result of bioturbation.

The associated beds overlying sequences of this facies association represent tidal or lagoon environments.

Interpretation and discussion — The sediments of this facies association show many similarities with both ancient and recent prograding shoreline deposits. A common feature for all the sedimentary sequences deposited in such environments today is the coarsening upwards trend from silt and mud at the base to well sorted low dipping parallel to subparallel well laminated sets in the upper (e.g. Davies et al. 1971; Harms et al. 1975). Harms et al. (1975)

showed a vertical log through a sandstone sequence from the Cretaceous Gallup Sandstone in the south-western San Juan basin, interpreted as prograding sandy shoreline deposits. The upper half of this sequence shows almost identical vertical development as some of the Landnørdingsvika examples (e.g. Fig. 34A). However, the lower part of our sequences differs considerably from Gallup Sandstone, as the hummocky cross-stratified sandstone and laminated siltstone and shales are not developed here.

The interpretation of the sequences of this facies association in terms of sub-environments is indicated in Fig. 34. The upper zone of low angle cross-stratified, well laminated sandstone is thought to represent foreshore sediments, where swash processes dominate (Harms et al. 1975). The few shallow troughs observed in this unit, truncating the plane parallel laminae, may represent beach cusps.

The trough and planar cross-stratified sediments (unit 4) in the lower and middle parts of the sequences are thought to have been deposited by migrating, high sinuosity and lunate dunes in an upper shoreface, subenvironment where longshore current, rip current and coastal currents dominate.

A complete prograding shoreline sequence is not present in any of the sequences assigned to this facies association, as the lower shoreface and offshore facies are absent. Most of the sequences of this facies association reflect mainly prograding shorelines, with no obvious sign of thick transgressive sequences. (The lower part of profile B, Fig. 34 may be an exception here.) To get such shoreline profiles directly overlying continental sediments with no obvious sign of transgressive phases, requires sudden changes in sea level and very rapid transgressions. Sudden tectonic movements in the "basement" (downthrow of the depositional area) have most likely been responsible for such sudden changes of sea level. Sediments as a response of tectonic movements will be discussed below.

Facies Associations LE1 and LE2

Only one sequence from each of these two facies associations were recorded from Landnørdingsvika Formation. A common feature for both of them is that limestone is dominating lithology. The sequences differ from each other, however, so much so that they have to be discussed separately.

Facies Association LE1

This sequence (Fig. 37) is located in Nordhamna on the north coast. It overlies a red siltstone/mudstone unit interpreted as intertidal and supratidal sediments (Facies Association LC1).

The basal part of this association consits of grey, mica-rich mudstone/siltstone interbedded with a few, very thin limestone strata. The accompanying sediments consist of a two metres thick, micaceous siltstone and sandstone unit, with tabular beds of nearly horizontal stratification, and hummocky cross-stratification.

Above this hummocky cross-stratified unit follows a 2 metres thick unit of

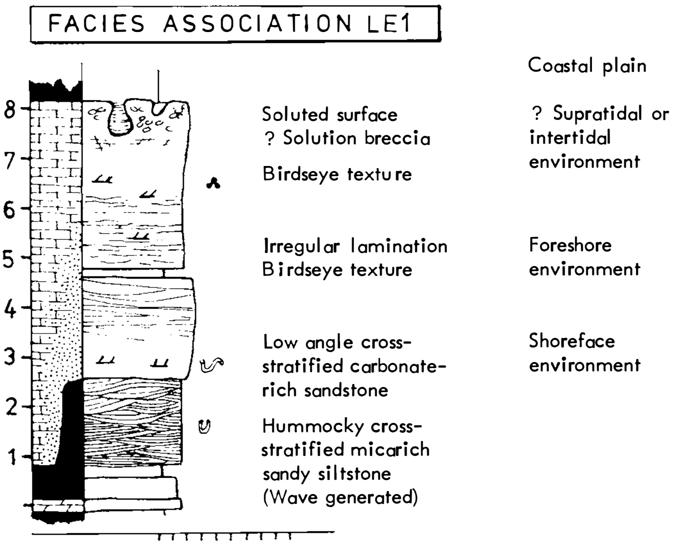

Fig. 37. *Detailed vertical log from Facies Association LE 1 (Nordhamna).*

fine to very fine carbonate-rich sandstone. The lower part of it is mainly ripple laminated while the upper part consists of low angle planar cross-stratified sandstone (Fig. 37). Parting lineation is present on some of the bedding-planes. These sediments show many similarities with the fore-shore facies described from Facies Association LD. The uppermost 2.5 metres of this sequence consist mainly of grey micritic limestone, containing floating quartz grains. The lower part of this unit is more sandy than the upper part. No primary structures were observed except for some zones of very irregular lamination. Pisolithlike structures are present on the upper part. The top of this limestone shows local extensive solution, and collapse breccia. Sparry calcite cement, mixed with small, occasional quartz grains, fills the interstices. Also a few solution channels (filled with laminated siltstone) occur (Fig. 38). Some of the brecciated limestone fragments in the top surface have obviously been transported over a short distance, as fragments of slightly differing lithology are mixed together randomly. Vugs, probably of more or less syndepositional origin, which later have been filled with sparry calcite make birdeye or fenestral structures.

Quartz grains occurring within this limestone have been partly dissolved and silica has been replaced by calcite.

Interpretation — The lower part of this sequence may represent sediments from a prograding shoreline environment, where lower mudstone and the hummocky cross-stratified unit represents shallow offshore or shore-face environment. Such structures may be formed by strong surges of varied direction that are generated by relatively large storm waves in a rough sea (Harms et. al. 1975). The low angle, plane parallel laminated sandstone unit in the middle of the sequence probably represent a foreshore environment, where swash and backwash was the predominant process. The overlying carbonate

Fig. 38. *Solution channel filled with laminated siltstone. From the upper part of Facies Association LE 1 (Nordhamna).*

unit then, represents a shoreline or tidal environment. LUCIA (1972) listed seven criteria which may be used to identify ancient shoreline carbonates. These are, in order of importance:

a) Irregular lamination
b) Scarcity of or lack of fossils
c) Birdeye structures formed by dessication
d) Mud cracks
e) LLH algal stromatolites
f) Lithoclastic conglomerates
g) Associated with shallow marine sediments

Carbonates of this type are located immediately below the supratidal environment.

Since most of the criteria listed above are present in the carbonates of this facies association, such an interpretation seems to be satisfactory, even though LLH algal stromatolites were not recorded.

The solution zone in the top of the sequence, with occurence of intraclastic conglomerates may be indicative of subaerial exposure during a relatively long period of time. The indications of subaerial exposure support a tidal or shoreline depositional environment. However, as it is impossible to estimate how much sediment has been removed by erosion and solution above this surface, there is still no definite evidence of syndepositional or nearly syndepositional subaerial exposure. The limestone has been strongly recrystallized, probably due to early fresh water diagenesis.

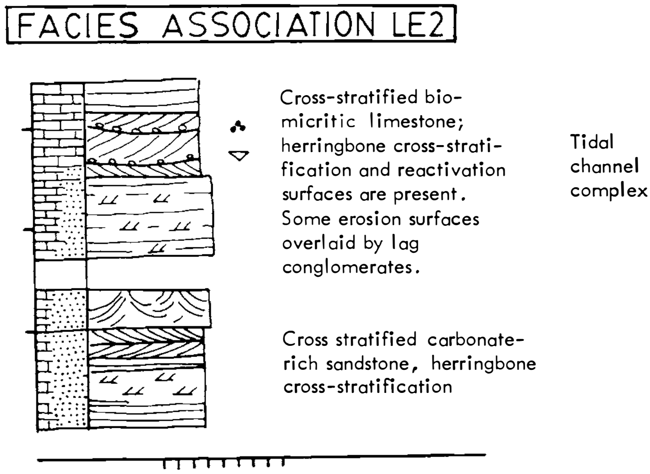

Fig. 39. *Detailed vertical log of Facies Association LE 2. From the exposures at Raudnuten.*

Facies Association LE2

These limestone beds were located on the north side of Raudnuten, where they constitute the uppermost exposure of Landnørdingsvika Formation in this area (Fig. 22). A detailed vertical log of this facies association is shown in Fig. 39.

The sequences consist mainly of micrite, fossil fragments, pellets and floating quartz grains. The concentration of floating quartz grains decreases upwards, and in certain zones the rock is pure limestone (bio-micrite of the packstone type). A few thin sets with concentrated quartz pebbles occur. These pebbly zones occur as lag conglomerates above erosion surfaces, which represent the base of shallow channels.

The sedimentary structures of this facies association are shown in Fig. 39 and it is of interest to note that herringbone cross-stratification and reactivation surfaces are common.

The fossils occurring in the sediments are mainly foraminifera (fusilinids), some of which are well preserved.

Interpretation — Because of the poor exposures and lack of diagnostic data, there is no clear interpretation of this facies association. However, most of the sedimentary structures which do occur suggest that it represents a near-shore sedimentary environment, where there was bedload transport in which bipolar reversals of flow directions dominated (as seen by the development of herringbone cross-stratification). Time-velocity asymmetry of current transport is indicated by the reactivation surfaces. Such structures, together with shallow channel scours may suggest that these sediments represent some kind of tidal channel complex, probably from a subtidal or shoreface environment.

Paleocurrent measurements indicate that the dominating migration directions were towards north, which (for associated facies) probably represents the seaward direction.

A common feature for all the limestones occurring in Landnørdingsvika

Formation is that they contain floating quartz grains. This indicates that the limestones were deposited adjacent to an area where quartz grains were available, and where faunal activity was high enough to produce sufficient amounts of carbonate material. The source of the quartz grains may have been the suggested, nearby elevated area in the west, responsible for the outbuilding of alluvial fans. The clastic materials were probably brought into the area of carbonate deposition by tidal currents and wave generated current or they may be of eolian origin. This nearby elevated area was probably the source for most of the clastic material of Landnørdingsvika Formation. In fact, some of the carbonate material itself was probably derived from this same area and deposited as detrital grains, as it is known from composition measurements of the alluvial fan conglomerates that carbonate pebbles account for about 30% of the clast population.

3. PALEOGEOGRAPHY AND PALEOENVIRONMENT

Figure 21 gives a generalized interpretation of the type profile according to depositional environment and paleogeography. Fig. 22 shows a correlation between the different profiles.

Type profile

The following summarizes the vertical evolution of depositional environments within the type profile of Landnørdingsvika Formation:

The lower 95 metres consist mainly of flood plain and coastal sediments deposited by high sinuosity streams (Figs. 21, 26), flowing towards north and east. At a level of about 60 metres above base, the first conglomerates of the distal alluvial fans (fan toes) appear (Facies Association B, Figs. 21, 26), interbedded with the flood plain or coastal plain sediments. The frequency of this interbedding shows a tendency to increase upwards, as does the thickness of the intruding distal alluvial fan units. The first appearance of distinct tidal flat sediments (Facies Association LC1, Figs. 21, 29) occurs at a level of about 97 metres above base. Just above this tidal sequence the first thick and prominent red conglomerate bed (Facies Association LB, Fig. 21) occurs. At a level of 107 metres above the base, the first north and eastward prograding shoreline sequence appears. The succeeding 40 metres of the formation consist of prominent, alluvial fan conglomerates in alternation with tidal flat, tidal lagoon and prograding shoreline sediments. This is followed by 10 metres of mainly alluvial fan deposits and interfingering red, coastal plain mudstone, and a further 33 metres of fining upwards tidal flat sequences with one of prograding shoreline sediments in the upper part. The uppermost 10 metres of the profile represent an outstanding, fossil bearing, marine sandstone bed, rich in carbonate matrix.

Most of the paleocurrent data obtained, indicate that the alluvial fan lobes were derived from an "elevated" area, located just west or south-west of the depositional area of the type profile, while most of the tidal and shallow marine (shoreline) sediments reflect a marine transgression from between north and east.

4. SEDIMENTATION AND TECTONISM

The general trend through the Landnørdingsvika Formation is a gradual transition from continental environments in the lower part to typical marginal marine environments at the top of the formation, where the tidal flat sediments represent a transitional environment. The formation in its entirety reflects an overall transgression where influx of sediment into the basin has not been able to keep pace with a relative rise in sea level. A relative rise in sea level may be accounted for in the following ways:

a) Eustatic sea level rise.

b) Depression of the basin floor due to tectonic movements along basin margin faults.

c) Depression of the basin floor due to isostacy (also taken up along basin margin faults).

d) Depression due to compaction of unconsolidated sediments in the basin (clay and mud).

As indicated by modern global super cycle charts (VAIL et al. 1977), showing relative sea level fluctuation, eustatic sea level rise probably occurred during the whole depositional period of Landnørdingsvika Formation. It is also obvious that the basin has been subject to tectonic movements, as a consequence of which very sudden changes in relative sea level could be expected. This tectonic activity probably originated from a fault-line (lying somewhat west of Bjørnøya's present west coast) which was persistently active through much of the deposition of Landnørdingsvika Formation. This is supported by the following facts:

a) Very coarse grained alluvial fan lobes migrated into the basin towards east and north-east. This suggests that an "elevated" source area, was located just west or south-west of the deposition area. In as much as this relief appears to have been periodically generated it may have been caused by faulting.

b) Many of the sedimentary sequences of Landnørdingsvika Formation reflect a sudden marine transgression over coastal plain and tidal flat areas, accompanied by the development of prograding shoreline and fining-upwards tidal flat sequences, apparently without the presence of any obviously transgressive sequences below. These sudden transgressions may well reflect sudden, periodic tectonic downthrow of the basin area, resulting in a relative rise of sea level. Immediately overlying such sequences, resultant from sudden transgression, there often occurs continuing evidence for regression in the form of extensive outbuilding of alluvial fan lobes. These, an immediate result of increased topography and the flushing out of accumulated weathered debris, were also caused by the faulting. It is hence probable that both the sudden transgressions and the accompanying outbuilding of alluvial fan lobes are a direct response to tectonic events.

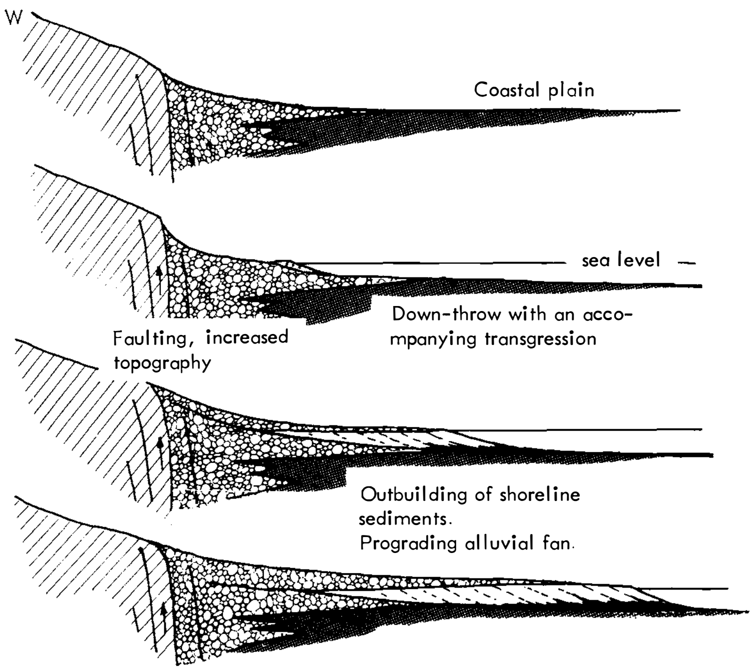

Fig. 40. *Model for the tectonic events and their sedimentological response. Landnørdingsvika Formation.*

c) Extensive liquefaction of unconsolidated sandstone beds may have been triggered by earthquake shocks associated with the faulting. (This possibility has been discussed above.)

A model for the tectonic events and their sedimentological response is illustrated in Fig. 40. It is suggested that the area to west has undergone a more intense uplift than the basinal area. The gradually accumulating shear stress has, through time, been released by faulting resulting in a relative downward movement of the basin (Fig. 40). A general conclusion must be that the development of the various facies patterns up through Landnørdingsvika Formation was controlled by a complex interplay of eustatic sea level rise and tectonic movements along a nearby fault line.

The suggested fault line in the west may be a part of the complex of major north-south structural lineaments observed on western Spitsbergen, where block faulting first occurred in late Devonian, with rejuvenation during the Mesozoic and Tertiary (ORVIN 1940). Such structural north-south trends have been recorded from recent seismograms from the area just north of Bjørnøya (SUNDVOR and ELDHOLM 1976). One of the most distinct of these structures (Hornsund fault) probably extended to the area west of Bjørnøya (unfortunately seismic data from the actual area is lacking). This line may represent a zone of crustal weakness, along which tectonic activity occurred in Lower-Middle Carboniferous, with a downthrow of the basin floor on its east side. Later rejuvenations, with reversed movements, have resulted in a vertical downthrow of the block on the west side of the fault.

In the upper part of the formation, the thick conglomerate sequences completely disappear; this may reflect a reduction of tectonic activity with the approach of Moscovian, with an accompanying reduction of topography in west. On the other hand, a change in climatic conditions may have altered the tendency for alluvial fan development, or the locus of fault activity may have shifted farther west so that the Landnørdingsvika area no longer received the obvious immediate effects of the faulting. It should be noted, however, that there are further repeated signs of similar fault movements higher in the Palaeozoic succession, with repeated influx of coarse conglomeratic sediments (Worsley pers. comm. 1976).

5. RED BEDS

The red beds of this formation are mainly distributed in non-marine sediments which contain a sufficient amount of fine-grained material. The occurrence of red beds with respect to depositional environments are as follows:

a) Overbank, fine-grained sediments of the flood plain and coastal plain assemblage.

b) The most landward parts of tidal flat sequences, for example supratidal mudstones and, to some extent, intertidal mud- and siltstones. In a few sandy mudstone units associated with tidal lagoons, red and green sediments are regularly interstratified at intervals of tens of centimetres with fairly sharp boundaries between adjacent rock layers.

c) Fanglomerates (Facies Association B). Those are almost entirely red.

In addition, a few greyish-red sandstone beds of subtidal- intertidal- and fluvial origin were recorded, but generally the sandstone beds are grey.

A detailed interpretation of the formation of red beds in Landnørdingsvika Formation is not attempted here. It is, however, likely that the same main sedimentary processes were responsible for the formation both in fluvial and tidal environments, as sediments of such environments are closely associated. It is also likely that the formation was closely associated with primary sedimentary features, and hence of syndepositional character, reflecting a good ground-water drainage with low flood-plain water table. This is also indicated by associated caliche beds (even though most of those are rather immature).

The suggestion that some of the red pigments were derived by hydration of soil-derived ferric-oxide, implies an upland area where climatic conditions were hot and moist enough to form red-brown soil (laterite) by weathering processes. Even though red beds are unreliable as a palaeoclimatic indicator alone, it may be a useful guide supported with other implications (e.g. caliche). Information given above combined with general information about paleoclimatic indicators suggest that Landnørdingsvika Formation accumulated in a savanna type of climate.

Mature calcareous soil profiles indicate an arid to semi-arid climate (STEEL 1974a). The cornstone profiles of Landnørdingsvika Formation are, however, mainly immature, this may reflect a more moist climate. STEEL (1974a) also found that a gradual disappearance of mature cornstone profiles towards the top of the New Red Sandstone succession (Western Scotland) reflected a progressively wetter climate with onset of Jurassic environments.

V. Paleoclimate

It is suggested here that the climate during deposition of Røedvika Formation and Nordkapp Formation was generally moist, with the development of poorly drained highly vegetated flood plain areas (Fig. 41). This was changed rather dramatically during deposition of Landnørdingsvika Formation, where a much drier climate dominated with well drained flood plain and coastal plain areas. Red beds and caliche were developed. From the proposed reconstruction of the continents, presented paleolatitude for "Bjørnøya" was located just below 30° N during Devonian and at about 30° N during Carboniferous (IRVING 1977).

VI. Petrography

The most obvious change in composition of the sandstones and conglomerates of the sedimentary succession examined is that chert becomes an important constitute of the conglomerates in Nordkapp Formation and that carbonate fragments become gradually more important in Landnørdingsvika Formation (Fig. 27). Carbonate clasts were not recorded below Landnørdingsvika Formation. Fragments of quartzite seem to be more important in Røedvika Formation than in the overlying Nordkapp and Landnørdingsvika Formation. Feldspar is very rare, and it was recorded here only in small amount (in Landnørdingsvika Formation). However, small concentrations of illite and kaolinite occur and this may be an alternation product of primary deposited feldspar (or other minerals) which have become instable after burial. Such concentrations of clay minerals were most frequently recorded from Nordkapp Formation. The change in composition of the conglomerates may reflect a changing drainage area (and its geology), or it may be a result of sedimentary maturity (e.g. carbonate clasts may have been broken down or "winnowed" out from the sediments of Nordkapp and Røedvika Formation, while the much dryer climate during deposition of Landnørdingsvika Formation increased the preservation potential for carbonate material).

Most of the sandstones contain very little matrix, and may generally be classified as quartz arenites and sublith-arenites according to FOLKS classification system (1968).

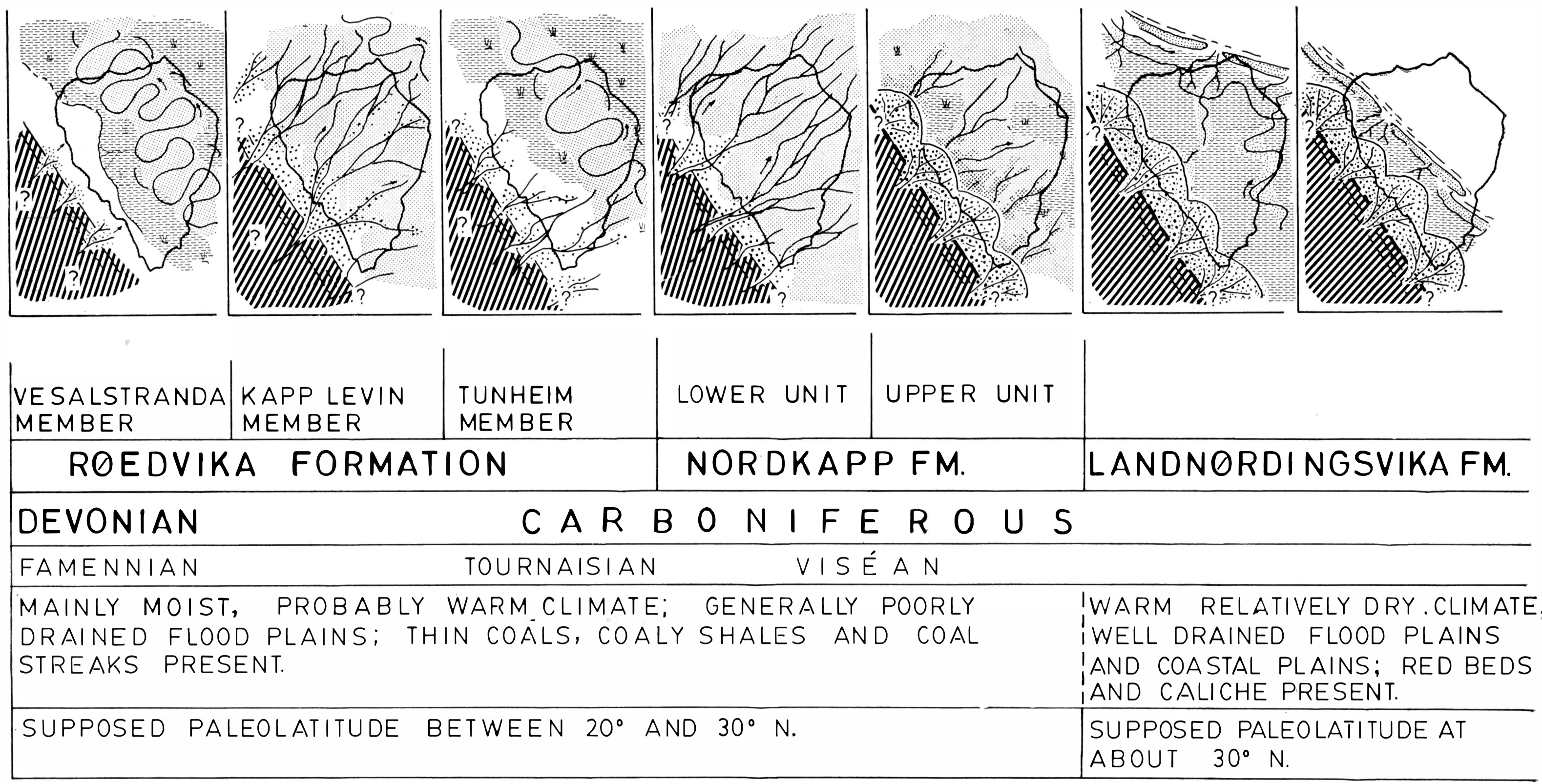

Fig. 41. *Generalized illustration of paleoenvironment, paleogeography and paleoclimate of the Upper Devonian — Middle Carboniferous succession of Bjørnøya. The figure also shows suggested paleolatitude for the basin during deposition.*

VII. Regional trends

The assumed fault zone in the west or south-west which was active during long periods of Lower-Middle Carboniferous, may reflect major north-south trending block faulting similar to that which occurred on Spitsbergen, in Late Devonian and along which rejuvenation took place when passing from Middle to upper Carboniferous. (Rejuvenation also occurred in the Mesozoic and Tertiary, ORVIN 1940.) From recent seismograms (SUNDVOR and ELDHOLM 1976) a relatively distinct fault zone has been recorded just north of Bjørnøya. Unfortunately seismic data are lacking in the area around Bjørnøya, but it is likely that this fault (or fault system) extended to the area just west of Bjørnøya. This fault may reflect a zone of crustal weakness, along which tectonic movements occurred during deposition of the Upper Devonian — Middle Carboniferous succession of Bjørnøya, with highest activity during deposition of the middle part of Landnørdingsvika Formation (? Lower — Middle Carboniferous). This is consistent with the Carboniferous block faulting activity on Spitsbergen, where rejuvenation of the older (Upper Devonian) fault system took place when passing from Lower to Middle Carboniferous (ORVIN 1940).

Other points of resemblance exist between the Lower Carboniferous succession of Bjørnøya and Spitsbergen: the "Culm" sandstone, exposed on the west coast of Spitsbergen, Orustdalen Formation and Hornsundneset Formation, are similar in facies and transport direction to Nordkapp Formation. The transition from grey sandstone to red debris-flow conglomerates and mudstones in Middle Carboniferous has also been recorded on Spitsbergen from the inner Hornsund area (BIRKENMAJER 1964; GJELBERG and STEEL 1979), from the south side of Bellsund from the Kongsfjorden area (ORVIN 1934; CUTBILL and CHALLINOR 1965) and from the Billefjorden area. A similar transition from grey to red sediments have also been recorded from other parts of the Arctic region (e.g. North Greenland and Arctic Canada). It is suggested that this is a result of a change in climate of large regional significance (GJELBERG and STEEL 1979). The tectonic movements reflected in the Middle-Upper Devonian on Spitsbergen, as seen by the extensive block faulting occurring in this area (ORVIN 1940) were a part of the late Caledonian movements of the "Svalbardian" phase (VOGT 1936). The most active movements of the "Svalbardian" phase are probably also represented on Bjørnøya, reflected by the extensive uplift and erosion of the Hecla Hoek basement prior to the deposition of the Røedvika Formation.

From available evidence outside Spitsbergen, HARLAND (1969) suggested that the main tectonic movements in the Arctic region in Late Devonian time caused Europe to be moved several hundred kilometres north with respect to North America and Greenland, placing Spitsbergen near Ellesmere Island. He also suggested that such movements took place by a set of transcurrent faults which formed along the zone of later North Atlantic Ocean opening.

In view of the evidence provided directly and indirectly by Spitsbergen, HARLAND (1969) also concluded that it was appropriate to apply VOGT's

(1936) term "Svalbardian" and to refer to this whole phase of (Late Devonian) sinistral strike-slip movement (transcurrent fault) as the "Svalbardian" movements. Similarly HARLAND (1969) also concluded that the Carboniferous movements can be regarded as adjustments at the conclusion of the Svalbardian movements, and thus essentially as resurgent Caledonian activity.

It is suggested here that the tectonic movements reflected in the Early – Middle Carboniferous succession of Bjørnøya were caused by rejuvenation along the older structural lines. It is also probable that some of these movements were related to the Variscan diastrophism. (? beginning in Late Devonian and continuing to the end of Permian).

VIII. Conclusion

Fig. 41 illustrates, in outline, the suggested evolution of paleogeography and depositional environment from Upper Devonian (Vesalstranda Member) to Middle Carboniferous (Landnørdingsvika Formation). A north or northwestward orientated meandering belt with highly vegetated flood basin areas and lakes, dominated the deposition of Vesalstranda Member. During the deposition of the overlying Kapp Levin Member, east or northeastward flowing braided rivers dominated the depositional environment (Fig. 41). Tunheim Member was probably dominated by north or northwestward orientated meander belts, while Nordkapp Formation originated mainly from east or northeastward flowing braided streams. Landnørdingsvika Formation is much more complex. The lower part is dominated by sediments deposited by probably northward flowing meandering streams. A complex interfingering of alluvial fan conglomerates with flood plain, coastal plain, tidal flat and shoreface sediments, dominates in the middle and upper part. Marginal marine and marine sediments become more important upwards, at the same time as the prominent alluvial fan conglomerates disappear. The alluvial fan conglomerates have migrated into the basin from west or southwest, while the sea probably transgressed from north or northeast.

On the basis of the data presented above, two main drainage systems generally dominated the investigated succession:

1) A north or northwestward orientated floodplain belt, mainly dominated by streams with a meandering channel pattern (Fig. 41).
2) An elevated area in the west or south-west was responsible for the repeated influx of coarse-grained sediments, deposited from braided streams and debris flows. Much of these sediments probably originated from adjacent alluvial fan complexes (Fig. 41).

As suggested above the elevated area in the west was probably controlled by tectonic movements along a suggested north-south orientated fracture zone. In fact, tectonic movements along this suggested structural trend seem to have controlled much of the sediments of the investigated part of the Upper Palaeozoic succession of Bjørnøya. This is especially the case for Landnørdingsvika

Formation where it is suggested that much of the complex building was directly related to tectonic movements of basin floor, with an accompanying change of base level.

Tectonic activity and climate probably determined which of the two main drainage systems dominated the now exposed part of the basin during any period of time.

Acknowledgements

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