EARLY – MIDDLE CARBONIFEROUS SEDIMENTATION ON SVALBARD

A study of ancient alluvial and coastal marine sedimentation in rift and strike-slip basins

by

John Gjelberg

Dr. scient thesis, 1984
Geological Institute
University of Bergen
Norway

Til Erik
Takk for hjelpen
Hilsen John

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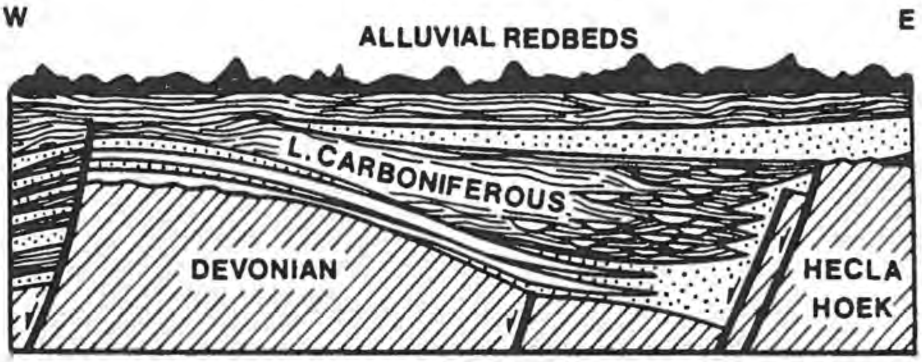

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III 3 LOWER-MIDDLE CARBONIFEROUS (NAMURIAN-BASHKIRIAN) SUCCESSION ON WESTERN SPITSBERGEN (ST.JONSFJORDEN TROUGH)

P A R T I V, S U M M A R Y

PART I

INTRODUCTION

TO THE STUDY

LIST OF WORK

This Dr. Scient thesis is subdivided into four parts:

Part I - This part represents an introduction to the study.

Part II - This part presents the Lower-Middle Carboniferous succession on Bjørnøya. It is the published and condensed version of my Cand. Real Thesis. The data collection and reworking of data for this work was made during the years 1975 til 1978. The interpretations made here are still thought to be valid, though a lot of relevant works about similar depositional environments have become available since this paper was published in 1981. A few minor changes, or extensions of some of the aspects have been made later. These are discussed in published and unpublished papers which are included in the appendix of this thesis. Because of strictly limited field seasons on Bjørnøya I later felt that my first field investigations of the Tunheim Member were not sufficient. I therefore visited the island in 1980, in connection with a Statoil expedition, and continued the investigations of the member.

These studies revealed that the traditional correlation of coal seams from Kohlbukta and southwards, which was made by Horn and Orvin (1928) and adopted by Gjelberg (1981), is wrong. This is corrected now in the field guide prepared by Gjelberg (1982), and which is included in the appendix.

The interpretation of the Landnørdingsvika Fm made by Gjelberg (1981) is believed to be still basically correct though the following two reconsiderations have been made (see Gjelberg and Steel, 1983): 1) some of the sheetlike sand bodies (<2m thick) in the lower part of the formation, previously interpreted as fluvial channe sand, have been reconsidered as possible sheet sandflow or splays, at the foot of alluvial fans. 2) The prominent limestone bed in Nordhavna on the north coast was first tentatively interpreted as recrystallized marine limestone. However, further studies (based on 2 thin sections) suggest that this rock is a diagenetic limestone (calcrete) and that it is difficult to say anything about the rock it replaced, except that it probably contained fossils, which now can be seen as "ghost structures".

Part III - This part presents the Lower-Middle Carboniferous succession on Spitsbergen. It is subdivided into four chapters with a general introducti (Chapter I). The three other chapters present investigations from; the Southern Spitsbergen (Sørkapp Land) area, Western Spitsbergen and Central Spitsbergen respectively. The field-work for these investigations was carried out during the summers of 1977, 1978, 1979 and 1981.

Part IV - This represents a short summary, conclusion a discussion of regional trends.

PROBLEMS AND METHODS

The Lower-Middle Carboniferous succession on Spitsberge and Bjørnøya has been the subject of geological investigations since the beginning of this century (eg. Nathorst 1900, 1910, Anderson 1900, Antevs and Nathorst 1917, Holtedahl 1911, 1913). However, very little information has been published about sedimentary processes and basin style and extension. The study was therefore initiated in order to investigate these aspe of Svalbard's geology. In order to do so several thousand metres of rock sections have been logged, and palaeocurrent directions recorded. Primary sedimentary structures have been carefully studied in order to gain information about hydrodynamic conditions and processes during deposition. This is done by comparison with published information from recent and ancient deposits. An important tool in the interpretation of depositional environment is the definition of facies sequences, the basic consept of which was defined by Walther (1894) and which states that those environments and subenvironments which are laterally associated with each other geographically are likely to become associated in vertical sequences.

This work is mainly based on field-study with systematic logging of vertical profiles, followed by identification, definition and interpretation of facies sequences and preparation of palaeocurrent data for statistical use. Thin sections have been studied briefly in order to decide composition and to some extent textural and mineralogical maturity of the sediments. Diagenetic studies have not been done.

The identification of facies sequences with interpretation of depositional environments, together with extensive palaeocurrent data, have been the most important tool in order to obtain knowledge about palaeogeography and basinal evolution pattern.

OUTLINE OF STUDY

As already mentioned above, the main aim of this study was to evaluate the palaeoenvironmental, palaeogeographical, palaeotectonic and palaeoclimatic conditions during deposition of the Lower-Middle Carboniferous succession of Svalbard. The results of this study are summarized in Part IV, and will not be repeated here, except for the abstracts from the two mai parts of the thesis which are included below.

ABSTRACT, BJØRNØYA

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.

ABSTRACT, SPITSBERGEN

This paper presents a study of the Lower-Middle Carboniferous succession of Spitsbergen. Facies analysis have been carried out for all of the Lower-Middle Carboniferous formations exposed in the Sørkapp Land area, along the western part of Spitsbergen, and from the Central Spitsbergen area. Facies analysis combined with palaeocurrent data have been used as an important tool to establish the palaeogeography, and to analyse the sedimentary basins and their evolution.

Early Carboniferous (Tournaisian - Visean) time was characterized by relatively broad N-S or NW-SE trending basins. In the Hornsund area there developed deposited a relatively deep basin dominated by shale and siltstone, with some interfingering subaqueous debris flow conglomerates and sandstones in the lower part. The conglomerates were derived from the tectonically active eastern (and northern) margin of the basin. In the central area of Spitsbergen the basins were broad and shallow and were dominated by flood plain and occasional lakes in the axial parts, with alluvial fans along the margins. Namurian time across the whole of Spitsbergen was dominated by large humid alluvial fans which entered broad basins from the west. These fans developed laterally into flood-plains, whose deposits usually dominate the upper parts of the Namurian succession. In early Carboniferous times the basins on Spitsbergen were usually broad and shallow and most likely developed in tensional tectonic regimes. The Bashkirian (Mid Carboniferous) development was completely different, as narrow grabens in which there was relatively rapid sedimentation developed in southern, western and central parts of Spitsbergen, with coarse conglomerates along fault margins. The sedimentation took place mainly on alluvial fans coastal plains, tidal flats, coastal sabhka,, barrier bars and spit bars, and the resultant deposits accumulated in a cyclic, interfingering manner. The Middle Carboniferous successions probably developed in strike-slip related basins, and movements along important NNW-SSE fault lines are generally reflected by thick, very coarse clastic successions and more precisely by repeated (often cyclic) facies changes (each facies sequence 5 to 40m thick): for example, a sudden influx of marginal marine sandstones and carbonates followed by coarsening-upward coastal plain/alluvial fan sequences.

A large-scale change in sediment type from fluvial, grey sandstones, coal bearing shales and monomict conglomerates to red, ephemerial fluvial and polymict alluvial fan deposits, reflects a change from humid to a more arid climate near the Namurian/Bashkirian boundary. It is suggested that this dramatic climatic change may have resulted from sinistral megashear which was regionally important in Bashkirian times and which moved the present day Spitsbergen area 1000-2000km northward to its middle Carboniferous palaeoposition north of Greenland.

GENERAL SIGNIFICANCE OF STUDY

It is hoped that the information present within this study is a contribution to the understanding of the regional development and setting of the Carboniferous the northwestern Barents Sea area. In addition to thi information the study also exemplifies sedimentation i grabens of simple tensional, and transtensional settin Cyclic sedimentation with a complex interfingering of marine and marine deposits, probable as a result of tectonic and consequent sea level movements have been discribed, and may contribute to our understanding of relative roles played by eustatic tectonic and other factors in basin development

Because of the increasing oil exploration activity in t Barents Sea, all geological information gained from the surrounding land areas have become increasingly importa (also included the Upper Palaeozoic succession). From this point of view the study may be economically justified.

References for this part of the study are found at the end of Part II and at the end oft he thesis.

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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Printed February 1981
ISBN 82-90307-15-2

Contents

Abstract

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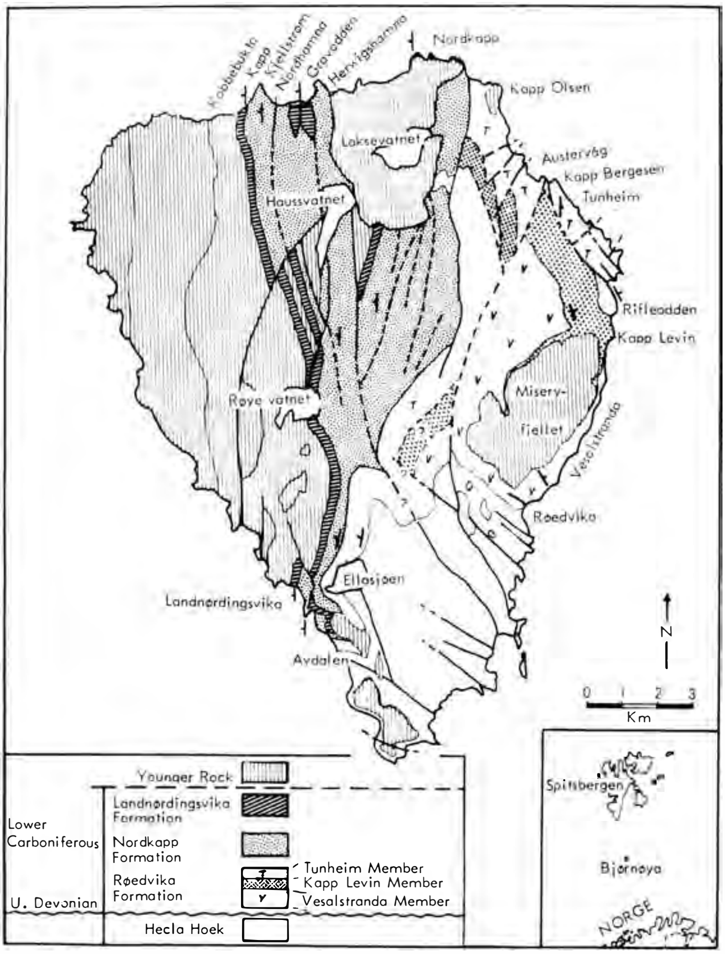


Fig. 1. *Geological map showing the distribution of the studied Formations (based on* HORN *and* ORVIN *1928).*

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).

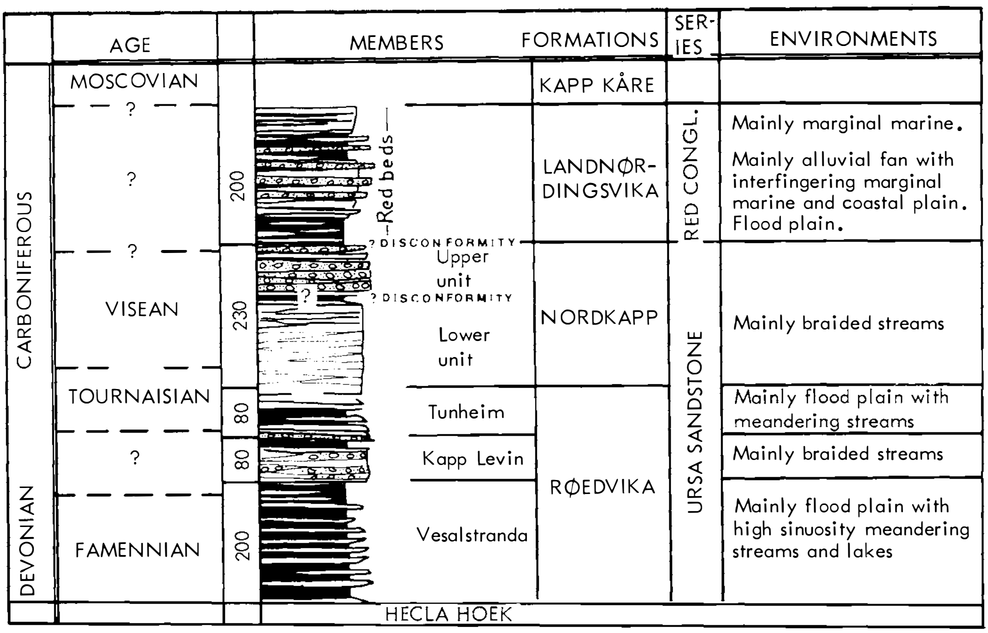


Fig. 2. *Generalized profile of the Upper Devonian-Middle Carboniferous succession of Bjørnøya (based on* WORSLEY *and* EDWARDS *1976).*

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.

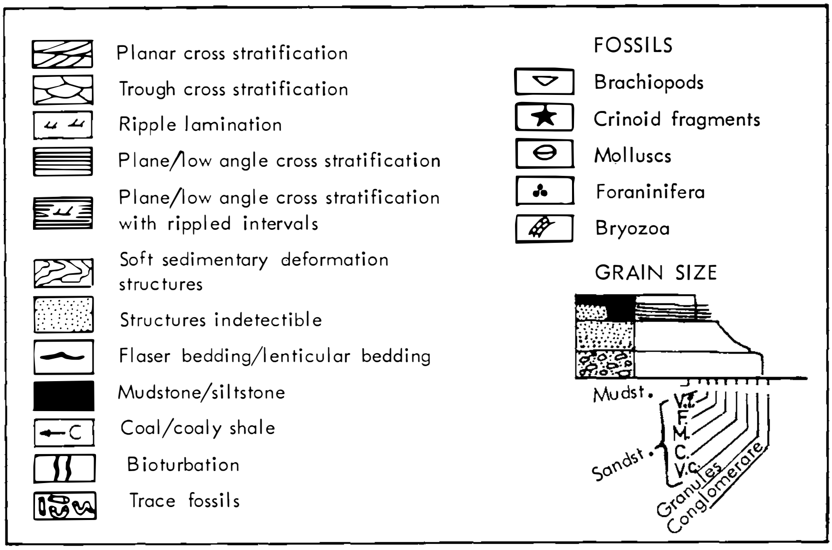


Fig. 3. *Legend for both structures and grain size as used in subsequent figures.*

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).

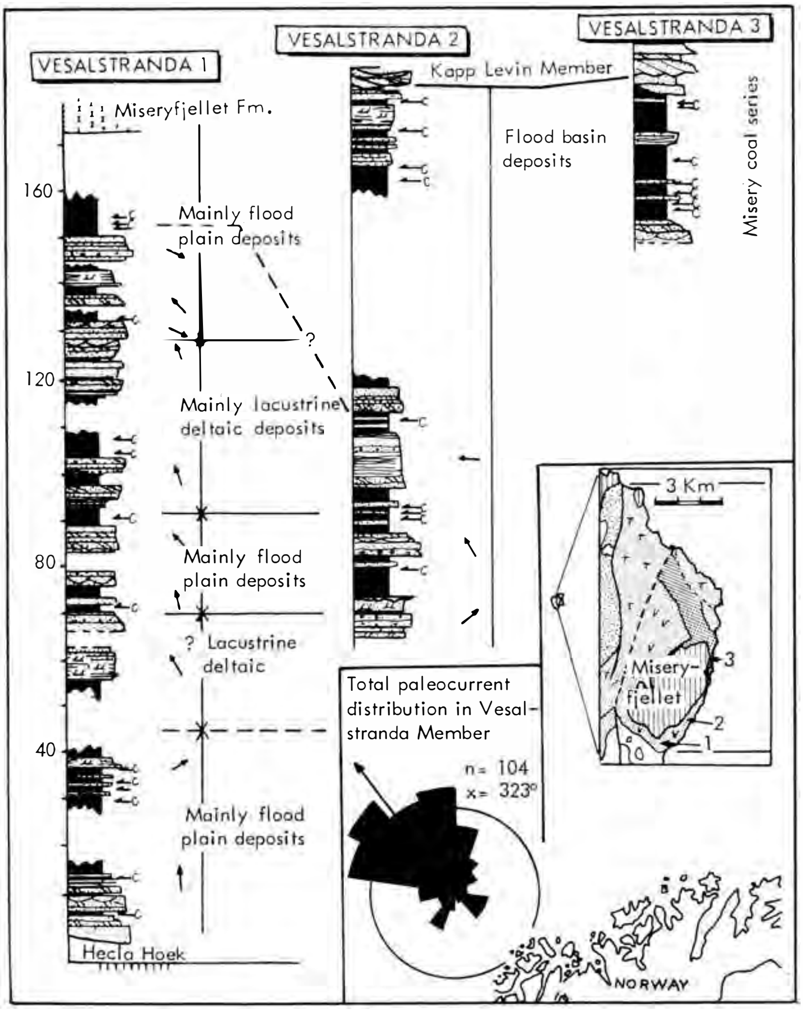


Fig. 4. *Generalized vertical log of Vesalstranda Member (Røedvika Formation). Location map for the three profiles is shown to the right.*

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

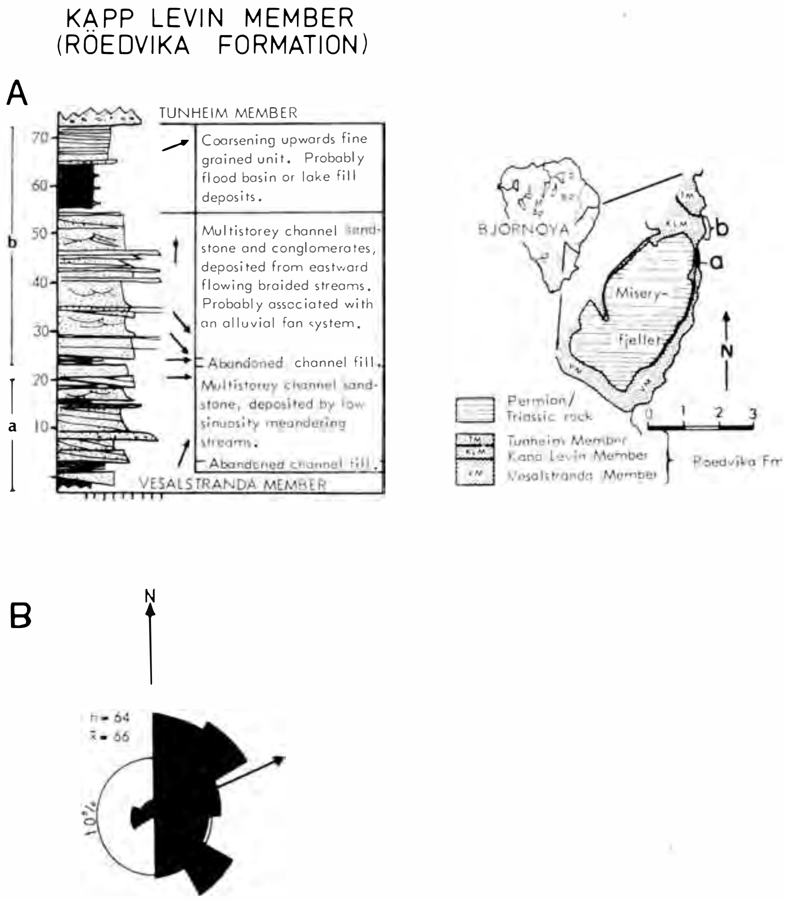


Fig. 5. *Type profile from Kapp Levin Member. The "rose diagram" in the lower part of the figure shows total paleocurrent distribution in Kapp Levin Member.*

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

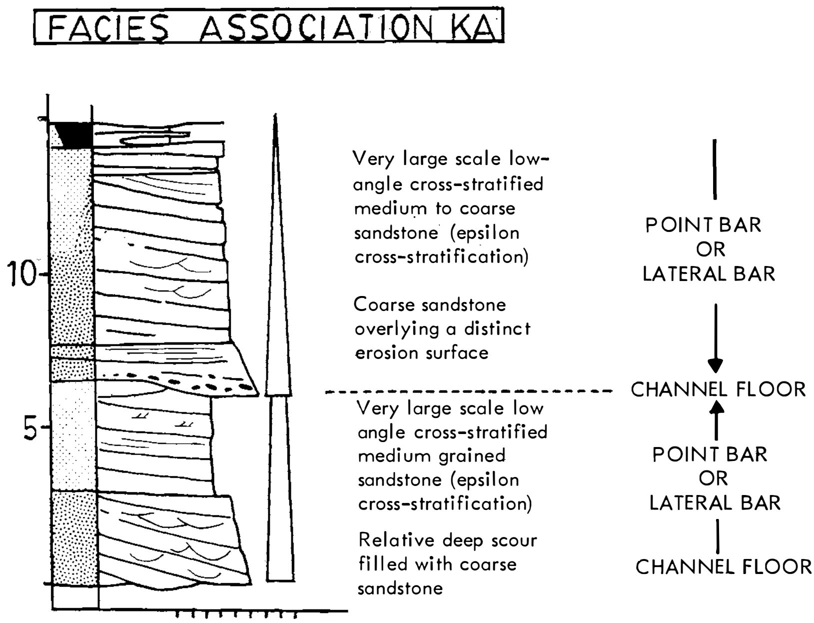


Fig. 6. *Two cyclic sequences of Facies Association KA. A common feature is the occurrence of very large-scale cross-stratification. The sequences show also slightly fining-upwards trends. The lower sequence has been considerably truncated by the overlying.*

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

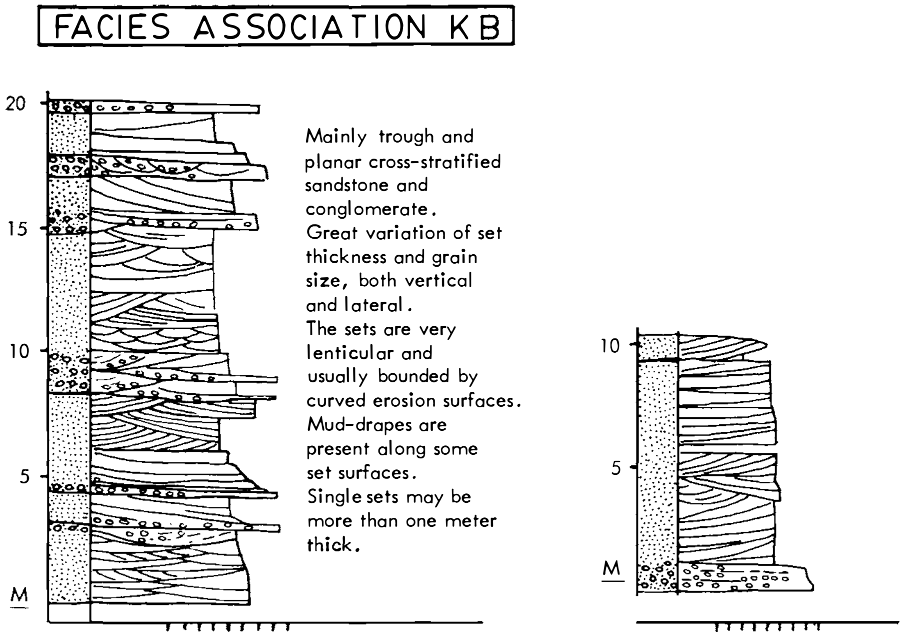


Fig. 7. *Two multistorey sandstone and conglomerate sequences of Facies Association KB. Probably deposited by braided river systems.*

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.

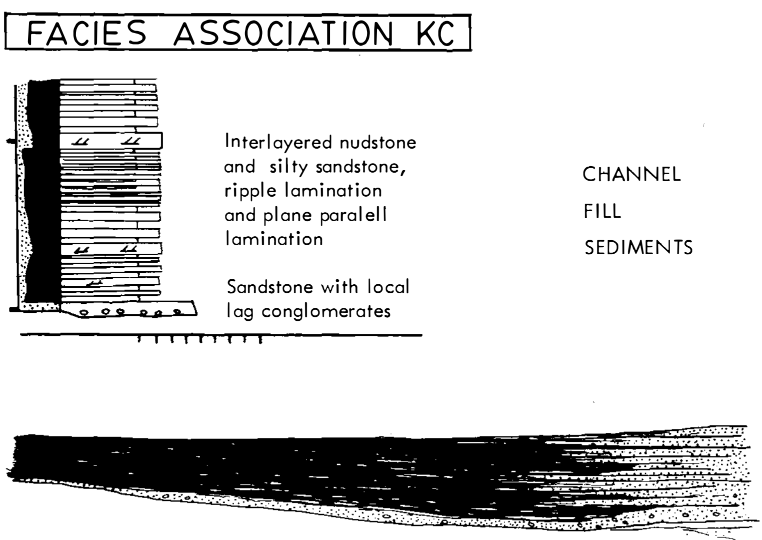


Fig. 8. *Vertical and lateral development of Facies Association KC.*

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

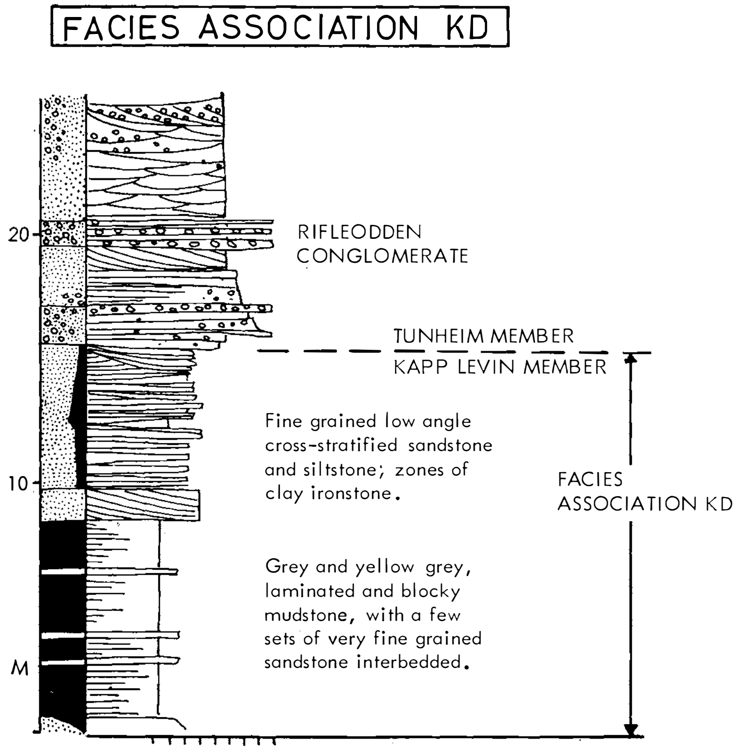


Fig. 9. *Vertical log of the only locality of Facies Association KD, with the accompanying Rifleodden Conglomerate.*

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

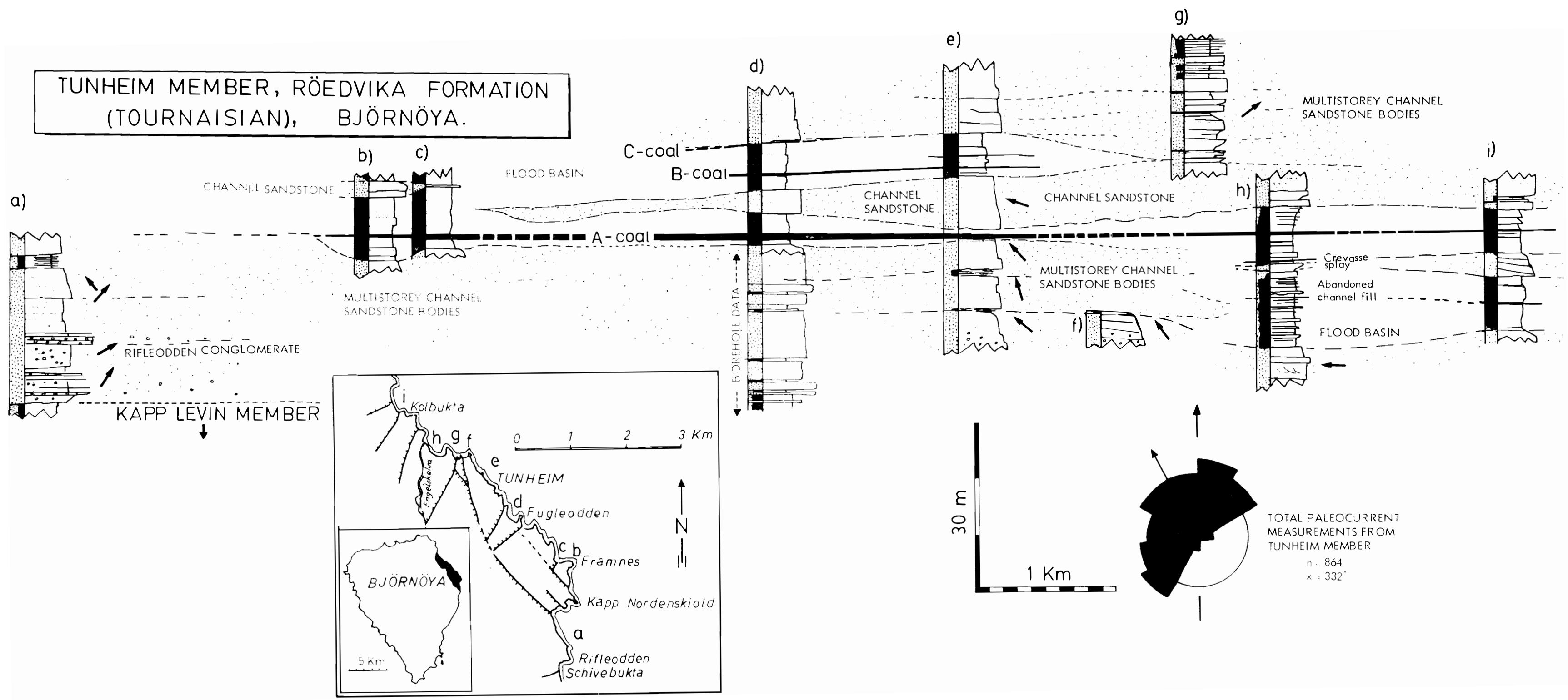


Fig. 10. *Generalized vertical logs from Tunheim Member, Röedvika Formation. The lateral correlation is based on the A-coal seam. The "rose diagram" below shows the total paleocurrent measurements obtained from the Member.*

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

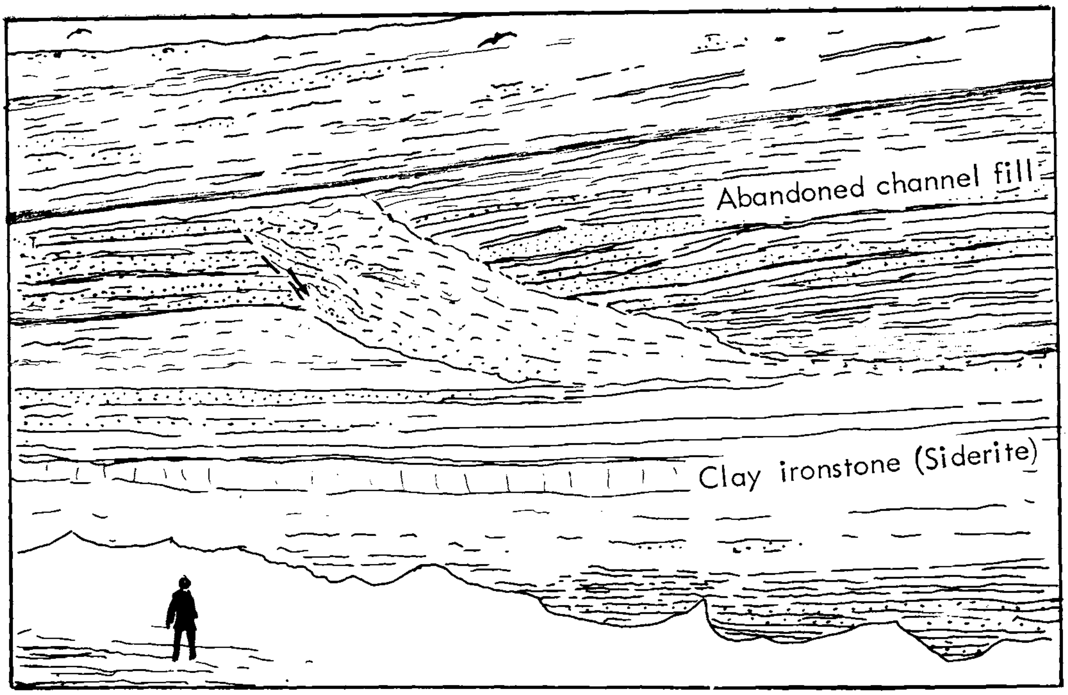


Fig. 11. *Part of the thick flood basin sequence exposed in Austervåg. Note syn-depositional faults probably developed on the margin of a pond or abandoned channel.*

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

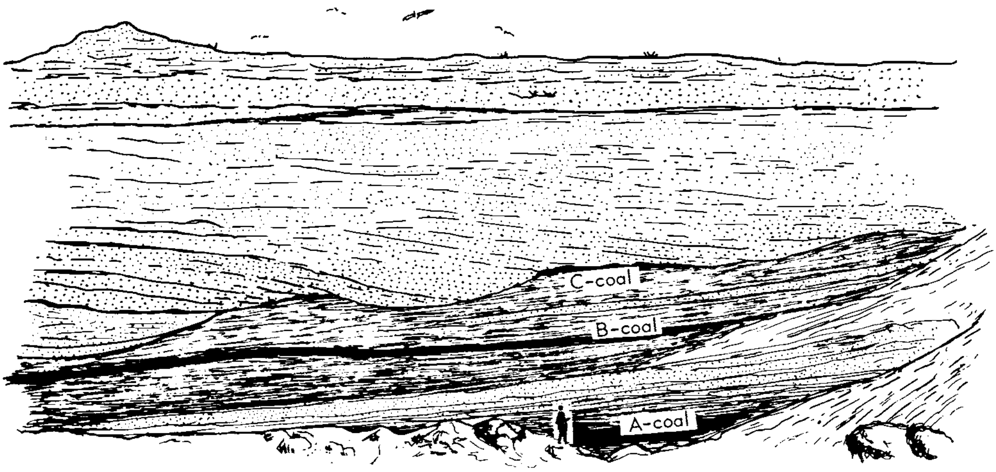


Fig. 12. *Occurrence of A-, B-, and C-coal in a location between Tunheim and Fugleodden. Note how the C-coal has been eroded by the succeeding sandstone sequence. Also note the very low-angle gigantic cross-stratification at the base of this sandstone.*

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.

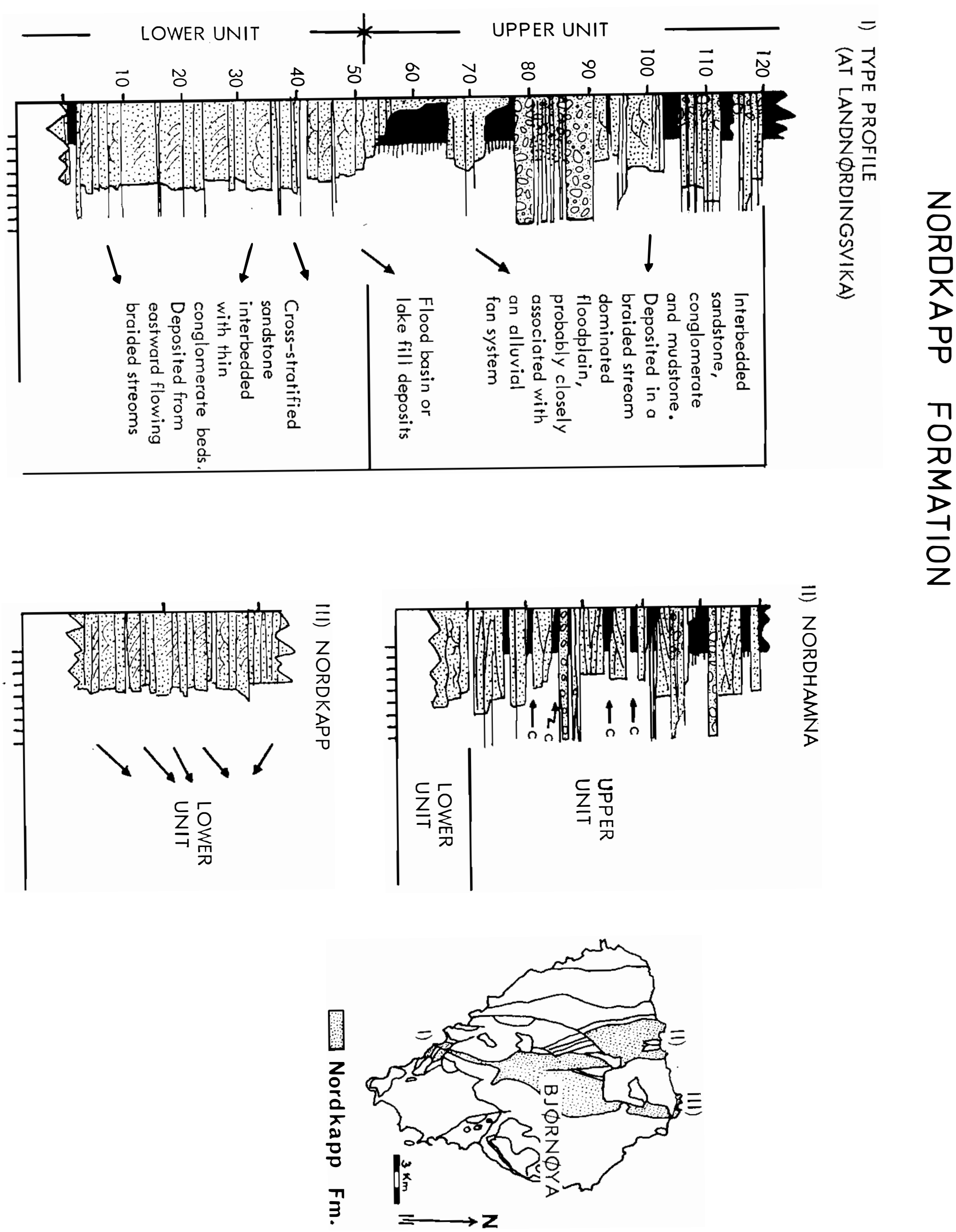


Fig. 15. *Generalized vertical logs from Nordkapp Formation.*

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.

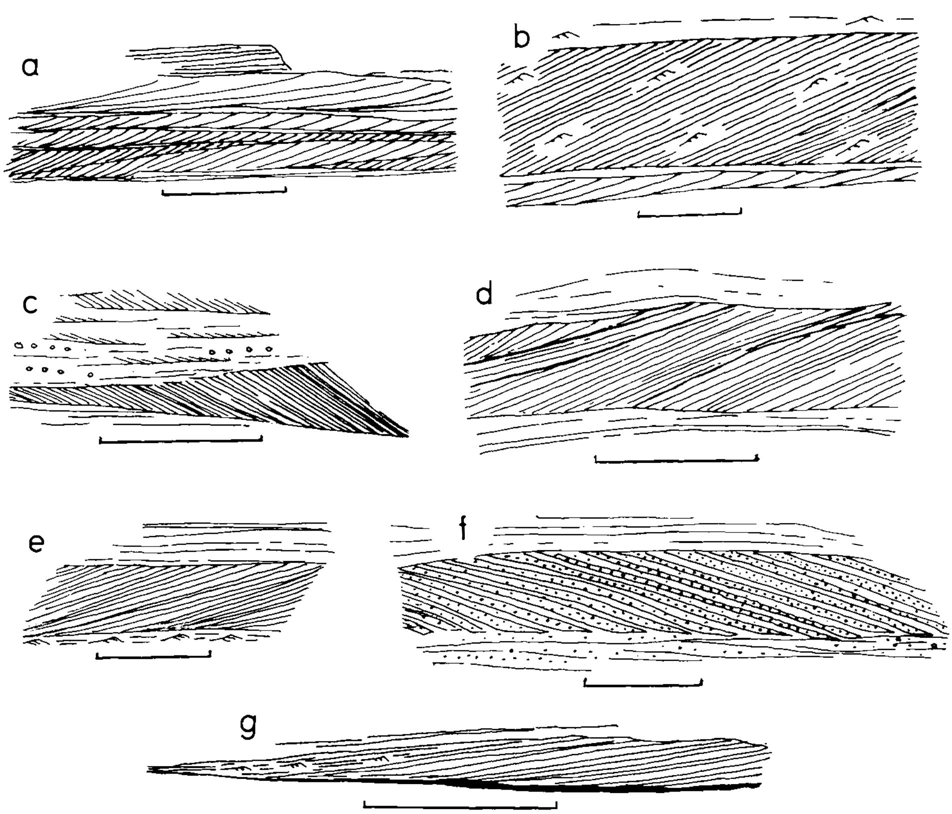


Fig. 16. *Various types of planar cross-stratifications recorded from Nordkapp Formation, lower unit, (scale is 1 m) :*

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

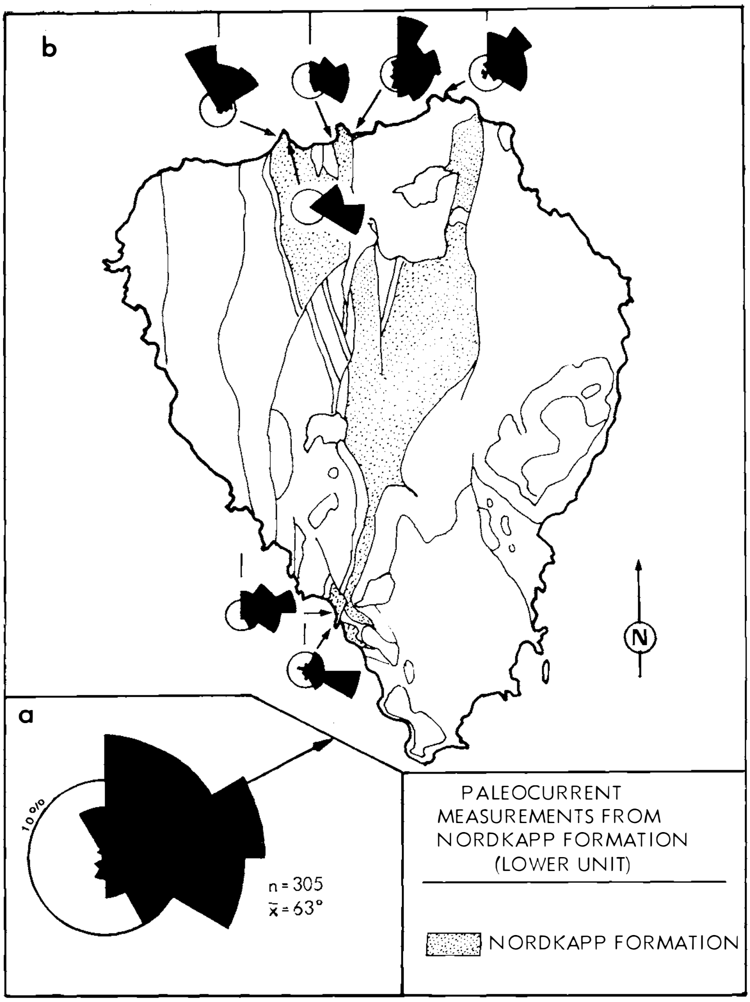


Fig. 18. *Paleocurrent data from Nordkapp Formation, lower unit.*

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.

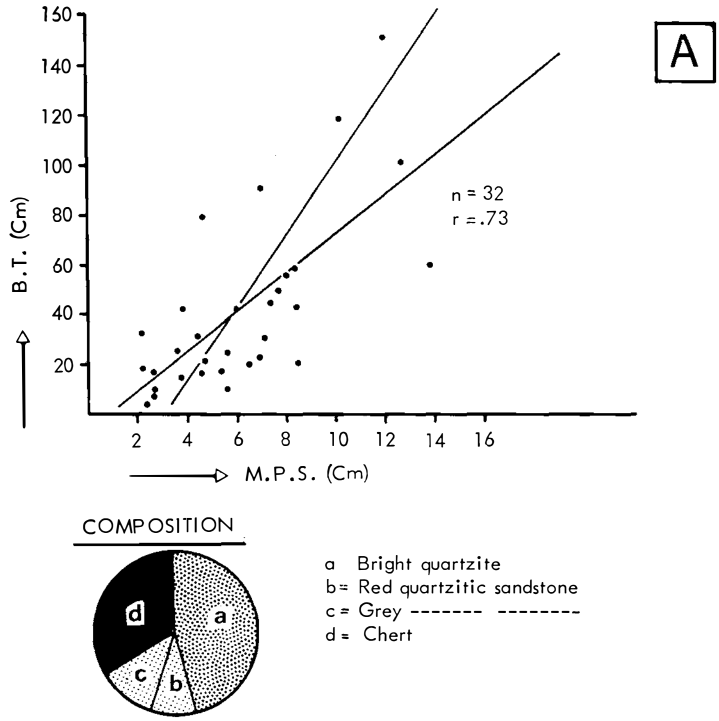
Prominent conglomerate sequences in the upper unit

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.



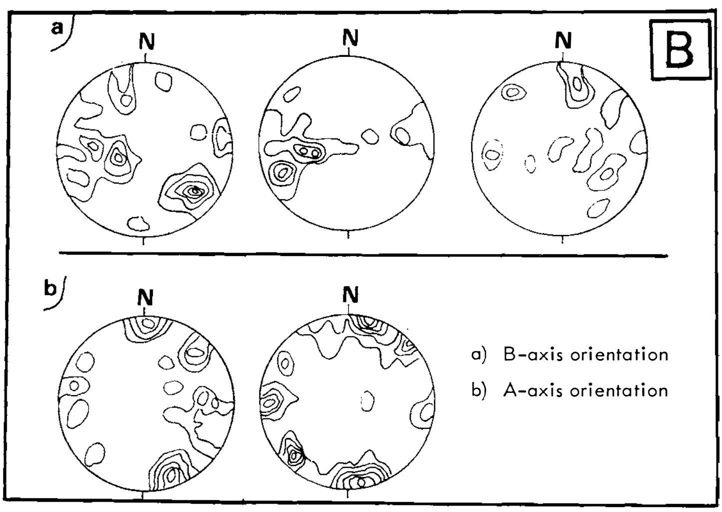


Fig. 19. *A. Plots of maximum particle size (M.P.S.) with respect to bed thickness (B.T.) from the most prominent conglomerate beds in Nordkapp Formation, upper unit. Note the correlation. Figure also shows clast composition.*

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

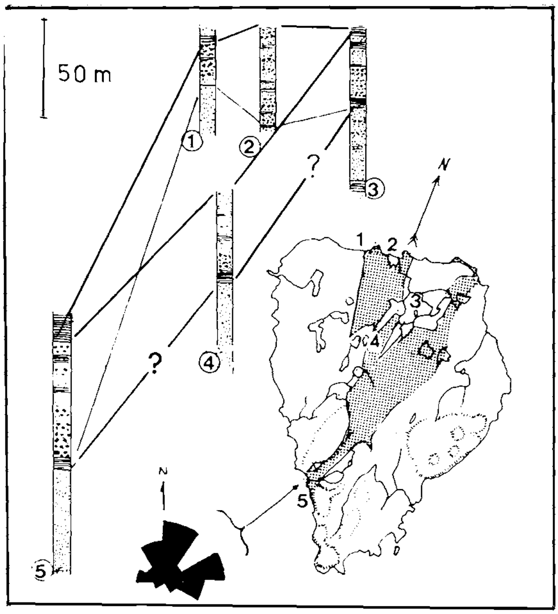


Fig. 20. *Thickness variation of the upper conglomerate unit of Nordkapp Formation. Figure also shows paleocurrent measurements from the south-west coast.*

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 south-west on which deposition by debris flow processes also were present. The inter-fingering 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.

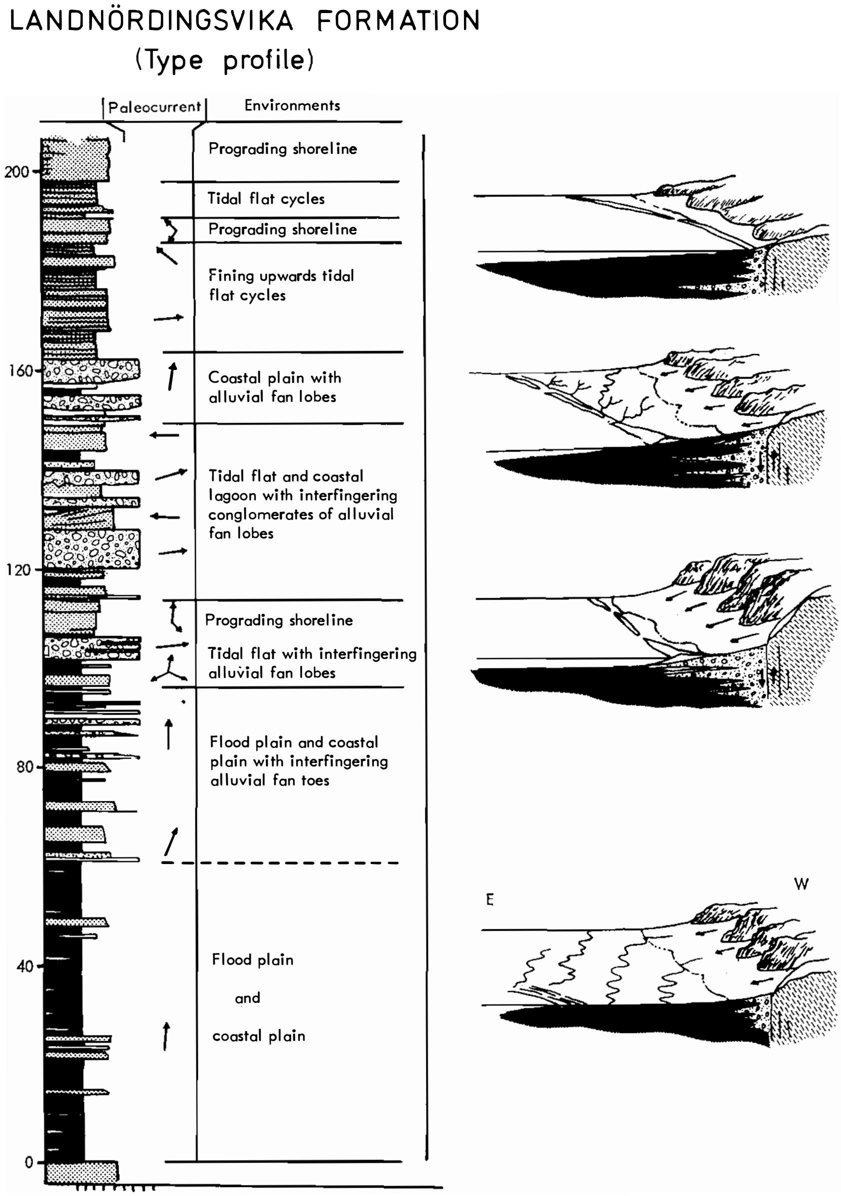


Fig. 21. *Generalized vertical log of the type profile of Landnørdingsvika Formation. Interpretation according to depositional environment and paleogeography.*

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).

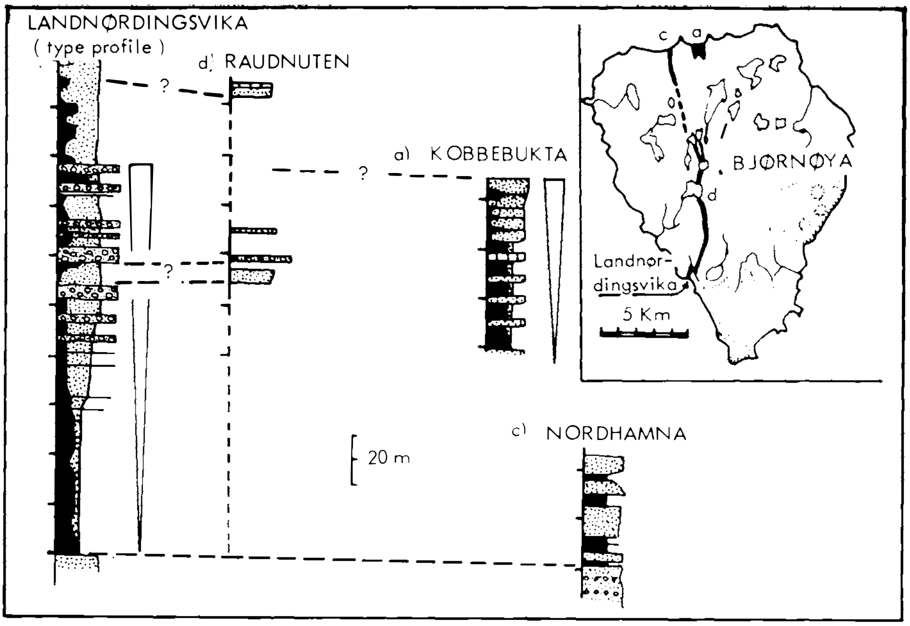


Fig. 22. *Suggested correlation between different profiles of Landnørdingsvika Formation.*

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

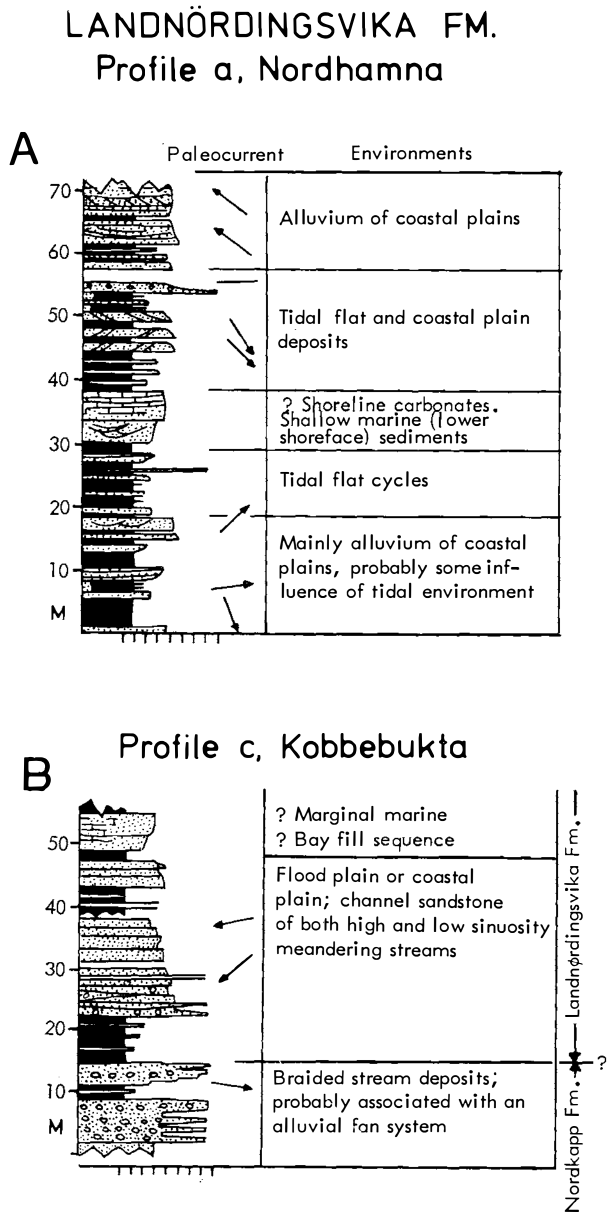


Fig. 23. *A. Generalized vertical log of Landnørdingsvika Formation. From the exposures in Nordhamna on the north coast.*
B. Generalized vertical log of lower part of Landnørdingsvika Formation and upper part of Nordkapp Formation. From the exposures in Kobbebukta on the north coast.

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

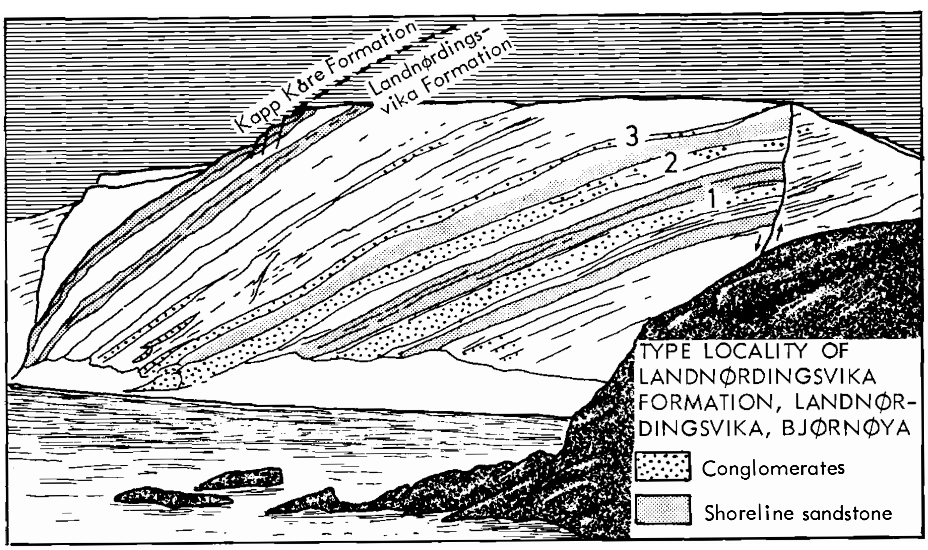


Fig. 24. *Type locality of Landnørdingsvika Formation, Landnørdingsvika, on the south-west coast of Bjørnøya. The cliff is 95 m high. The most prominent conglomerate lobes are marked with the numbers 1–3.*

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

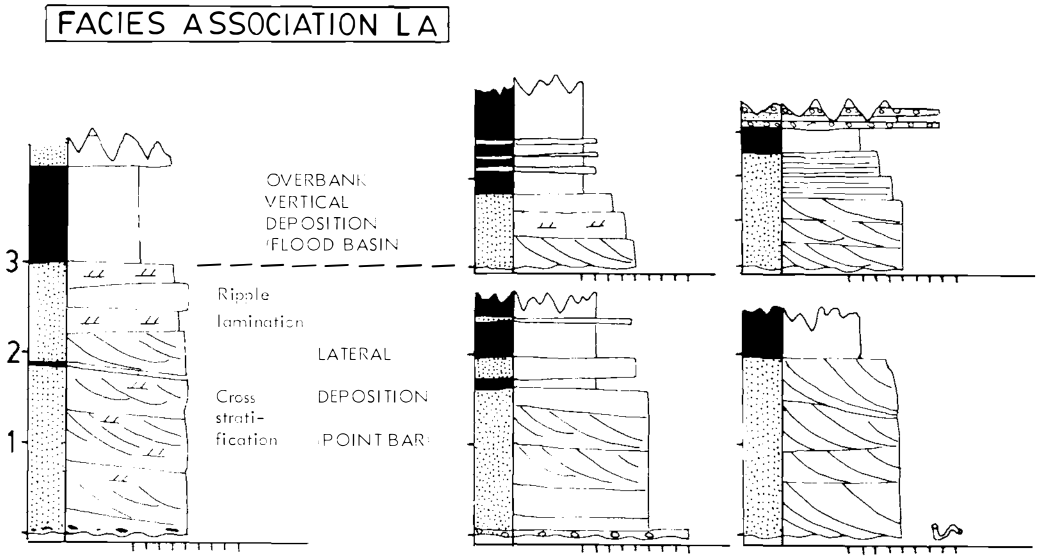


Fig. 25. *Detailed vertical logs from Facies Association LA (Landnørdingsvika Formation).*

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,

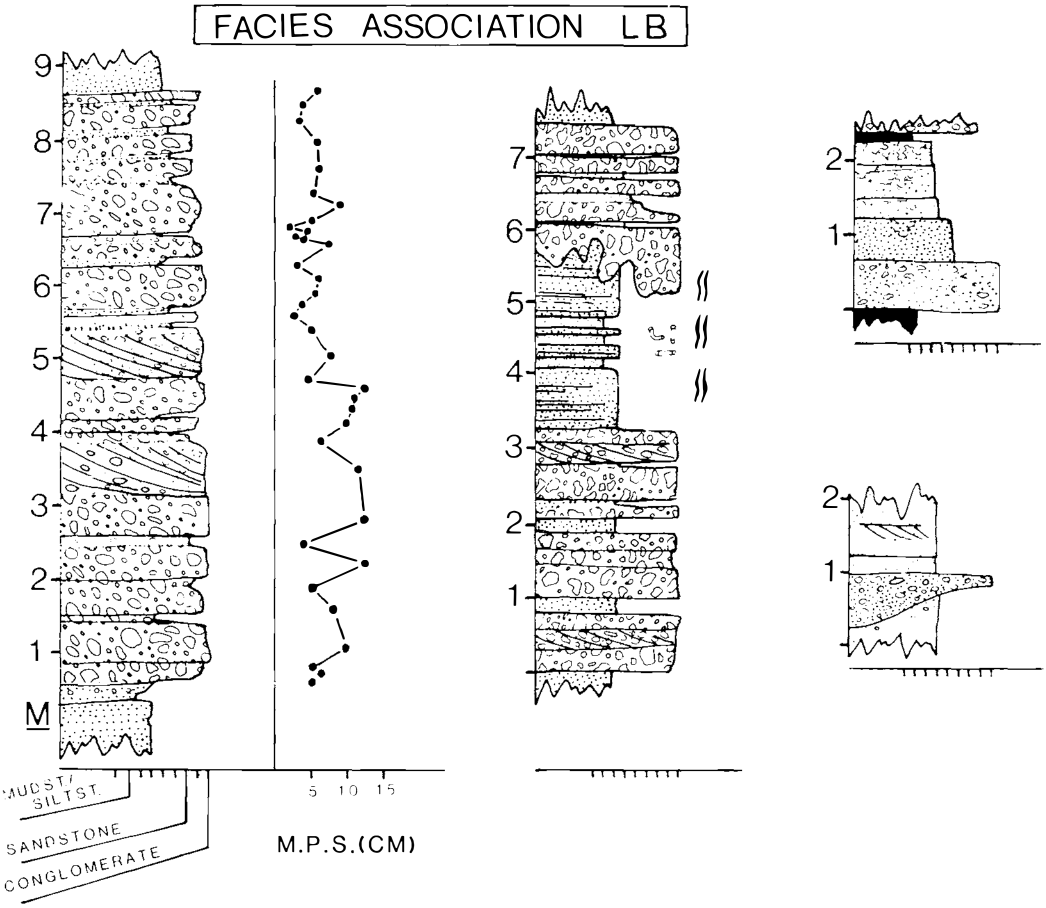


Fig. 26. *Detailed vertical log from some conglomerate lobes of Facies Association LB. The two profiles to the right represent alluvial fan toe deposits.*

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).

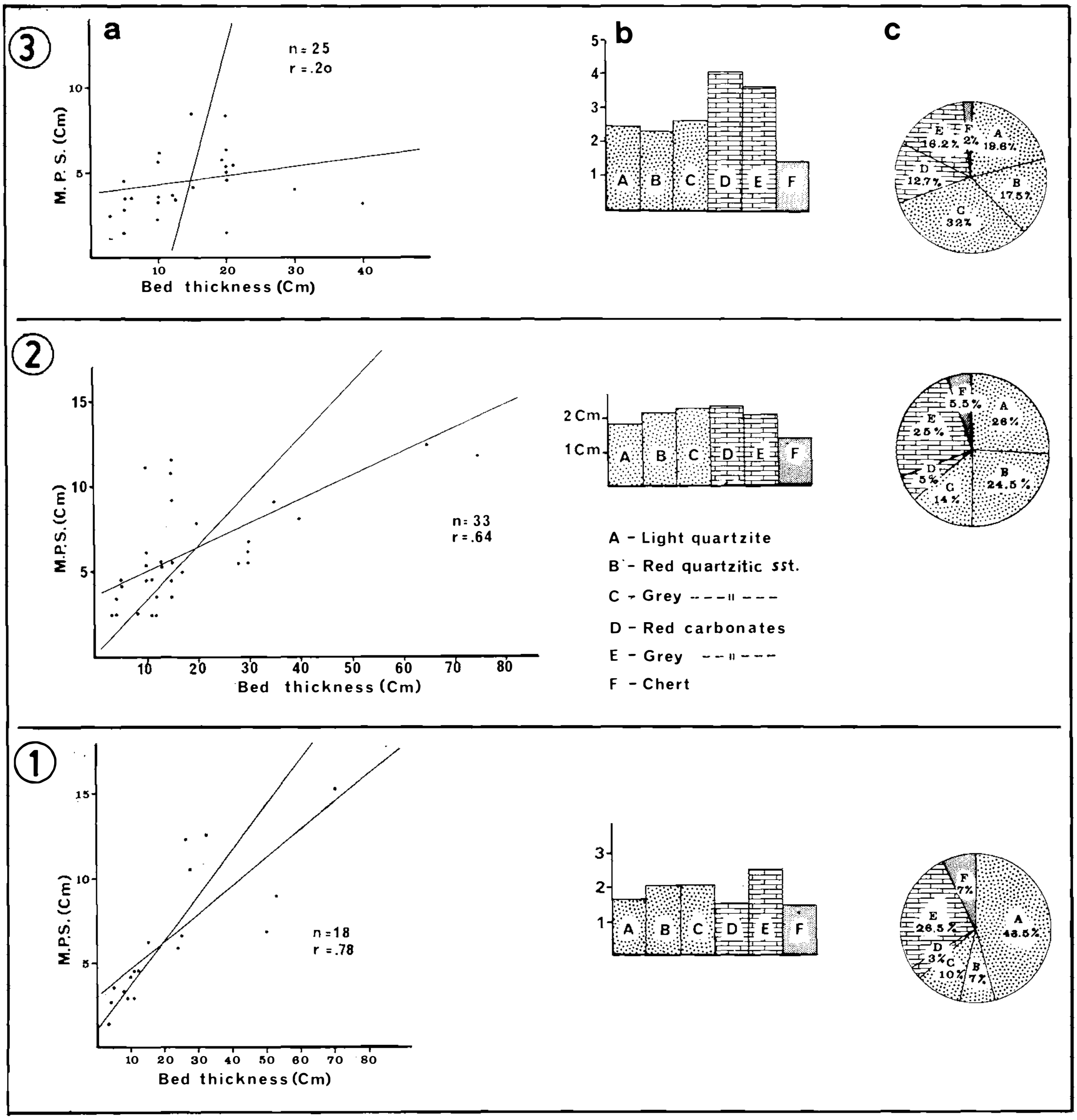


Fig. 27. *Plots of bed thickness against maximum particle size (M.P.S.) from three conglomerate lobes of Facies Association LB; clast composition for the respective conglomerate lobes are also shown, together with average size of different clast types (see Fig. 24 for location of lobe 1, 2, and 3).*

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

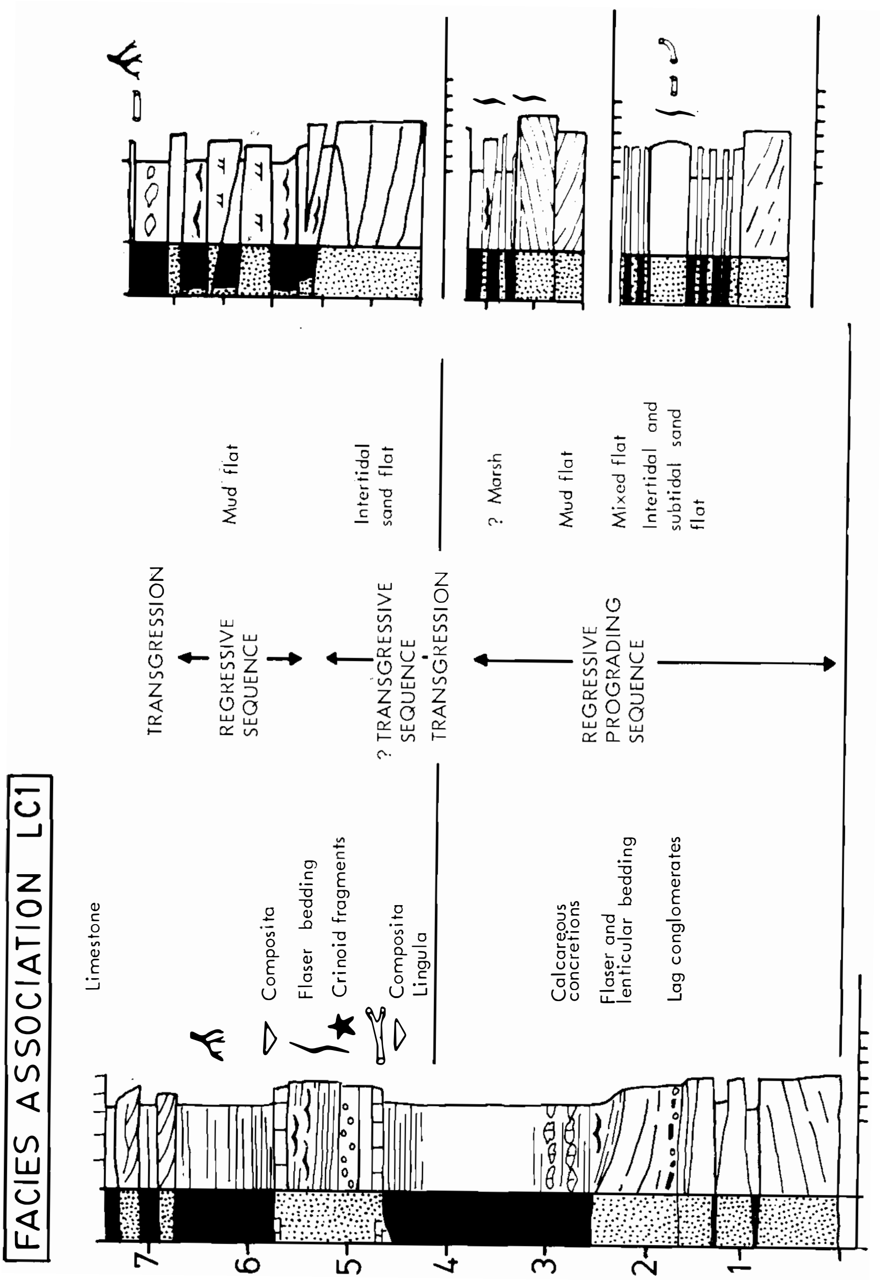


Fig. 29. *Detailed vertical logs to illustrate examples of Facies Association LC 1.*

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.

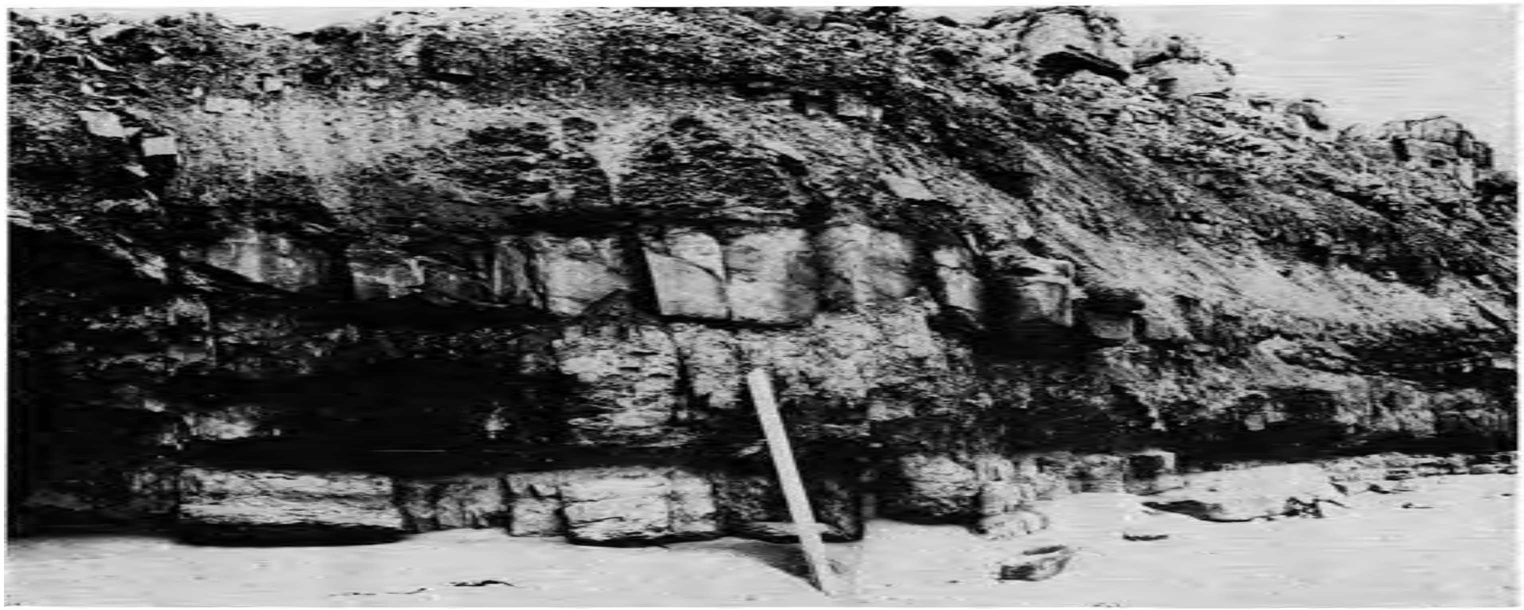


Fig. 30. *Large-scale cross-stratification probably produced by lateral migration of tidal channel (longitudinal cross-stratification). Note how the cross-stratified sandstone terminates into a mud-filled channel (to the right). From Nordhamna. The trunk is about 2 m long.*

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-

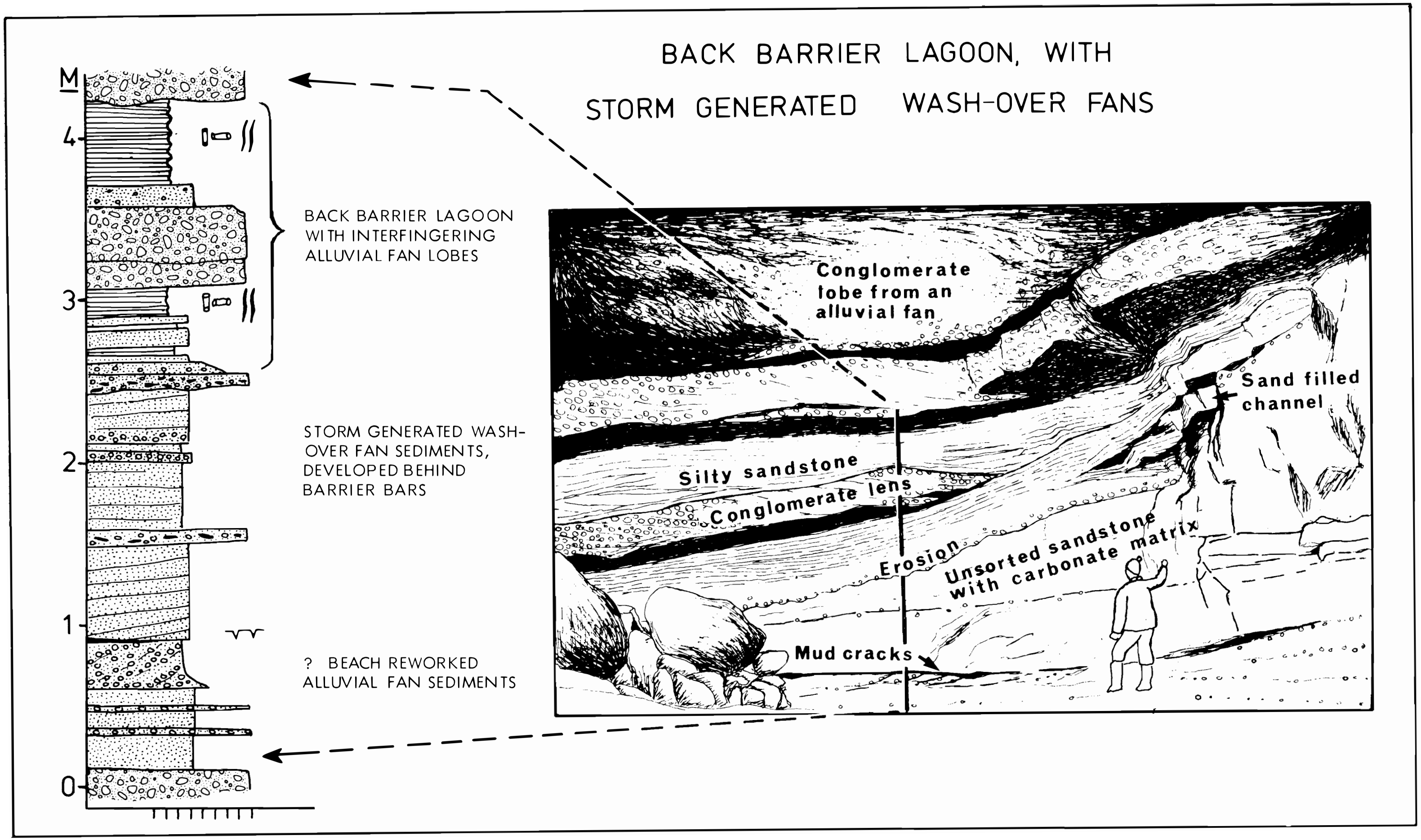


Fig. 32. *Sequence illustrating the occurrence of washover fan sediments in Landnørdingsvika Formation.*

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.*

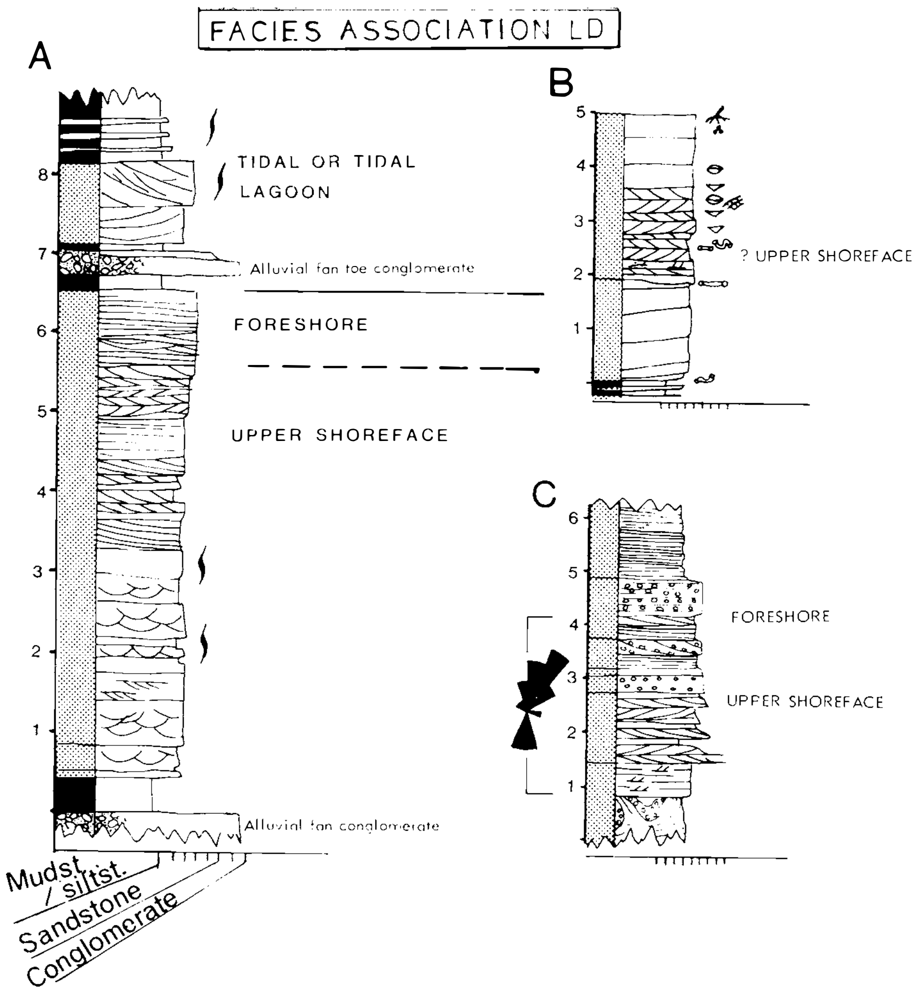


Fig. 34. *Detailed vertical logs from Facies Association LD.*

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

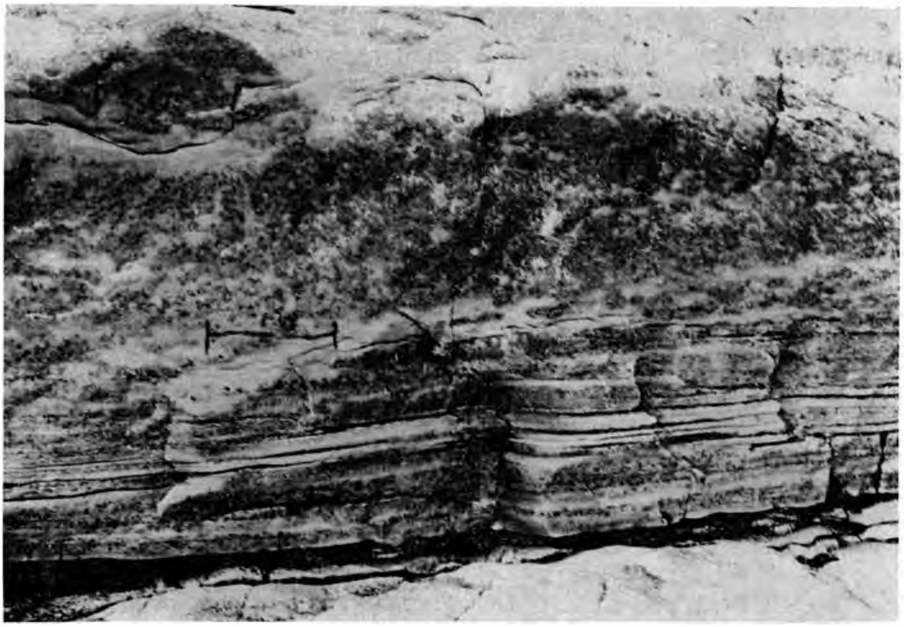


Fig. 36. *Plane parallel, horizontal laminated (or very low angle cross-stratified) sandstone in the upper part of Facies Association LD. Note the massive unit on the top of the laminated unit, and its very diffuse lower boundary.*

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

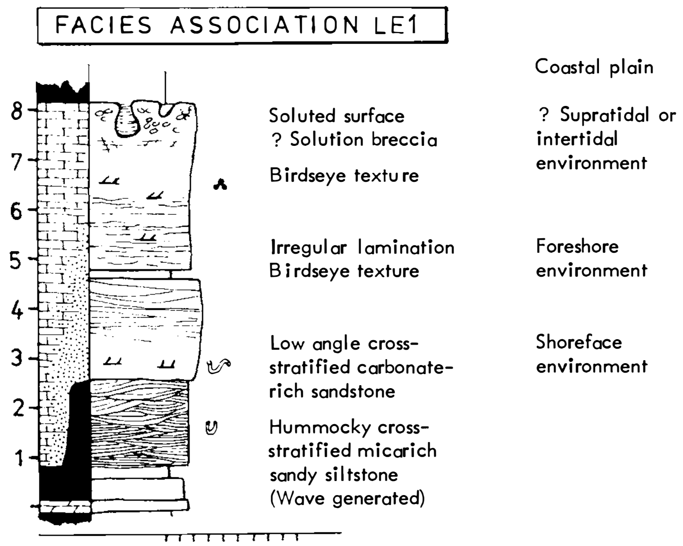


Fig. 37. *Detailed vertical log from Facies Association LE 1 (Nordhamna).*

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.

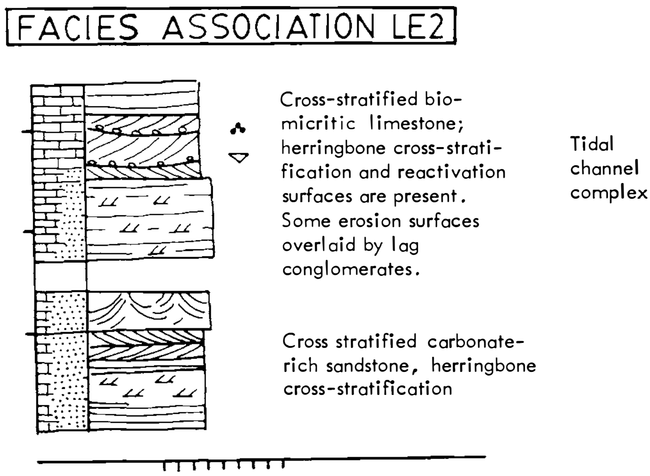


Fig. 39. *Detailed vertical log of Facies Association LE 2. From the exposures at Raudnuten.*

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.

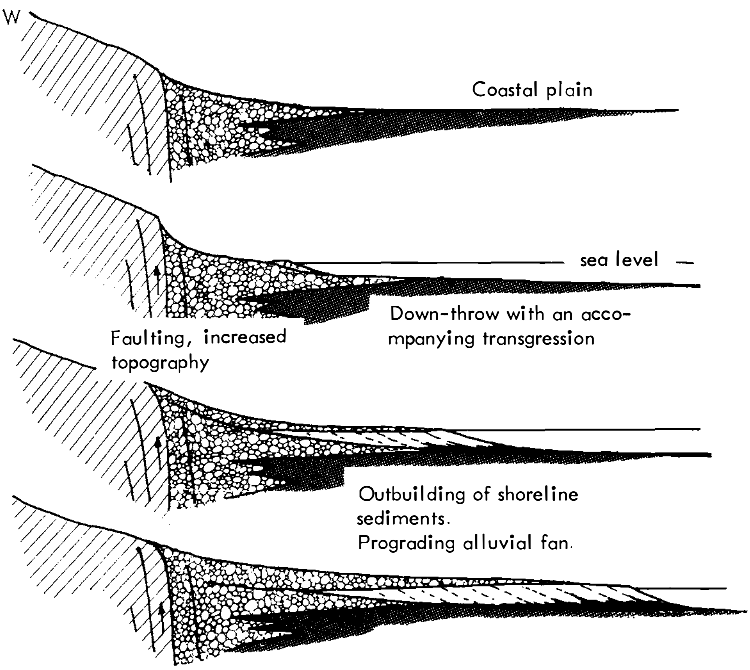


Fig. 40. *Model for the tectonic events and their sedimentological response. Landnørdingsvika Formation.*

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).

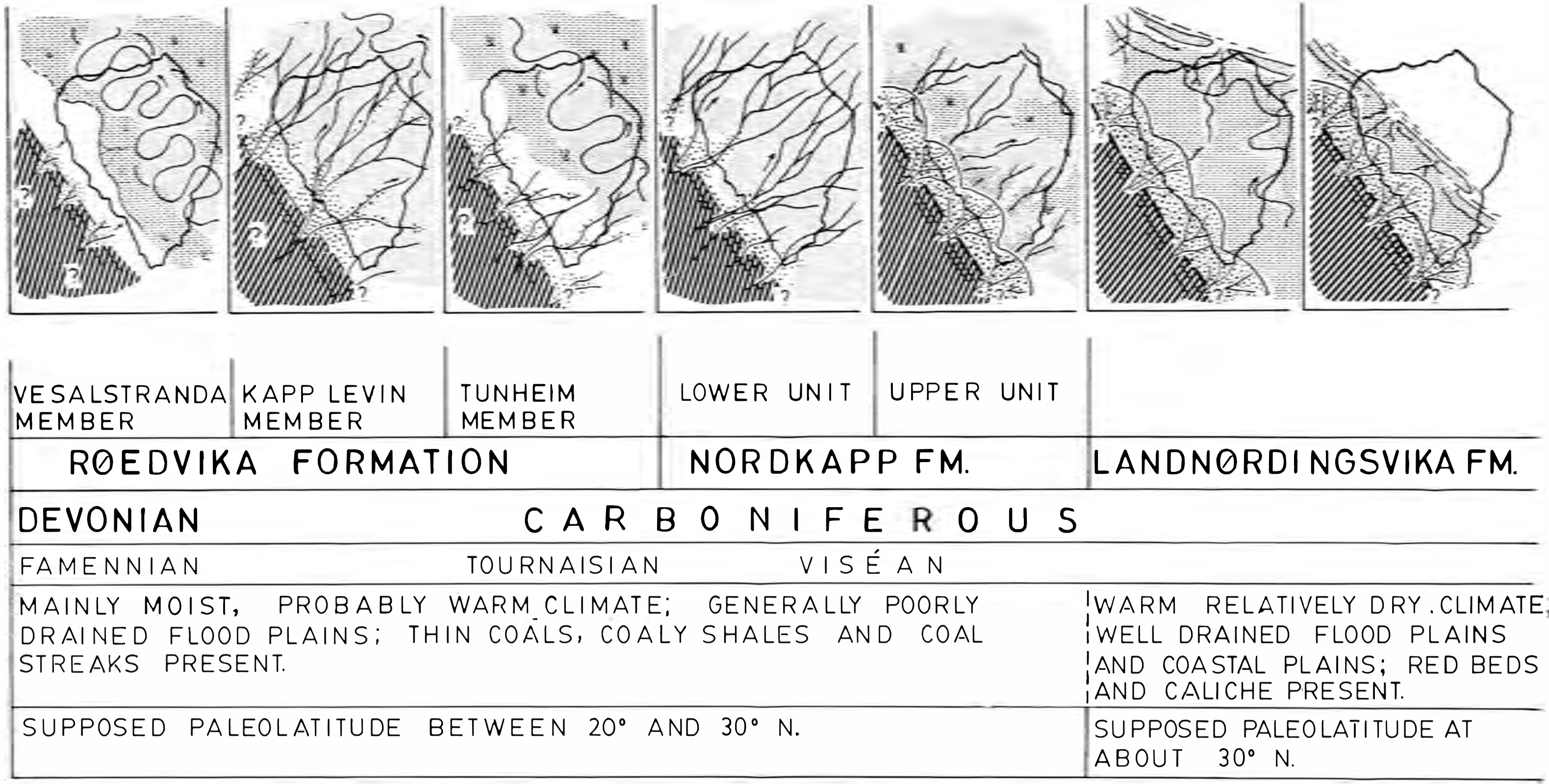


Fig. 41. *Generalized illustration of paleoenvironment, paleogeography and paleoclimate of the Upper Devonian — Middle Carboniferous succession of Bjørnøya. The figure also shows suggested paleolatitude for the basin during deposition.*

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

This work is part of a cand. real thesis submitted to the University of Bergen (1978). It was undertaken as part of the Svalbard Project (Geological Institute, University of Bergen) financed by the Norwegian Science Research Council (NTNF), the Norwegian Polar Research Institute, and the University of Bergen. I thank RON STEEL for suggesting and supervising the work and JOHAN PETTER NYSTUEN for critically reading the manuscript and proposing numerous improvements. I wish to thank ERIK JOHANNSEN for excellent assistance in the field.

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A.S JOHN GRIEG

PART III

LOWER - MID CARBONIFEROUS STRATA SPITSBERGEN

ABSTRACT

This paper presents a study of the Lower-Middle Carboniferous succession of Spitsbergen. Facies analysis have been carried out for all of the Lower-Middle Carboniferous formations exposed in the Sørkapp Land area, along the western part of Spitsbergen, and from the Central Spitsbergen area. Facies analysis combined with palaeocurrent data have been used as an important tool to establish the palaeogeography, and to analyse the sedimentary basins and their evolution.

Early Carboniferous (Tournaisian - Visean) time was characterized by relatively broad N-S or NW-SE trending basins. In the Hornsund area there developed a relatively deep basin dominated by shale and siltstone, with some interfingering subaqueous debris flow conglomerates and sandstones in the lower part. The conglomerates were derived from the tectonically active eastern (and northern) margin of the basin. In the central area of Spitsbergen the basins were broad and shallow and were dominated by flood plain and occasional lakes in the axial parts, with alluvial fans along the margins. Namurian time across the whole of Spitsbergen was dominated by large humid alluvial fans which entered broad basins from the west. These fans developed laterally into flood-plains, whose deposits usually dominate the upper parts of the Namurian succession. In early Carboniferous times the basins on Spitsbergen were usually broad and shallow and most likely developed in tensional tectonic regimes. The Bashkirian (Mid Carboniferous) development was completely different, as narrow grabens in which there was relatively rapid

sedimentation developed in southern, western and centr[al] parts of Spitsbergen, with coarse conglomerates along fault margins. The sedimentation took place mainly on alluvial fans coastal plains, tidal flats, coastal sabkha, barrier bars and spit bars, and the resultant deposits accumulated in a cyclic, interfingering manner. The Middle Carboniferous successions probably developed in strike-slip related basins, and movements along important NNW-SSE fault lines are generally reflected b[y] thick, very coarse clastic successions and more precise[ly] by repeated (often cyclic) facies changes (each facies sequence 5 to 40m thick): for example, a sudden influx [of] marginal marine sandstones and carbonates followed by coarsening-upward coastal plain/alluvial fan sequences.

A large-scale change in sediment type from fluvial, gr[ey] sandstones, coal bearing shales and monomict conglomerates to red, ephemerial fluvial and polymict alluvial fan deposits, reflects a change from humid to more arid climate near the Namurian/Bashkirian boundar[y]. It is suggested that this dramatic climatic change may have resulted from sinistral megashear which was regionally important in Bashkirian times and which mov[ed] the present day Spitsbergen area 1000-2000km northward[s from] its middle Carboniferous palaeoposition north of Greenland.

III. 1

INTRODUCTION

LOCATION AND STRATIGRAPHY

Spitsbergen is located on the northwestern corner of the Barents shelf, an area critical to our understanding of the geology of the North Atlantic region.

The name Svalbard dates back to the 12th century when the islands were first visited by Norwegian sailors, and it means literally "cold coast". Wilhelm Barents rediscovered the islands in the 16 th century, and introduced the name Spitsbergen which means something like "peaky mountains" and is fairly appropriate for the main island in the archipelago, which later has retained this name. The term Svalbard now includes all islands in the archipelago, included Bjørnøya (but excluded Jan Mayen). The area came under Norwegian sovereignty in 1920 under the Svalbard treaty.

This paper provides a description and interpretation of the Lower-Middle Carboniferous clastic succession on Spitsbergen. The field investigations were carried out during four field seasons (in 1977, 1978, 1979 and 1981) and were concentrated on three main areas: 1) Hornsund area, 2) Central western Spitsbergen and 3) Billefjorden area.

Observations on the Lower to Middle Carboniferous sedimentary succession show clearly that there were a number of widespread changes in the character of the sediments with time. the most significant change occurs near the Namurian-Bashkirian boundary, and represents a transition from grey, coal-bearing strata to red beds. This change has been examined in some detail at three localities on Svalbard. together with this, two other significant aspects of sedimentation are examined and evaluated: 1) the appearance of thick conglomerate sequences related to specific fault lines and graben formation and the cyclic organization of these sequences, possible reflecting discrete episodes of faulting, and 2) the gradual change from entirely continental to entirely marine strata through middle and late Carboniferous times.

A review of the Carboniferous stratigraphy on Svalbard is outlined in Table I. This stratigraphy differs slightly from that established by Cutbill and Challinor (1965). The reason for the change will be discussed in the text.

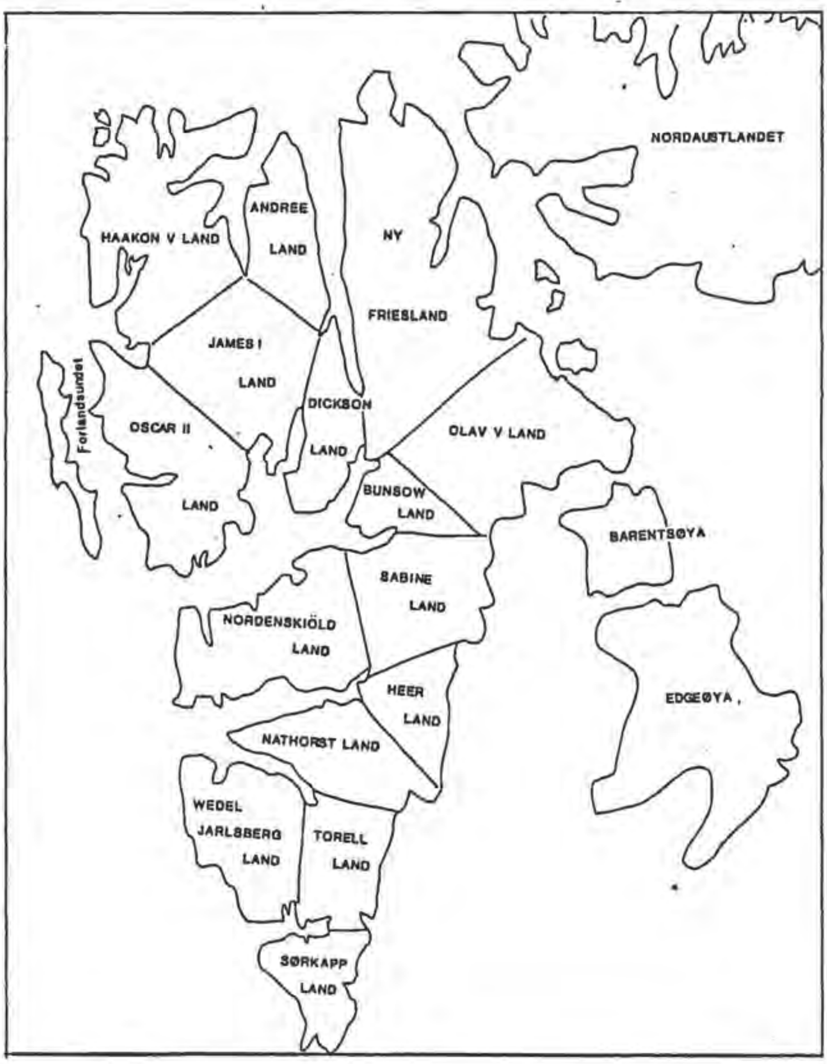


Fig. 1.1 Subdivision of Spitsbergen into Lands. Most of these Lands are referred to in the text.

TABLE 1.

CARBONIFEROUS STRATIGRAPHY OF SVALBARD

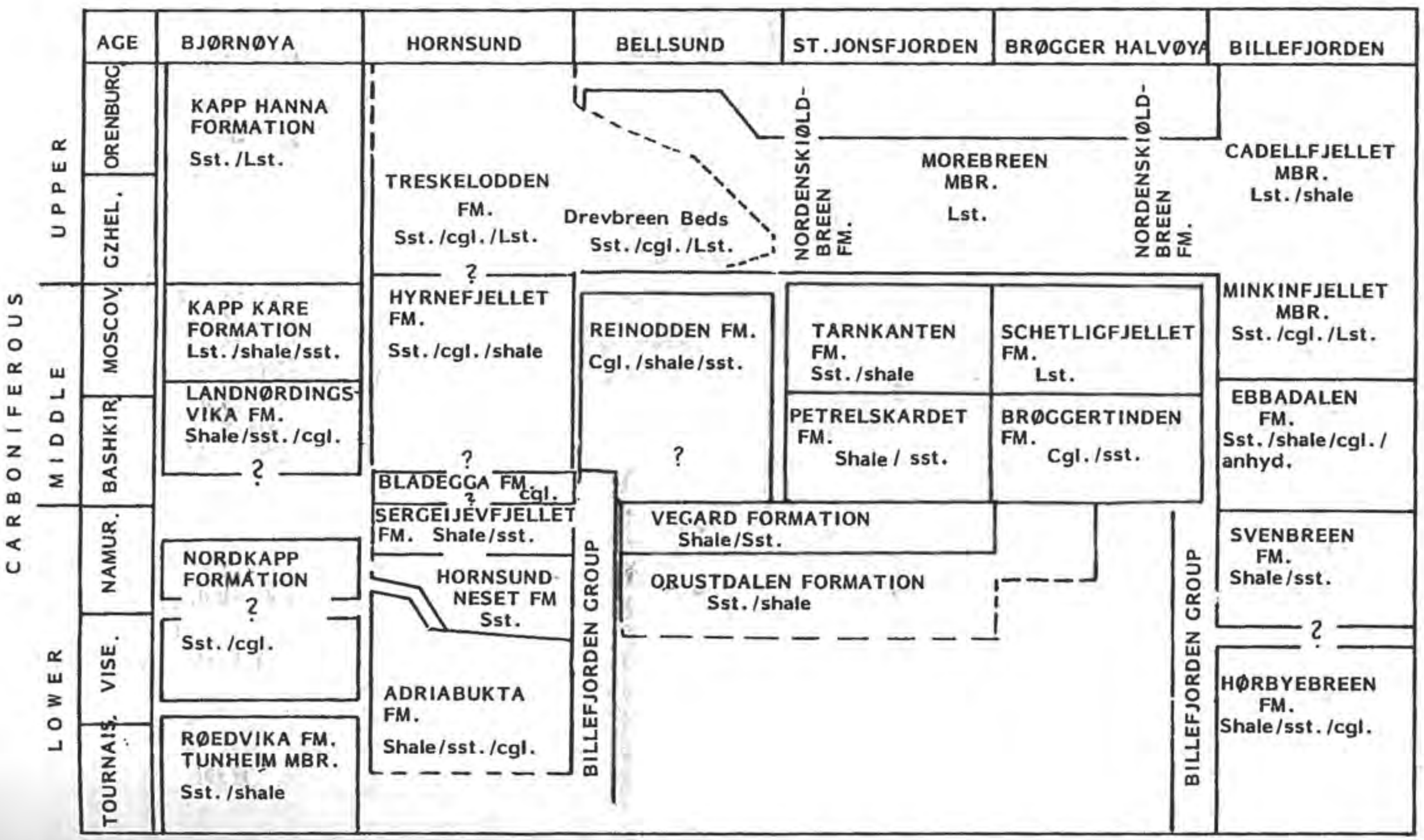


Fig. 1.1. shows the subdivision of Spitsbergen into 15 individual land areas. Most of these names will be referred to in the text.

The Lomfjorden area has not been included in this study, as I not was able to visit this area during the four seasons of fieldwork. It is, however, an important area, due to its isolated position on northeastern Spitsbergen. The Carboniferous succession in this location has previously been investigated by Cutbill (1968) and Lauritzen and Worsley (1975).

REGIONAL STRUCTURE AND TECTONIC SETTING

The Svalbard archipelago may be regarded as an uplifted NW corner of the otherwise submerged Barents shelf. The most intense uplift has occurred in the northern and western part of the area, where the oldest rocks (Hecla Hoek succession) are now exposed.

Most of the important faultlines are oriented in a NNW-SSE direction (Fig 1.2.), many of which reflect a complex history of activity, with a whole series of rejuvenations.

Several major periods of tectonic deformation have been identified from the stratigraphic record. Most intense was the Caledonian orogeny that folded, faulted, thrusted and partly metamorphoses the pre-Cambrian to Silurian sedimentary and igneous complex. These rocks now form the economical basement for petroleum prospecting in Svalbard.

In Devonian time the area was affected by extensive faulting along important NNW-SSE trending faultlines, and a deep and extensive Devonian graben developed eg. Orv. 1940, Friend and Moody-Stuart 1972 and Birkenmajer 198 The Balliobreen Fault (Billefjorden Fault Zone) played important role in this context, as it is suggested tha sinistral strike-slip motion of at least 200 km, and downthrow (to the West) of more than 2000 m occurred along this fault (Harland <u>et.al</u>. 1974).

From evidence outside of Spitsbergen, Harland (1969) suggested that "the principal tectonic event in the Ar region in Late Devonian time translated Europe several hundred kilometres north with respect to North America and Greenland, placing Spitsbergen near Ellesmere Island". He also suggested that "such movements would effected by a set of transcurrent faults, and that the would form a zone along which the North Atlantic Ocean would later open". In view of the evidence provided directly and indirectly by Spitsbergen, Harland (1969) concluded that the Vogt's (1936) term "Svalbardian" should be applied to refer to this whole phase of (Lat Devonion) sinistral strike-slip movement. It is also suggested that the tectonic movements reflected in th Lower-Middle carboniferous succession of Svalbard wer closely related to this structural trends by rejuvena and that large scale strike-slip movements also took place in this time (Harland <u>et al</u>.; 1984). Birkenmajer (1964, 1981) concluded that the only majo Carboniferous deformation of Spitsbergen correspond the Erzgebirge Phase (Variscan Movements), which is mainly seen in the Adriabukta, where it caused stron folding and slight dynamic metamorphism of Lower Carboniferous shale (Adriabukta Fm).

It is the contention of this study that there was important tectonic activity particularly along the NNW-SSE faults, throughout Carboniferous time. As be shown, those movements were especially marked during late Namurian through Moscovian times, and indeed continued in an intermittent manner along the major lineaments (Billefjorden Fault Zone, Inner Hornsund Fault and along boarding faults of the St. Jonsfjorden Trough). A major part of the study is devoted to documenting this tectonic activity as read from the details of the sedimentary sequences themselves (See also Johannessen 1980, Gjelberg & Steel 1979, Gjelberg & Steel 1981, Gjelberg et al. 1980, Gjelberg and Steel 1983).

During late Carboniferous-Permian and Triassic time further mild rejuvenation of the fault system occurred, and caused important facies changes across the fault lines (eg. Mørk and Worsley 1979, Hellem 1981, Sundsbø 1982).

In late Jurassic time, the Billefjorden lineament reassumed activity. This is apparent along its extension south of Sassenfjorden (Parker 1967).

The most extensive post-Carboniferous tectonic deformation occurred in Tertiary time and is known as the West Spitsbergen Tertiary orogeny (Harland 1969) or the "Spitsbergen phase" Birkenmajer (1972a). The main phases of the Tertiary orogeny occurred in Palaeogene time and were related to early opening of the Norwegian - Greenland Sea. The deformation probably occurred as a result of compressional strike-slip movement between the Greenland and the Eurasian plates (Harland 1965, 1969). Harland (1971) considered this type of movement as something intermediate between transcurrent and compression and he termed it transpression. Lowell (1972) emphasised the wrench regime and stated that the Tertiary Spitsbergen orogenic belt is a strike-slip orogenic belt. Deformation affected the western margin of the post-Caledonian platform of Svalbard, causing strong folding and low-angle thrusting in a zone 10-20 wide. The crustal shortening in the fold-belt due to thrusting is, according to Birkenmajer (1981) 10 km in the north and about 15 km in the south. Birkenmajer (1972 a,b) assumed that the whole NNW-trending strip o the west coast of Spitsbergen between Kongsfjorden and Sørknapp, including the major thrust zone and its hinterland, has been translated to the NNW from a southerly location, possible some 30 km. At Kongsfjor this zone collided with the rigid mass of northwest Spitsbergen (see also Birkenmajer 1981).

Kellogg (1975) gave a more detailed outline of the Tertiary tectonic history of the region, particularly emphasising that there was early transtension in addit to the later transpressional phases during the Palaeocene-Eocene history.

Steel et al. (1981) proposed (on the basis of basin analysis) a model for the Palaeogene development on Spitsbergen, suggesting that the initiation of transpression started in late Palaeocene, i.e. earlier than previously assumed. They also emphasised the ro of the Central Basin as a sedimentation sink on the f of a sheared continental margin.

Birkenmajer (1981) concluded that "three successive stages of Tertiary folding on Spitsbergen express ch in the stress regime in the zone of transcurrent betw the moving continental plates", 1) transpression 2) transtension (eg. Forlandsundet Graben) and 3) transpression.

Any further discussion about the "West Spitsbergen Orogeny" is beyond the shape of this study, and wil be attempted. However, there is another stage of tectonism which should be mentioned. This is represented by some major normal fault movements along western Spitsbergen. These faults seems to be a result of downthrow of previously upthrusted blocks, and probably moved after the formation of the "West Spitsbergen Orogeny", when tensional or transtensional forces dominated. An example is shown on Fig. 2.3., section A (from Hyrnefjellet, N-Hornsund). This fault zone shows typical characteristics of compressional forces. However, the fault itself is normal. It is also tentatively suggested that the poorly consolidated Tertiary, Renardodden deposits represents infilling of a basin, developed due to such late-stage, block-faulting. The development of the Forlandsundet graben seems to have been earlier, and in a different regime However, further investigations are needed in order to understand this graben.

A map with all known major fault lines on Spitsbergen is shown in Fig. 1.2. Seven interpretative cross sections (indicated on the map) are shown in Fig. 1.3. The map, and partly the cross-sections, are based on a large number of publications: From northwestern Spitsbergen; Hjelle 1979, Gjelsvik 1979, Burov and Semevskij 1979. From Oscar II land; Orvin 1934. Challinor 1967, Hjelle et al. 1979, Guterch et al. 1978. From Billefjorden and northwestern region; Cutbill 1968, McWhae 1953, Worsley and Lauritzen 1972, Harland et al. 1974. Nordaustlandet; Sandford, 1963. Central Spitsbergen; Hjelle 1962, Livshits 1965, Parker 1967, Dalland 1979. Steel et al. 1981. Southern Spitsbergen; Major and Winsnes 1955, Rozycki 1959. Birkenmajer 1964, 1975, 1977, 1978 Birkenmajer and Morawski 1960, Birkenmajer and Narebski 1960. Birkenmajer and Orlansk 1977, Mørk 1978. Bjørnøya: Horn and Orvin 1928, Agdestein 1980, Worsley

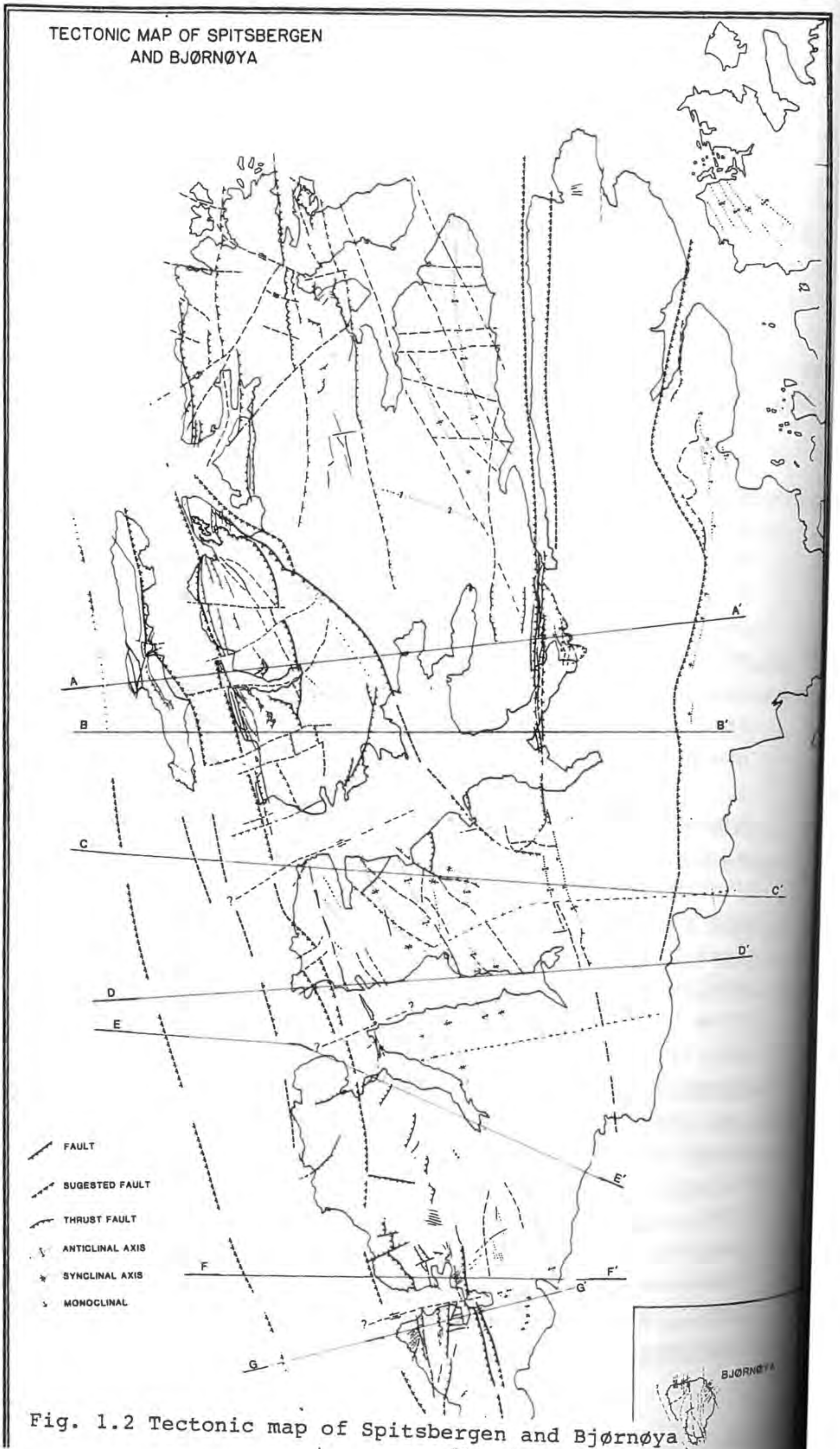


Fig. 1.2 Tectonic map of Spitsbergen and Bjørnøya

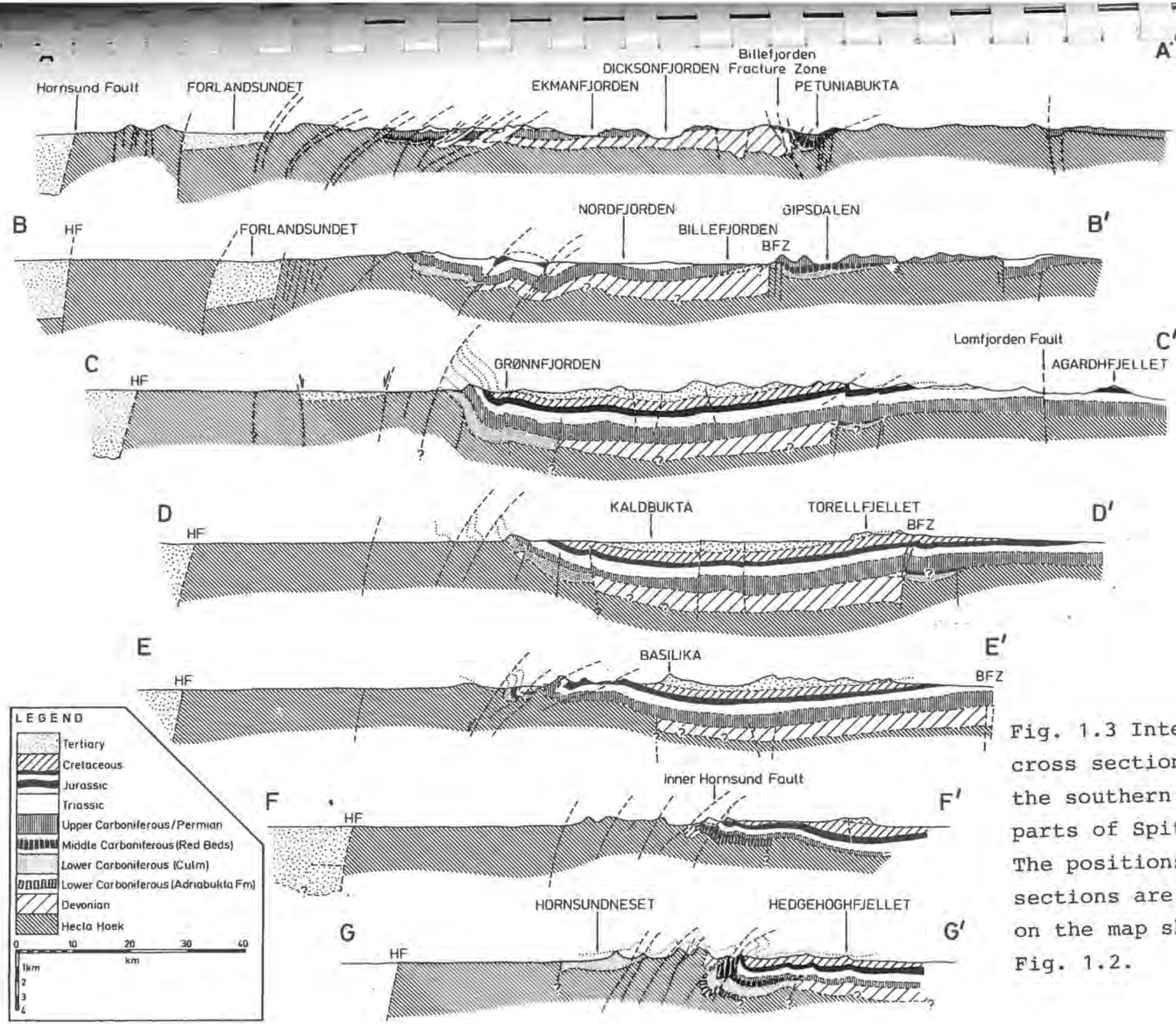


Fig. 1.3 Interpretative cross sections across the southern and central parts of Spitsbergen. The positions of the sections are indicated on the map shown in Fig. 1.2.

and Gjelberg 1980. Other important contributions have been taken from Orvin 1940, Flood et al. 1971, Lowell 1972 and Sundvor and Eldholm 1979.

An improved understanding of the main structural and tectonic elements on Spitsbergen has been obtained by study of landsat photographs and topographical and morphological lineaments which have been mapped (Fig. 1.4.). There is an obvious bimodal distribution of lineaments in the Hecla Hoek basement (especially in Ny Friesland and along the west coast) with a dominating N-S, NNW-SSE orientation, and a less dominating E-W, ENE - WSW direction, reflecting a conjugate system. The west coast Hecla Hoek shows a slightly different orientation of the lineaments compared to that of Ny Friesland, manifested with a slight anticlockwise rotation. This may confirm the suggestion of Birkenmajer (1981) that the westernmost part of Spitsbergen has been moved (some 30 km) northward and slightly rotated with respect to the rest of the area. Another significant trend in the topographic lineaments is the dominating NW-SE trend present in the Mesozoic and Cenozoic cover. It is probable that this is a result of late reactivation of basement "fractures" which have this particular orientation, and which seem to be more or less parallel with the Spitsbergen Fracture Zone (eg. Vogt et al. 1981). It is probable that they are related features, and that the strain that developed along the fracture zones transmitted into Spitsbergen.

REGIONAL PALAEOGEOGRAPHIC SETTING

During early to middle Carboniferous time Svalbard was located close to the northwestern corner of Greenland, east of Ellesmere Island, (eg. Harland 1969). The palaeolatitude for Svalbard was, during Early Carboniferous, some degrees south of 20°N, whereas the Middle Carboniferous it was just south of 30°N (eg. Seyfert and Sirkin 1979, Irving 1977, Steel and Worsley 1984), reflecting gradual northward motion of Laurasia

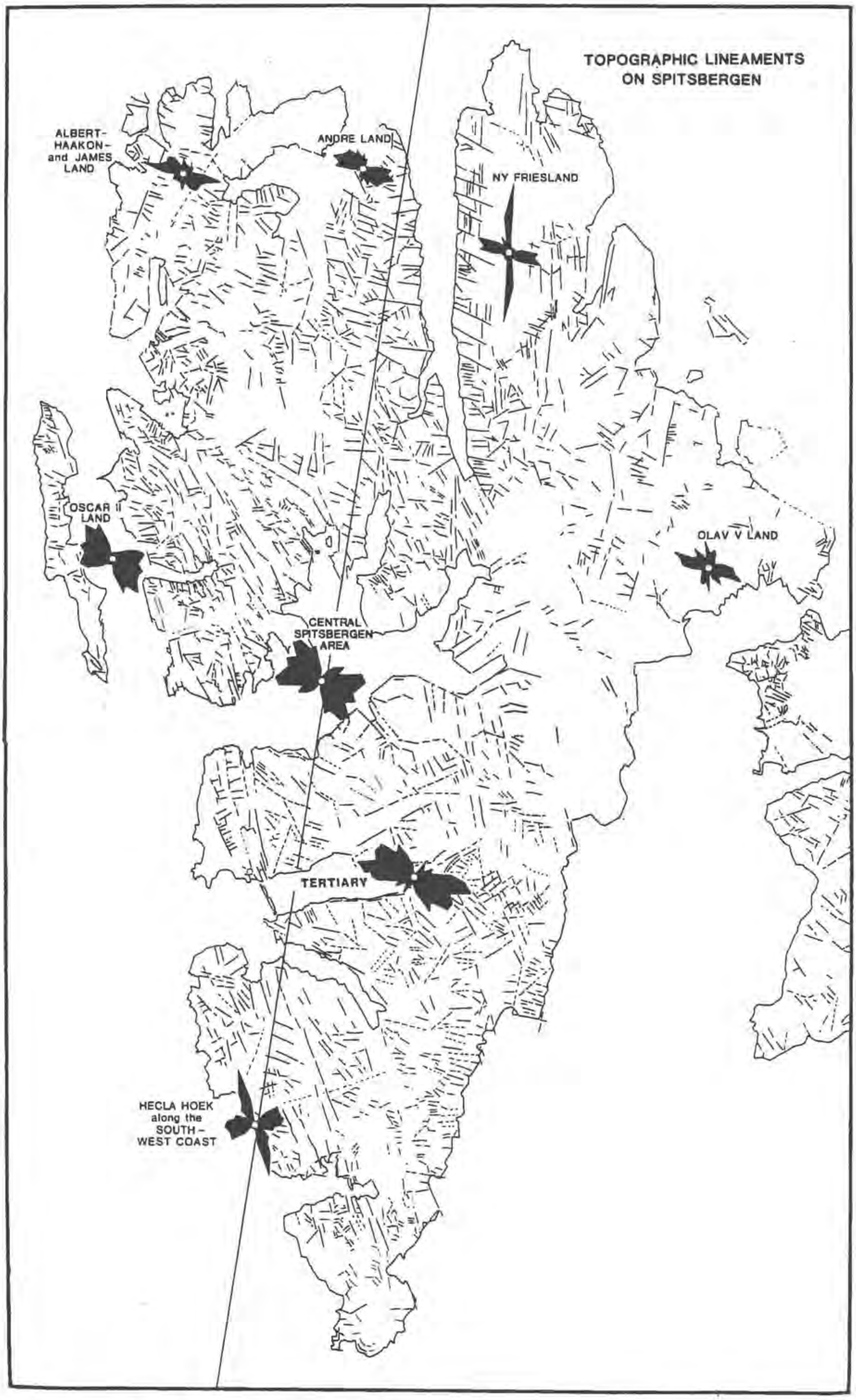


Fig. 1.4. Topographic lineaments on Spitsbergen obtained by study of Landat photographs.

MAIN CARBONIFEROUS TECTONIC ELEMENTS

Figure 1.5 shows the main palaeotectonic elements on Svalbard during early -middle Carboniferous time. Most of these elements have already been defined by Cutbill and Challinor (1965). The terms "Inner Hornsund Trough" and "West Bjørnøya Fault Zone" have been defined by Gjelberg and Steel 1983. The "Wedel Jarlsberg Block", however, is a new term, introduced here. It represent an extensive area between Van Keulen-Fjorden and Hornsund where the Lower-Carboniferous succession is completely missing.

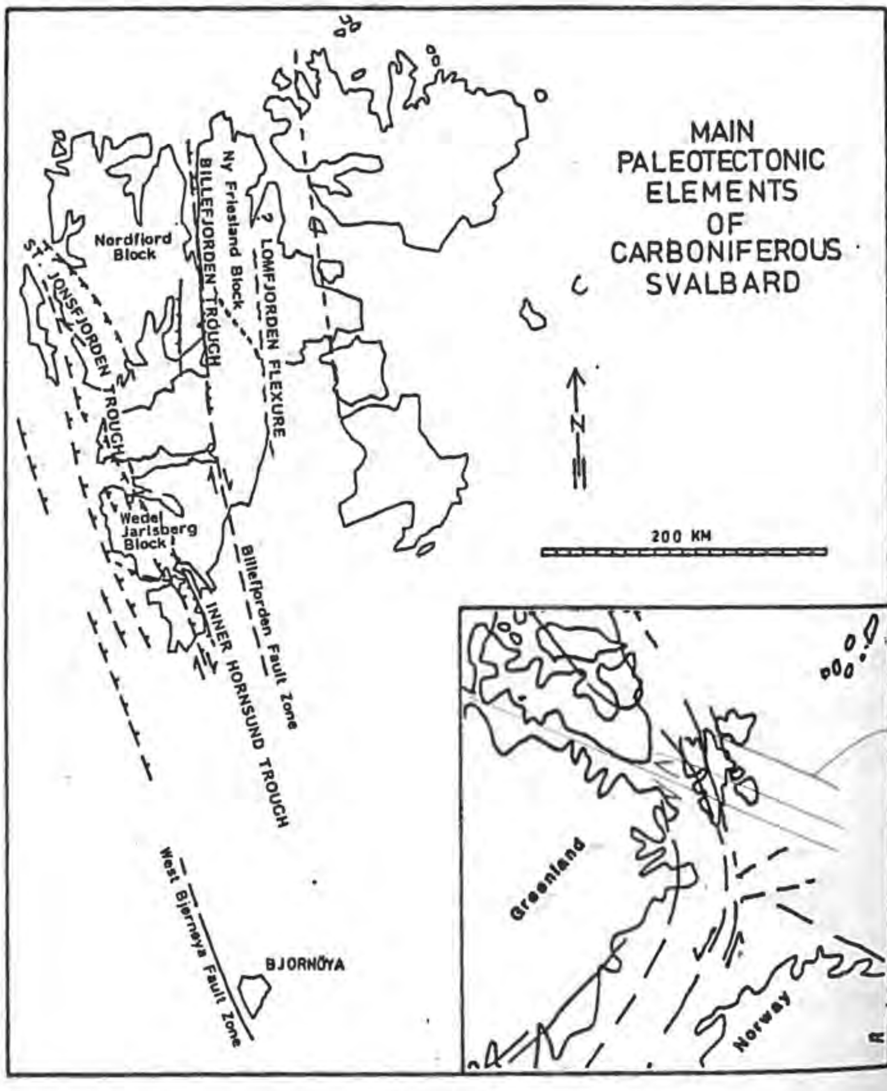


Fig. 1.5 Main palaeotectonic elements of Lower-Middle Carboniferous, Svalbard.

III. 2

LOWER - MIDDLE CARBONIFEROUS SUCCESSION
OF
THE HORNSUND AREA

INTRODUCTION

The Lower and Middle Carboniferous outcrops on Hornsundneset, around Inner Hornsund and Central Sørkapp Land have been studied in an effort to document sedimentological facies and to reconstruct basin development. A generalized stratigraphic column of the studied succession in Central Sørkapp Land is shown in Figure 2.1. The succession consists of 5 formations which span a time interval from Tournaisian to (?) Moscovian. These are: The Adriabukta Fm. (Tournaisian-Namurian), Hornsundneset Fm. (Namurian), Sergeijevfjellet Fm. (Namurian), Bladegga Fm. and the Hyrnefjellet Fm. (?Bashkirian - Moscovian).

Most of the recent published work from the area comes from Polish geologists. A review of the literature is presented within the successive descriptions of the formations below likewise also the stratigraphic and tectonic setting. The importance of the Inner Hornsund Fault Zone will be stressed here, because this zone contains most of the important exposures of the successions. A geological map of the Inner Hornsund Area is shown in Figure 2.2, and three cross sections, showing the nature of the fault zone are shown in Figure 2.3. Although due to the West Spitsbergen Orogeny these faults are now thrust faults. It is suggested that the thrusting occured along zones of crustal weakness, old normal faults, where tectonic activity had already been important in Carboniferous time, and probably earlier.

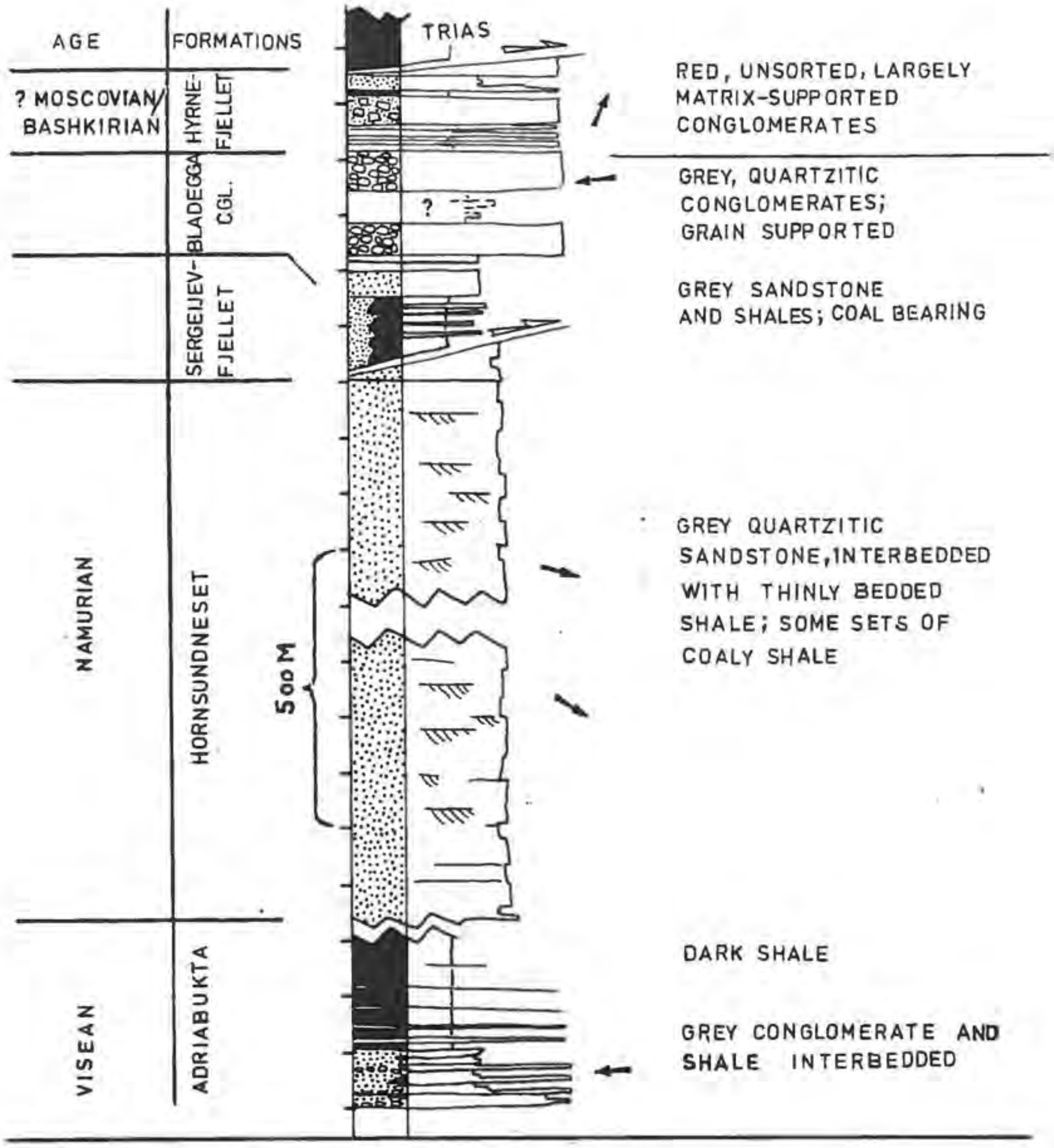


Fig. 2.1. Generalized stratigraphic column of the Lower-Middle Carboniferous succession from the south side of Inner Hornsund.

ADRIABUKTA FORMATION

AGE, STRATIGRAPHY AND TECTONIC SETTING

The Lower Carboniferous deposits in Inner Hornsund, known previously as "Wijde Bay Series" (Devonian) were distingushed, described and illustrated by Birkenmajer and Turnau (1962), who applied the term Adriabukta Series. Cutbill and Challinor (1965) gave the sequence formal formation status. Spore analysis carried out by Birkenmajer and Turnau (1962) on dark shales from the Adriabukta Fm. suggests an early Carboniferours (probably Visean) age for the rocks. Birkenmajer and Turnau (1962) concluded that the rocks were separated by unconformities from the underlying Devonian and Hecla Hoek and from the overlying possible Middle Carboniferous (Hyrnefjellet Fm.). This conclusion is based mainly on studies from the north side of Hornsund, but can be contested, as shown below, from analysis of the sequences on the south side of Hornsund.

Most of the Adriabukta Fm. is strongly disturbed tectonically and it is difficult to establish the stratigraphic sequence. Birkenmajer and Turnau (1962) distinguished two different units: The lower, autochtonous, which occurs in the western part of Adriabukta and the upper allochtonous which was traced from the SW slopes of Hyrnefjellet down to the shore (Fig. 2.4). In the autochtonous unit the Adriabukta Fm. overlies the Devonian Upper Marietoppen Series of Birkenmajer (1964), while it in the allochtonous unit overlies the Hecla Hoek Gåshamna Series (Fig. 2.4). The allochtonous tectonic unit is, according to Birkenmajer (1964, 1981) most likely due to overthrusting from the east. This suggested overthrusting occurred at the same time as more extensive folding and slight dynamic metamorphism of the Lower Carboniferous shales.

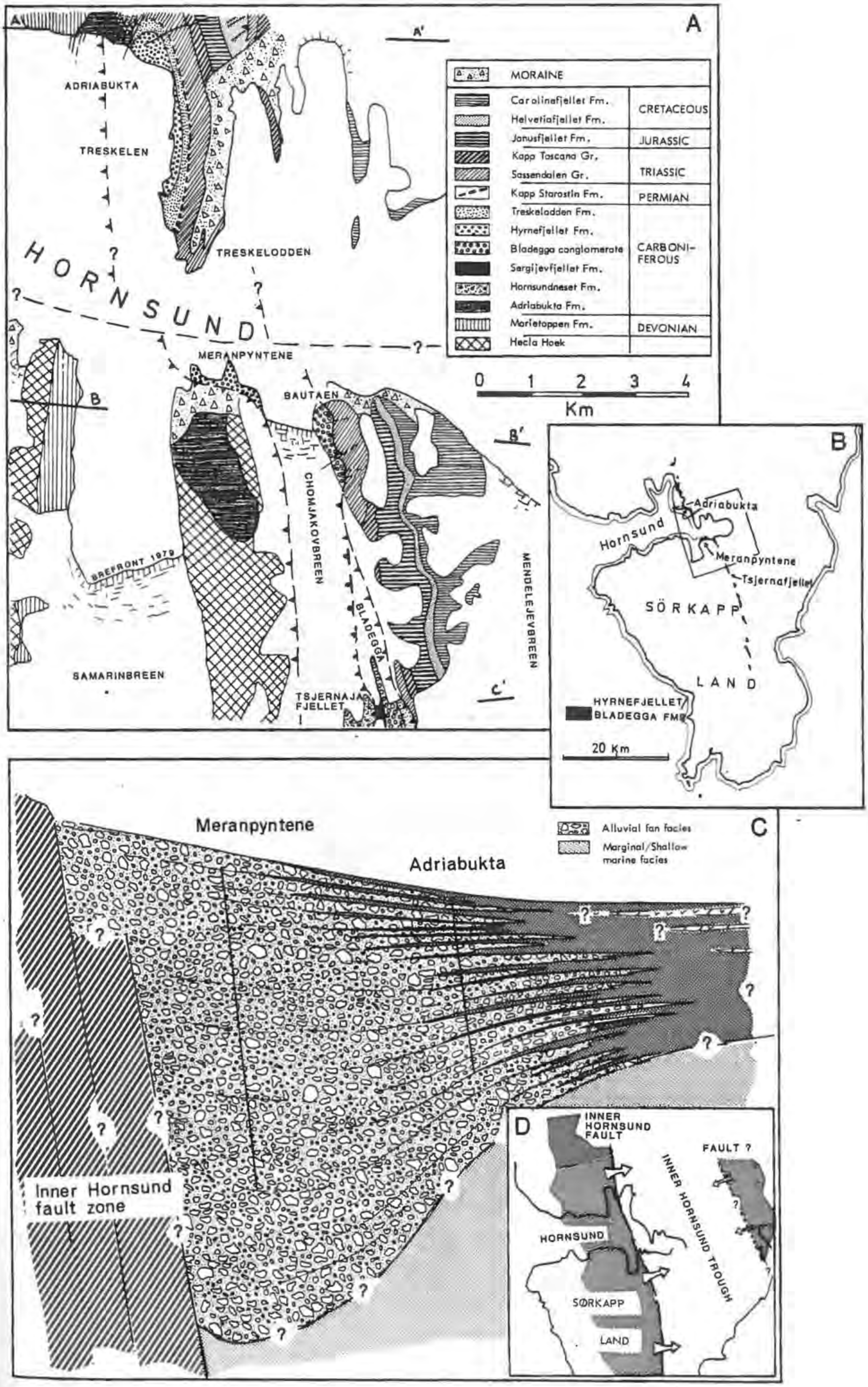


Fig. 2.2. Geology of the Inner Hornsund area.

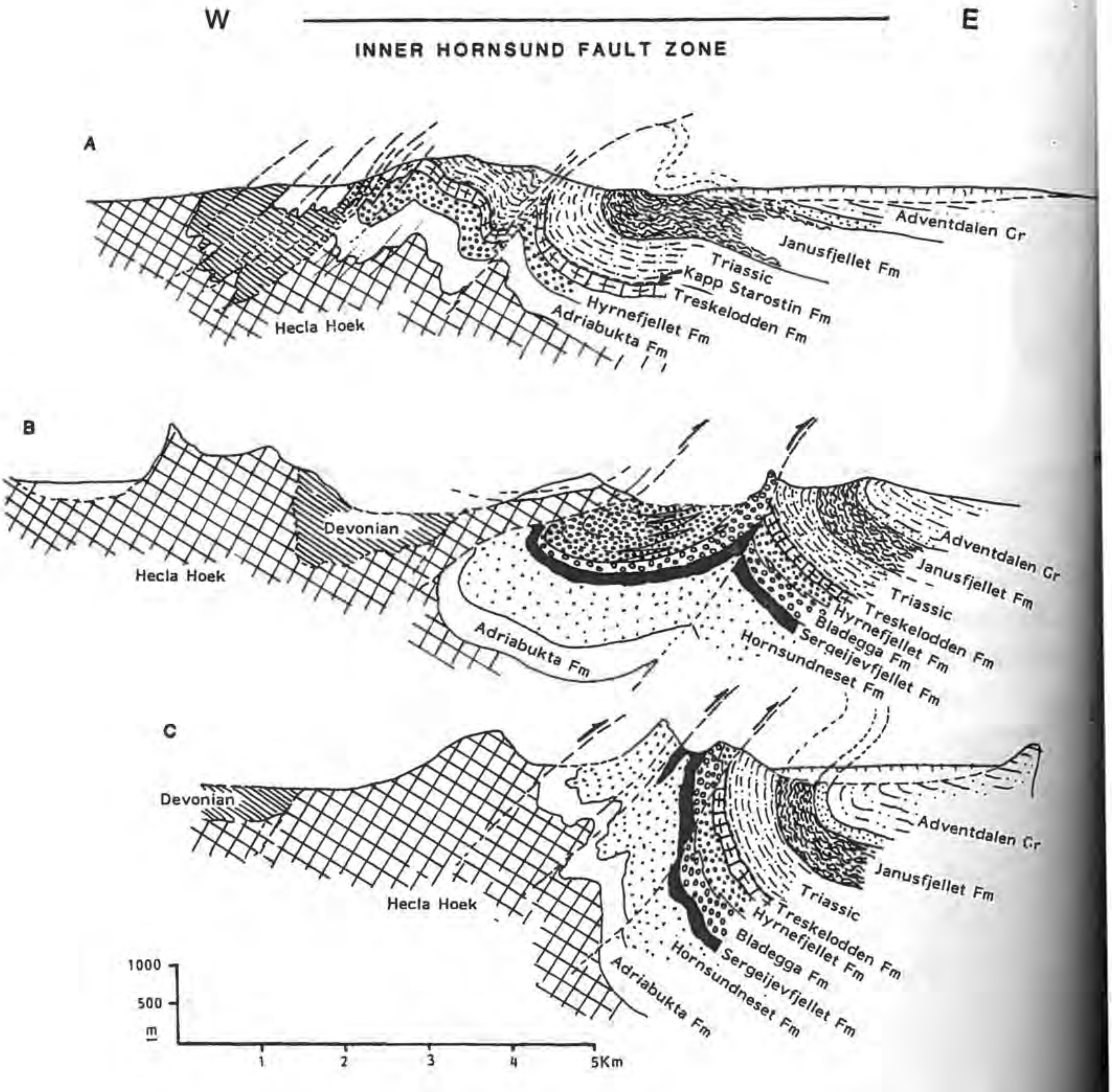
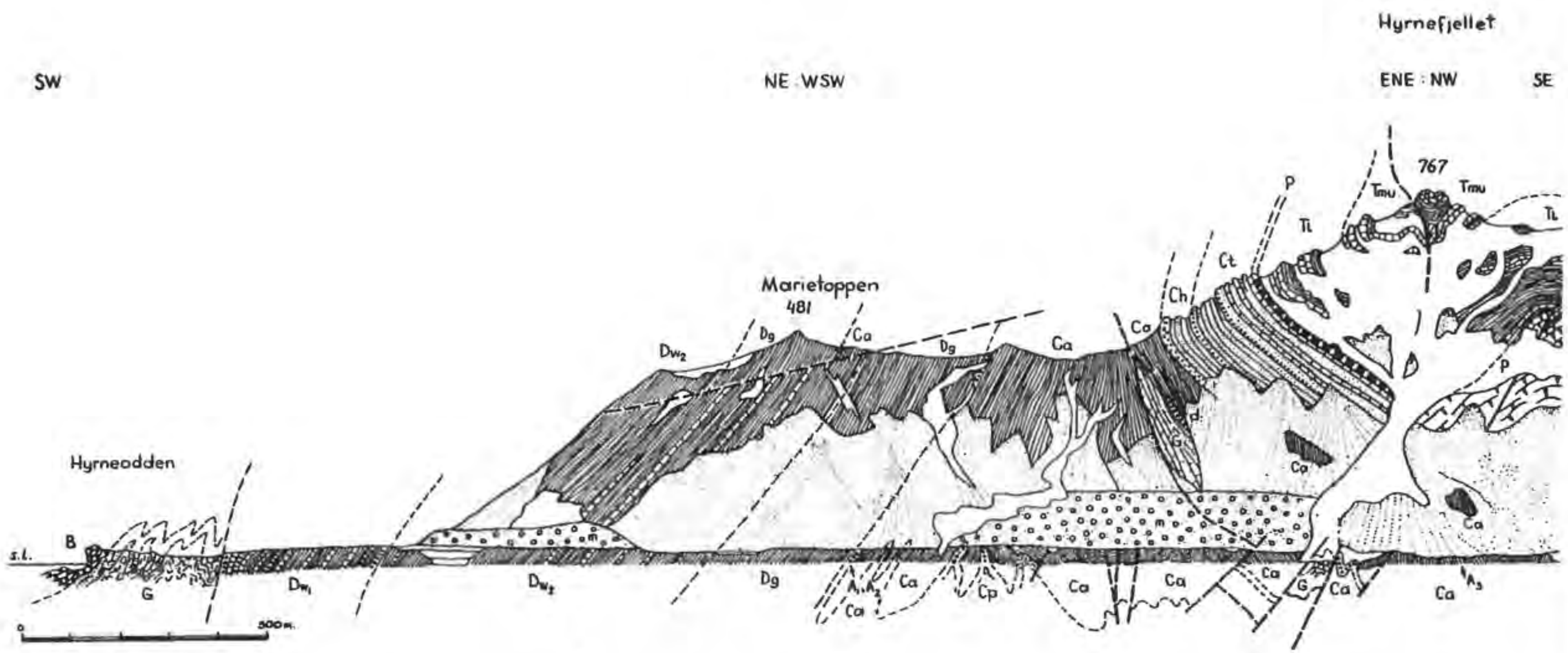


Fig. 2.3. Cross sections from the Inner Hornsund area. The positions of the cross sections are shown in Fig.2.1.



G – Gåshamna Series (Eocambrian); B – Blåstertoppen Dolomite (Lower lower Cambrian?); Dw_1 – Wood Bay Series (Keltiefjellet Division?); Dw_2 – Wood Bay Series (Stjørdalen Division?); Dg – Probably Grey Hoek Series; Ca – Adriabukta Series (Lower Carboniferous, probably Visean); Ch – Hyrnefjellet Beds (probably Middle Carboniferous); Ct – Treskelodden Beds (Upper Carboniferous-Lowermost Permian?); Brachiopod Cherty Limestone (Upper Permian); Tl – Lower Trias; Tmu – Middle and Upper Trias; d – dolerites (sills); A_1, A_2, A_3 – Localization of samples for spore investigations; m – moraines; s. l. – sea level; scree and talus cones dotted.

Fig. 2.4 The geology of the Hyrnefjellet/Adriabukta and Hyrneodden area (from Birkenmajer and Turnau 1962).

Birkenmajer (1964) correlated this deformation with the Erzgebirge Phase. Further discussion of the regional palaeotectonic setting is given in the summation, Part IV.

In addition to the type locality in Adriabukta, the formation is present for certain only at one other locality just north of Hornsund (between Loranbreen and Urnebreen, ca. 2,5 km north of Adriabukta). However, it outcrops at several localities south of Hornsund, along the Inner Hornsund Fault zone where it is conformably overlain by the Hornsundneset Fm. Recently, relatively thick units of black shale have been recorded from the Reinodden area, (S. Bellsund) and it is suggested that these shales may be equivalent to the Adriabukta Fm (Yen Sun, 1980).

The Adriabukta Formation has been described by Birkenmajer and Turnau (1964) who assumed that the rocks have been deposited in a part of an Early Carboniferous sedimentary basin more distant from the source area of clastics than the remaining formations of the same age in Svalbard.

Facies analysis has been made to get a better understanding of the nature and extension of this basin. This analysis (see below) is based mainly upon data collected from the type profile in Adriabukta (Fig. 2.5). As already mentioned, the stratigraphic sequence is very difficult to establish, due to intense folding and faulting, and the absolute thickness of the formation is unknown. An approximate thickness of 300 m is, however, suggested for the type profile.

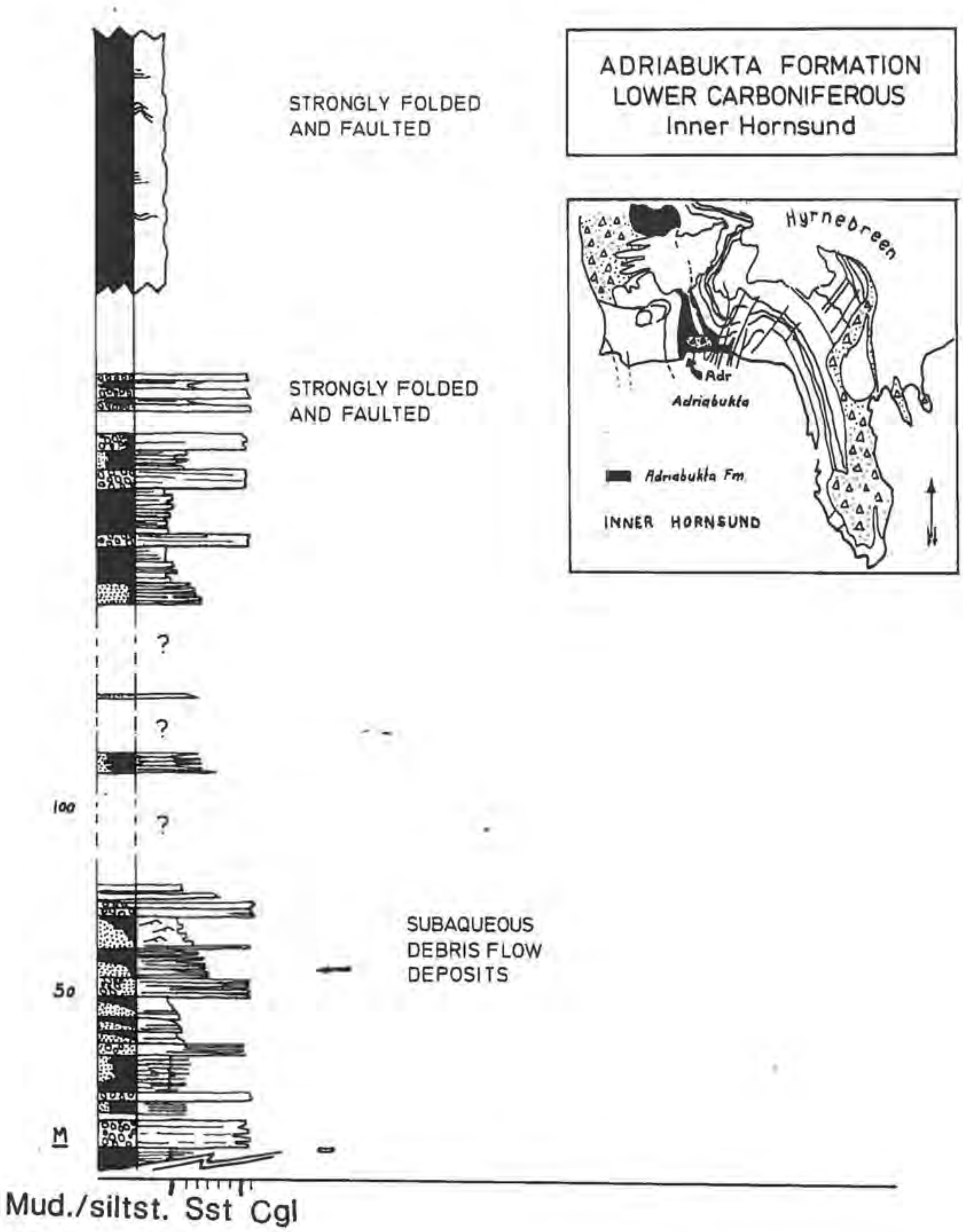


Fig. 2.5 The Adriabukta Fm. section as it appears along the shore of Adriabukta. The section represents the lowermost part of the Formation. It is still uncertain whether the conglomerates in the upper part of the section represent the same stratigraphic level as the lowermost conglomerates, as suggested by Birkenmajer and Turnau 1962, and Birkenmajer 1964 (See also Figure 2.4).)

FACIES DESCRIPTION

Seven different facies or combinations of lithofacies have been distinguished, mainly from the lower part of the formation.

Facies A - Facies A was recorded only at a few localities, and it consists of grey, relatively coarse, mainly matrix-supported conglomerates of subangular (rarely subrounded) quartzitic pebbles, up to 8 cm in diamter. The matrix is sandy, and usually poorly sorted. Characteristic of beds of this faceis is that they show no internal organization such as grading or sedimentary structures (Fig. 2.6). A maximum set thickness of 80 cm has been recorded. The facies is associated with sandstones and shales of Facies D and E (see below).

Facies B - Facies B consists of grey conglomerates, mainly grain-supported, with pebbles of subangular and subrounded quartzites. The maximum particle size is mainly the same as for facies A (5-8 cm). Thin sets of mudstone and siltstone are present between some of the sets, which may be superimposed to form relatively thick units. Sets are usually normally or inverse/normally graded. Some of the inversely graded sets show a clear tendency for increasing matrix upwards, the upper part of which contains zones of matrix-supported conglomerates (Fig. 2.6).

Facies C - Normally graded sandstone and pebbly sandstone dominate Facies C. Individual sets often grade up from thin zone of pebbly sandstone (maximum particle size <2 cm) into very fine sandstone (Fig. 2.6). Poorly developed cross-stratification and contorted lamination are present in the upper part of a few sets. Various types of sole structures (mainly flute casts and tool marks) are present. Individual sets are often overlain by thin mudstone and siltstone strata.

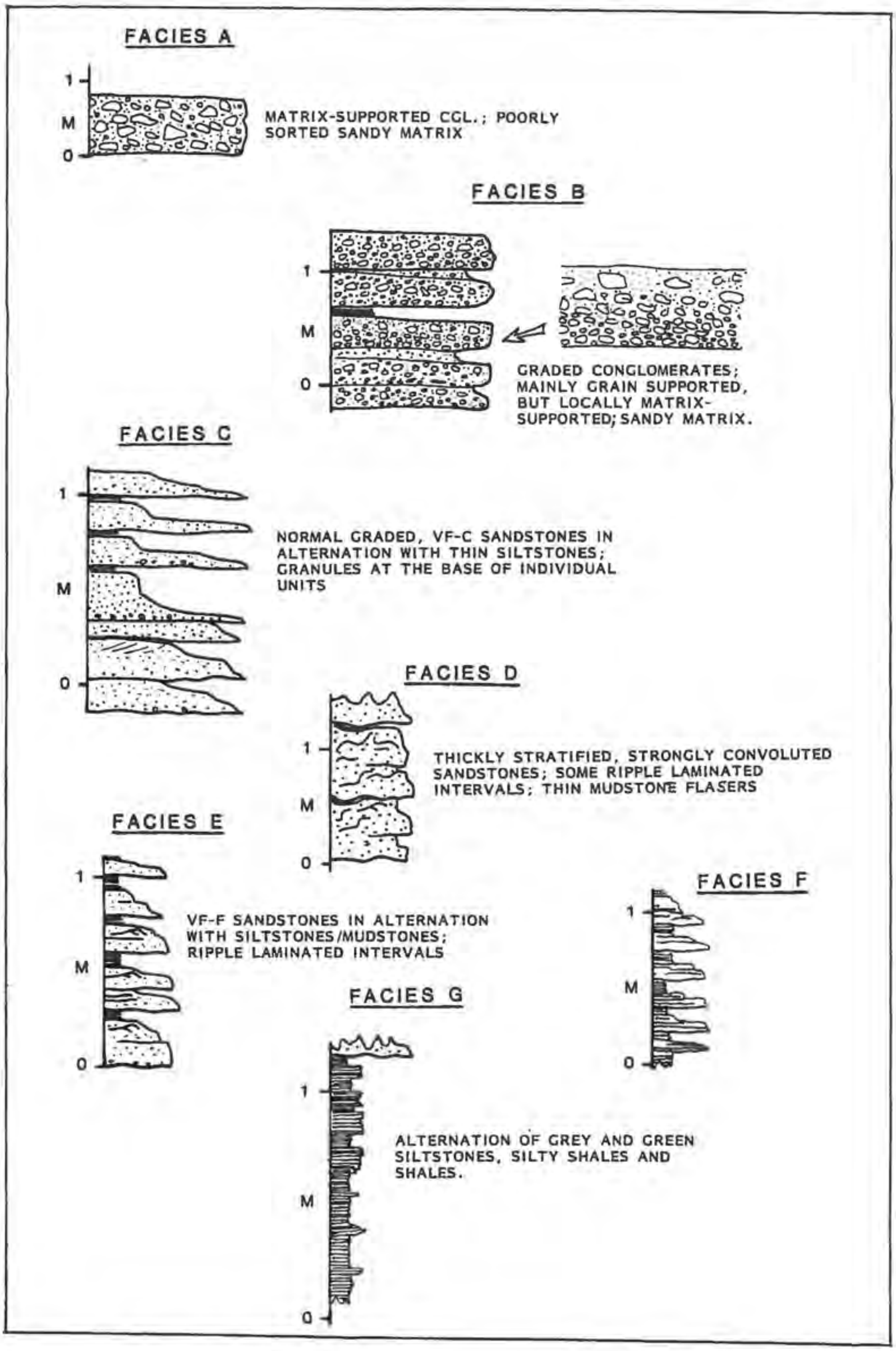


Fig. 2.6. Lithofacies and lithofacies sequences commonly present in the Adriabukta Formation.

Facies D - Grey, very fine and fine-grained greywackes are the dominating lithologies of Facies D. The sandstones commonly are massive probably due to intense soft sediment deformation, but ripple lamination may still be recognized in some intervals. There is some tendency for fining upwards within some individual sets, but most commonly there are no such trends. The set thickness ranges between a few centimeters to nearly hal a meter. Thin drapes of mud and siltstone are occasionally preserved between and scarcely within sets (Fig. 2.6).

Facies E - Facies E is characterized by a rhythmic chang between fine/very fine sandstone and siltstone/shale. The majority of the sandstones are massive but ripple laminated intervals are present in the upper part of som sets. The sandstone strata are slightly thicker than th shales, but none of the lithologies are clearly dominating. The thickness of the sandstone sets usually ranges between 5 and 25 cm. Most of the sandstones are fining upwards from fine sandstone through siltstone and mudstone.

Facies F and G - Facies F and G have a common characteristic in that they consist of a rhythmic interstratification of fine-grained lithologies. Facies F represents an interstratification of thin sets of very fine sandstone with thicker sets of siltstone and shale, while Facies G generally consists of greenish, black shales and siltstones, which dominate the upper part of the formation. There is a gradual transition between Facies F and G.

VERTICAL DEVELOPMENT

Most of the coarse-grained facies in the autochtonous unit appear within the lowermost 80 m of the formation where sandstone, shale and conglomerates occur in a complex association. Sandstones and conglomerates are present also in other localities along the shore of Adriabukta, but it is difficult to establish their exact stratigraphic position. Birkenmajer (1964) suggested that all the coarse-grained facies represent the basal part of the formation which have been repeated several times along the shore of Adriabukta due to intense folding (Fig. 2.4). It is, however, suggested here that within the lowermost 80 m of the Adriabukta shore profile such repetition is not present. This suggestion is made because there is no significant similarity between the vertical arrangement of facies within the different conglomeratic intervals, and no tectonic evidence for such close folding as that suggested by Birkenmajer (1964) has been identified. It is therefore probable that, at least the lowermost 80 m of the auchtonous unit consists of shales and siltstones with several interfingering lobes of conglomerates and sandstones. The lobes of conglomeratic material wedge out laterally and disappear over a distance less than 500 m (as very little of these facies are present along the edge of Hyrnefjellet, which represents a lateral equivalent to the exposures along the shore of Adriabukta).

The upper and middle part of the formation consist of dark grey shales, somewhat phyllitized and strongly folded and faulted. Thinly bedded, dark green, fine-grained sandstones and siltstones, showing sometimes normal grading are interstratified within the shales with variable frequency. Some of the thickest sandstone sets may be more than 50 cm thick.

Generally the coarsest facies (Facies A-E) are concentrated in the lowermost part of the formation, whereas the fine-grained sediments (Facies F and G) make up the majority of the formation. Fine-grained facies are, however, also present in the lower part. At the base of the formation there is a distinct shale unit

(0,7 m thick) which contains poorly preserved bivalves (Birkenmajer and Turnau 1962). This unit also contains trace fossils which are preserved as moulds at the base of an overlying sandstone set (of the Facies C type). These moulds probably represent resting traces of some arthropods.

Plant fragments are common at several intervals of the formation.

OVERALL INTERPRETATION AND PALAEOGEOGRAPHY

There are no signs of subaerial exposures in the formation, and the coarse facies may be explained in terms of subaqueous sediment gravity flow. Facies A and B probably represent subaqueous debris-flows. The conglomerates do not have the clast-supported finer cappings which are characteristic of subaerial debris-flow deposits (e.g. Bull 1972, Larsen and Steel 1978, Nemec et. al. 1980) and the associated facies have the character of "proximal" turbidites rather than traction current deposits. There seems to be a close relation between the coarse-grained, matrix-supported conglomerates of Facies A, to the grain-supported types of Facies B, and all of the conglomerates correspond fairly well with the resedimented conglomerates of Walk (1978). The sediments of Facies A are thought to represent more immature stage of flow than the graded conglomerates of Facies B, which represents relative mature flows in which lateral and vertical clast size segregation existed, and where the main supportive ag was dispersive pressure and turbulence (c.f. Davies and Walker 1974). The inversly graded beds (Fig. 2.6) are thought to reflect sediment gravity flows in which dispersive pressure generated by clast collisions was main supporting factor (Bagnold 1954 a,b) and repre less turbulence than the normally graded beds.

Facies C and D probably represent classic turbidites, though, well-developed Bouma sequences were not recorded. The interstratified mudstones most likely represent deposition from suspension between episodes of gravity flows.

Facies E and F are probably thinly bedded turbidites and interstratified in relatively thick units of mudstone shale, deposited from suspension during long periods with no gravity flows.

The Adriabukta Formation was deposited in a subaqueous environment, where debris flows and turbidity currents were transport agencies for most of the coarse-grained sediments. The extension and form of the basin are not known, but the few palaeocurrent data recorded, suggest a source area to the east. It is also likely that the northward extension of the basin was partly limited by the Wedel Jarlsberg Block (Fig. 1.5), which probably acted as a structurally high area during most of the early Carboniferous time (Fig.5.1). The westward extension of the basin is completely unknown as no parts of the formation are preserved on the Hornsund-Sørkapp High. No attempt has been made to estimate or calculate the depth of the basin at the various stages of deposition, however, it is likely that the bottom conditions were rather anoxic at times (as seen by the presence of black shales, relatively rich in organic content).

Finally it may be pointed out that the Adriabukta Fm. has much more in common with the Culm of S.W. England and the Kulm of Germany than any other Carboniferous formations on Svalbard.

HORNSUNDNESET FORMATION

AGE, STRATIGRAPHY AND TECTONIC SETTING

The Lower Carboniferous deposits on Hornsundneset have been known since the investigations of Geer (1910). Further information was supplied by Orvin (1940) and by Major and Winsnes (1955). The first systematic investigations were made by Siedlecki (1960) who described the stratigraphic sequence and lithology in detail, and distinguished between the Hornsundneset Beds and the overlying Sergeijevfjellet Beds. Palynological investigations in the area were carried out by Siedlecki and Turnau (1964) who suggested, on the basis of microspore studies, a Namurian age of the succession. Cutbill and Challinor (1965) gave the Hornsundneset and Sergeijevjfellet Beds status as Formations.

The Hornsundneset Formation is exposed at several localities on Hornsundneset and in the area south of Gåshamna (Fig. 2.8). Beside these localities the formation is also present in the central area of Sørkapp Land where it outcrops along a line of south-eastward extension from Chomjakovbreen to Sørfonna (Fig. 2.2). I Sigfredbogen, on north-western Sørkapp Land, the Hornsundneset Formation overlies the Hecla Hoek succession (of Pre-Cambrian and Eocambrian age), with a marked angular unconformity. In the central area, however, the formation has an apparently concordant contact with the underlying Adriabukta Formation. The upper boundary of the Hornsundneset Formation is always concordant with the overlying Sergeijevfjellet Formati

The Lower Carboniferous of NW Sørkapplandet forms a f syncline (Fig. 2.7), dissected by NE-SW trending Tert faults.

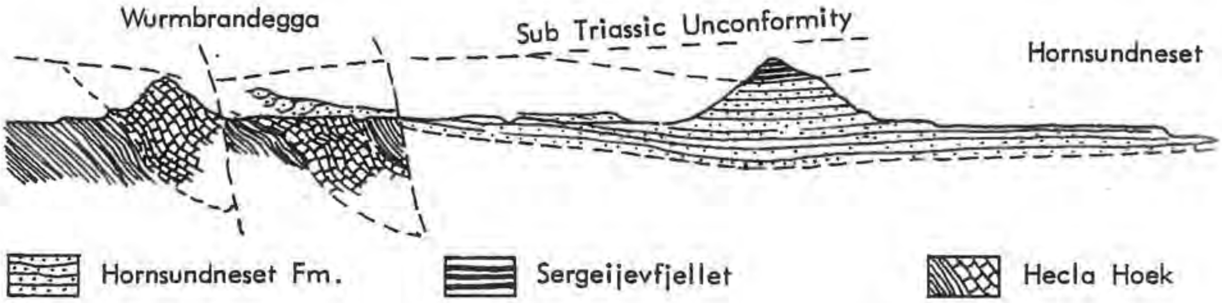


Fig. 2.7 Cross section from Hornsundneset, showing the stratigraphic and tectonic setting of the lower Carboniferous (Hornsundneset and Sergeijevfjellet Fms.) in the area. Modified from Birkenmajer (1964).

The folding and faulting are much more intense along the Wurmbrandegga, and in this area N-S orientated major reverse faults are the dominating structural elements (Fig. 2.7).

In the central Sørkapp Land area the formation is intensely folded along a prominent NNW-SSE trending fault zone (Fig. 2.3), defined as the Inner Hornsund Fault Zone by Gjelberg and Steel (1981).

GENERAL DESCRIPTION

A detailed lithological description of the Hornsundneset Fm. will not be given here, as all the facies also are typical for the Orustdalen Formation, and a more detailed description of the relevant lithofacies will be given in the next chapter.

The Hornsundneset Fm. is about 800 m thick at the type locality and probably up to 1500 m (estimated) in the central Sørkapp Land area.

At Sigfredbogen (on northern side of Hornsundneset) the contact beween the "Culm" and the underlying Hecla Hoek succession is exposed. In this location the Lower Carboniferous succession starts with a thin basal conglomerate (15 cm thick), and continues upwards (within the lowermost 3 m) with an alternation of massive and laminated, rusty-red and green shales, interstratified with a few sandstone and siltstone sets (Fig 2.9). Then follows a new conglomerate (20 cm thick) which is overlain by grey, quartzitic, fine and medium sandstone. The conglomerates in this basal part are orthoquartzitic in composition (mainly vein quartz). They are clast-supported but contain a muddy, organic-rich matrix. The maximum particle size rarely exceeds 3 cm. This is probably the succession which Birkenmajer (1964) tentatively referred to as Devonian, but which was doubted by Siedlecki and Turnau (1964).

It is not possible to measure a complete stratigraphic section in the Hornsundneset area, due to insufficient exposure. The stratigraphic section shown in Fig. 2.8 represents the lower part of the Hornsundneset Formation as it appears in the northern part of Hornsundneset. It is obvious that most of the formation consists of grey and white quartzitic sandstone varying in grain size from fine to coarse, though the medium grain fraction dominates. Conglomerates and fine-grained sediments constitute a very minor part of the exposed succession. It is, however, possible that sediments of the fine-grained association (siltstone, mudstone and shale) make up a larger part of the formation than that seen in the exposures, as such lithologies generally are less well exposed than the more resistant sandstones.

The most important sedimentary structures observed are, in order of importance: planar cross-stratification, trough cross-stratification and low angle or horizontal stratification. Certain intervals may, however, be massive or dominated by soft sediment deformation structures of various types. The set thickness of the cross-stratified units are highly variable. Giant sets are very rare, and only a few planar cross-stratified sets thicker than 2 m were recorded. A detailed stratigraphic sequence from the lower part of the formation is shown in Fig. 2.9. Birkenmajer (1964) argued the possibility that the wedge of shale and conglomerate preserved below the prominent sandstones in Sigfredbogen (Fig. 2.9) could be an erosional remnant of Devonian age. This was, however, doubted by Siedlecki and Turnau (1964). This study does not give an absolute answer to the problem as no palynological investigations have been made.

A common feature for most Lower Carboniferous sandstones and conglomerates on Spitsbergen is that they are usually strongly silica-cemented. This is also the case for the Hornsundneset Formation, but some intervals of the formation (usually only a few m thick) are remarkably poorly consolidated (Fig. 2.9).

Such intervals have often a yellow, rusty colour, and it is suggested that the poor consolidation is a result of solution of the primary cement which originally was probably some type of carbonate. The diagenetic history, however, is beyond the scope of this study.

No indications of marine or brackish water conditions were recognized from the formation. Fossil plant fragments (Sigmaria and stems of Lepidophyta) were occasionally recorded. (See also Siedlecki 1960).

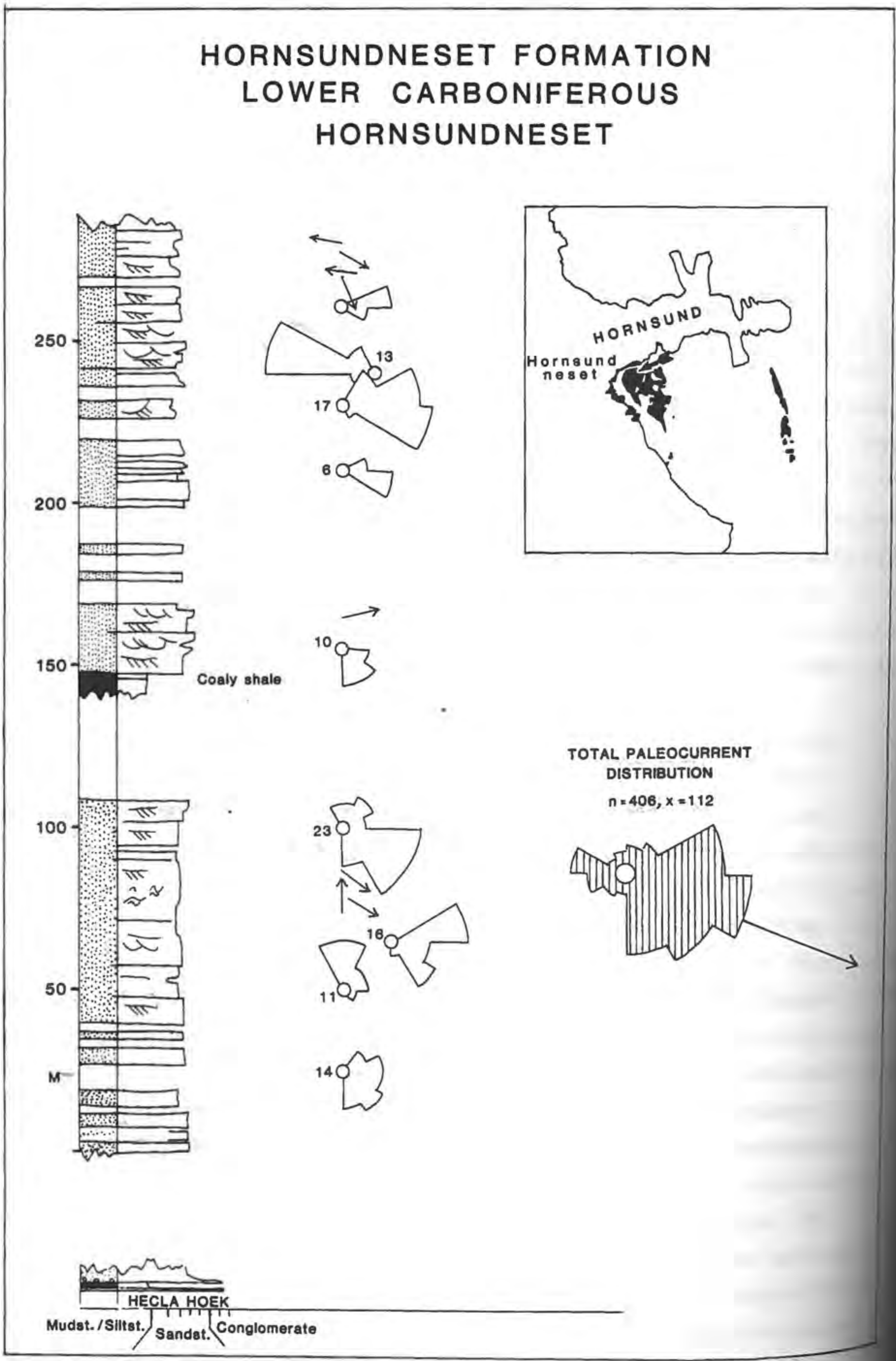


Fig. 2.8 Stratigraphic section and palaeocurrent distribution from the lower part of the Hornsundneset Fm. on Hornsundneset.

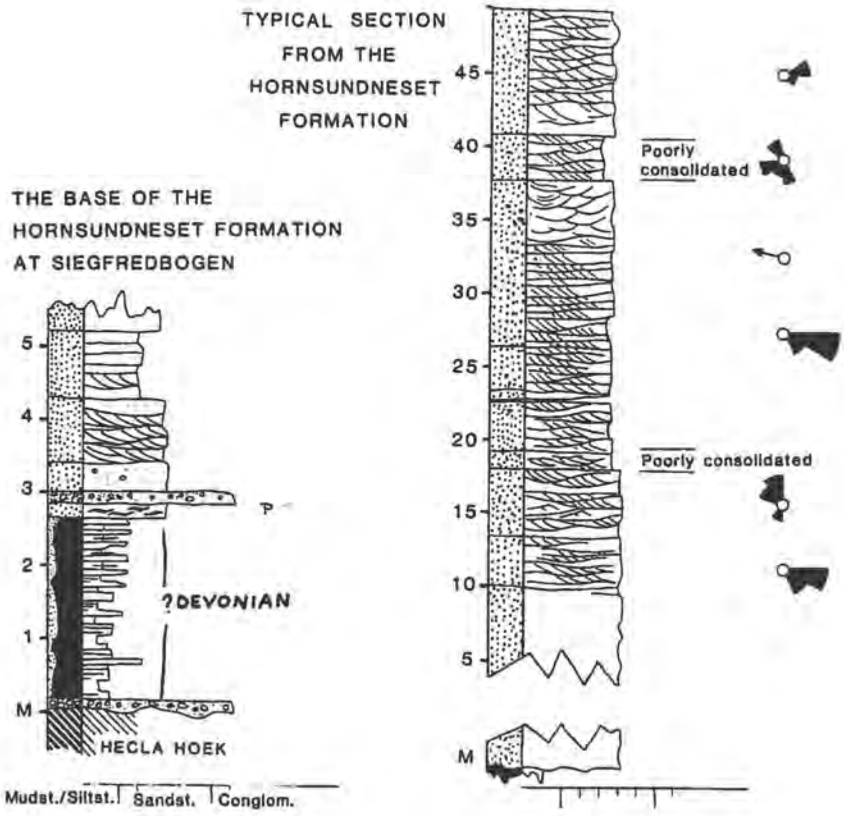


Fig. 2.9. The section to the left shows the base of the Hornsundneset Fm. of Sigfredbogen. The section to the right shows a typical portion of the Hornsundneset Fm.

OVERALL INTERPRETATION AND PALAEOGEOGRAPHY

Using the same arguments as used for the Nordkapp Fm. on Bjørnøya (Gjelberg 1981b) and for the Orustdalen Fm. in the central western part of Spitsbergen (see section III.3) the Hornsundneset Fm. probably originated as braided stream deposits.

Using Miall's (1977) classification of braided stream deposits most of the Hornsundneset Formation appear to be of the Platt River type, i.e. a relatively distal development, in which large bars and sandwaves rather than dunes are the dominant bedforms. Some intervals, however, especially in the middle part of the formation are more comparable with the Facies Assemblages of Rust (1978), which represent proximal sandy braided rivers and alluvial plains formed in an environment where gravel is not available. Such sequences are characterized by the dominance of low angle (or horizontal) stratification and trough cross-stratification.

A total of 406 palaeocurrent measurements (mainly from planar cross-stratifications) were recorded from different stratigraphic and geographic locations. Statistics from this data are shown in Figure 2.8. At the base of the figure all palaeocurrent data are collected in one diagram (30° intervals). The azimuth of the resultant vector ($\bar{x}$) gives a mean palaeocurrent direction of 112°, and a source area to the west or northwest is consequently suggested. This corresponds fairly well with the palaeocurrent observations made by Birkenmajer (1979) from the area around Sigfredbogen.

SERGEIJEVFJELLET FORMATION

AGE AND STRATIGRAPHY

The Sergeijevfjellet Formation, first defined as the Sergeijevfjellet Beds by Siedlecki (1960) and later given formation status by Cutbill and Challinor (1965), concordantly overlies the Hornsundneset Fm. in the central Sørkapp Land area (Fig. 2.10) and on Hornsundneset. In the central area of Sørkapp Land it is overlain by the prominent Bladegga Formation (Fig. 2.12), whereas on Hornsundneset it is truncated by the sub-Triassic unconformity (Fig. 2.7).

Microspore studies carried out by Siedlecki and Turnau (1964) suggested a Namurian age for the formation.

GENERAL DESCRIPTION AND FACIES SEQUENCES

The Sergeijevfjellet Formation (Fig. 2.10), consists generally of grey, strongly silica-cemented quartzitic sandstones and relatively thick sequences of grey shales, mudstones and siltstones which are interbedded with thin sandstones, coaly shales, coals and horizons of clay ironstone (siderite). The formation is very similar to the Vesalstranda Memeber on Bjørnøya (Worsley and Edwards 1976, Gjelberg 1978) and to the Vegard Fm. on Oscar II Land, both with respect to lithology and development of facies sequences.

Fining upward sandstone sequences - These sandstone sequences which range between 6 and 18 m in thickness, are composed mainly of medium and coarse quartzitic sandstone, typically sharply based, often erosional. Each sequence shows a gradual transition upwards to the overlying, often coaly mudstones and siltstones. Trough and planar cross-stratification together with low-angle, or horizontal stratification dominate. However, very often primary sedimentary structures are difficult to detect and the sandstones appear massive.

There are many points of resemblance between the thinnest of these fining upwards sandstone sequences and the sandstones of Facies Association A of Vesalstranda Member (Gjelberg 1978) and a similar interpretation is suggested (i.e. point bar deposits of high-sinuosity streams).

The thickest sequences (from 12-18m) are, however, much more complex in their vertical development, and it is probable that they represent stacked point bar deposits, similar to those below the A-coal seam of the Tunheim Member on Bjørnøya (Gjelberg 1982), or braided stream

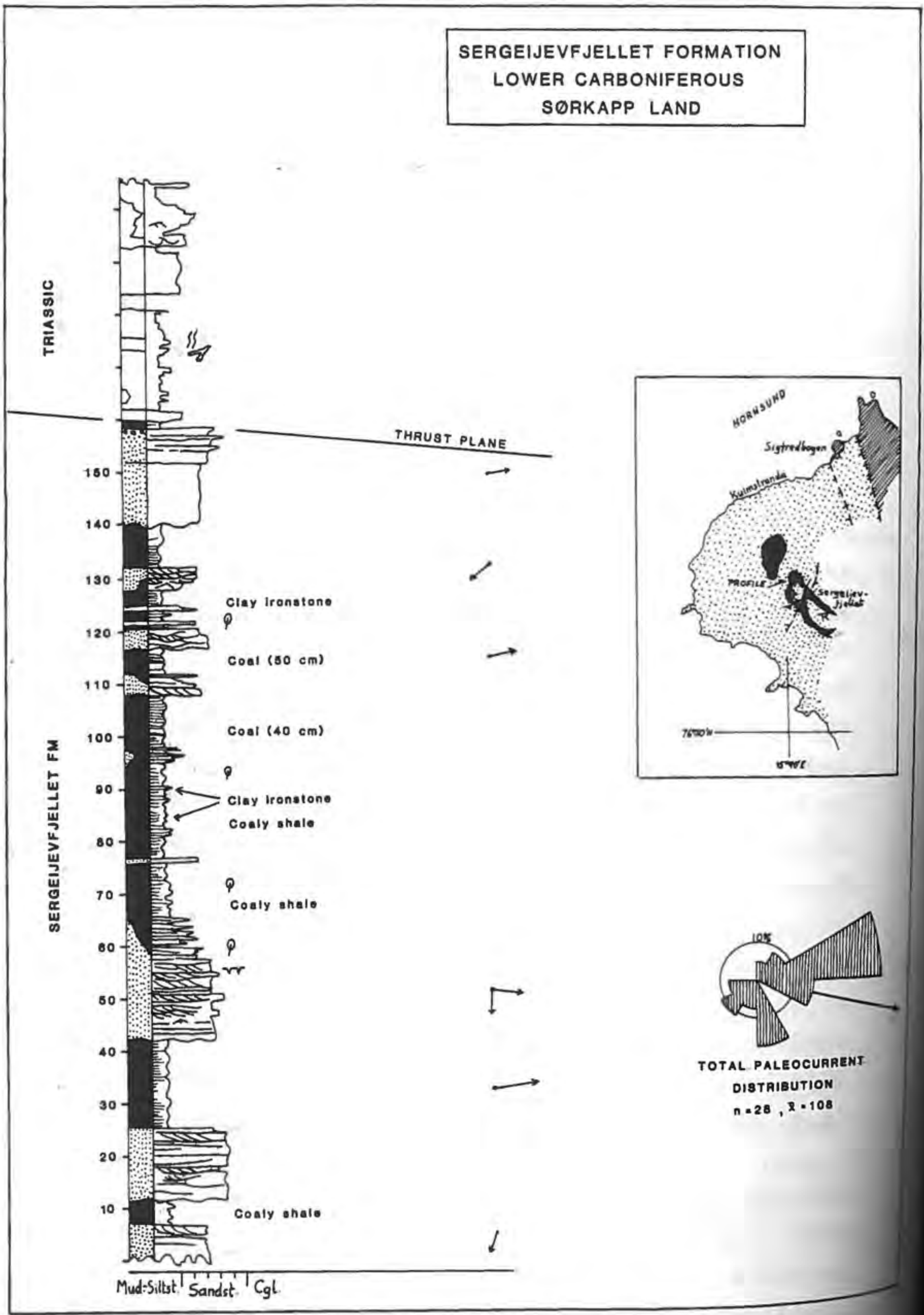


Fig. 2.10 Stratigraphic section from the Sergeijevfjellet Formation on Sergeijevfjellet, NW Sørkapp Land.

deposits, where the upwards fining reflects the gradual abandonment of a segment of the braid plain (eg Rust 1978). The latter interpretation is consistent with the fact that there is a gradual transition between the braided stream-dominated Hornsundneset Fm. below, to the Sergeijevfjellet Fm., particularly as the thick, complexly stratified sandstone sequences usually occur in the lower part of the Sergeijevfjellet Fm.

The available data are, however, insufficient to make further speculation about this.

Coarsening upward sequences - Such sequences are of about the same scale and configuration as the sequences described as Facies association D of the Vesalstranda Member. They were recorded both from the type profile (only one example) and from the Inner Hornsund area (Fig. 2.12). The sequences, which range in thickness from less than a meter to 6-7 meters, show a clear coarsening upward tendency from mudstone (at the base) to medium sandstone in the upper part. Fossil plant root horizons are often present in the topmost part of sequences.

By using the same arguments as for Facies association D (Vesalstranda Member) it is suggested here that these sequences are a result of outgrowth of delta lobes into more or less standing water bodies or lakes. Sand may have been transported into the lacustrine environment directly by the main distributary channels or by smaller scale, crevasse channels. No indications of marine influence have been recorded.

Interstratified sandstone, siltstone/mudstone sequences
These sequences are present only at two localities in the Hornsundneset profile, and the most distinct of them are shown in Fig. 2.11. Characteristic of these sediments is a rythmic alternation between thin, evenly bedded, grey (and white), very fine sandstones and thin, finely laminated, grey siltstones/mudstones.

The sandstones may be plane/parallell laminated and ripple laminated, but most commonly sedimentary structures were not obvious.

These sequences correspond well with the Facies association B2 of the Vesalstranda Member, interpretated as levee deposits. This is also confirmed by the fact that one of the sequences is directly connected with channel sandstones (Fig. 2.11).

Fine-grained facies sequences - Thick sequences of grey/blackish-grey, thinly laminated and blocky mudstones and siltstones with thin, sharply based fine/very fine sandstones and coals, dominate thick intervals of the formation (Fig. 2.10). The coal seams reach a maximum thickness of 50 cm in the type profile, while the interstratified sandstones average 30-40 cm. Occasional plant fossils, preserved as imprints of stigmaria and carbonized leaves (of Cordaites?) were recorded.

These facies sequences show mainly the same development as Facies association B1 of the Vesalstranda Member, and the critical features by which this association was interpretated (Gjelberg 1978) are also present here. Consequently they are interpretated as flood-basin/flood plain deposits.

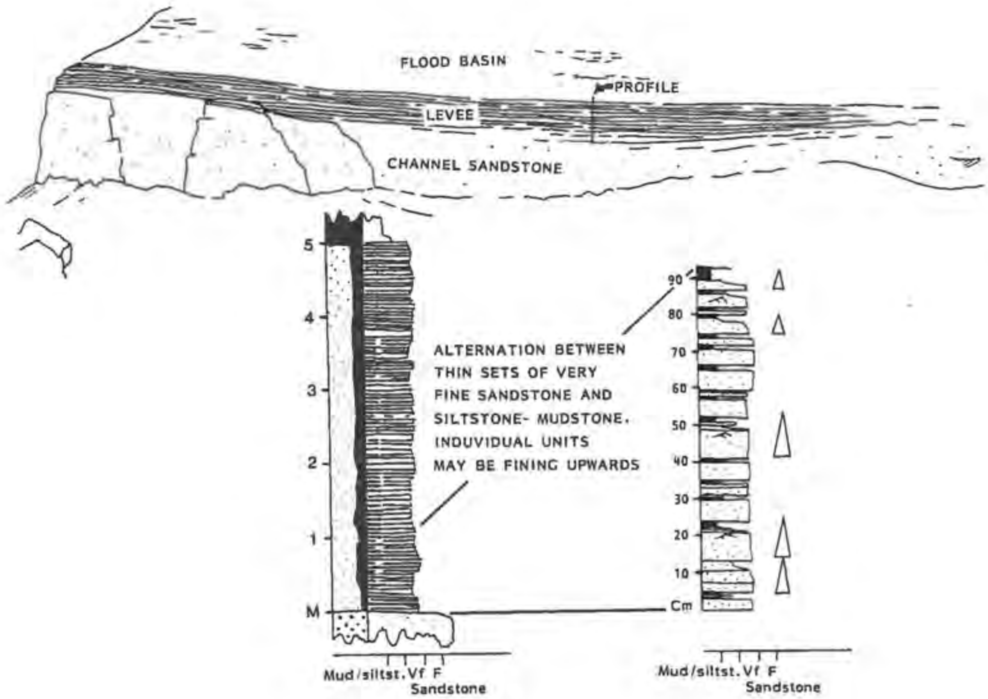


Fig. 2.11. Levee deposits in the Sergeijevfjellet Fm. The upper figure (field sketch) shows the relationship between the levee and one of the channel sandstone bodies at the base of the Formation.

OVERALL INTERPRETATION AND PALAEOGEOGRAPHY

On the basis of their interpretated mode of origin and their stratigraphic association, the facies sequences of the Sergeijevfjellet Formation can be grouped together into a single fluvial facies model. The process and conditions of deposition of the formation suggest a flood plain and delta plain environment constructed largely from sedimentation in and adjacent to streams of high sinuosity. However, some of the thickest sandstone sequences may represent braided river systems of the same nature and origin as that dominating the deposition of the underlying Hornsundneset Fm. It is also possible that the Sergeijevfjellet Fm. in general represents a lateral/distal development of the Hornsundneset Formation, and that the upward change from braided stream to meandering stream deposits reflects a diachronous development where the distal, meandering stream environment became dominant in time. This may be a result of decreased palaeoslope (eg. due to reduced uplift in the source area, or elevated base level, due to eustatic sea level rise). Climatic changes in the source area probably could give a similar effect. Palaeocurrent data recorded from the formation suggest that eastward and southward drainage directions predominated (Fig. 2.10), which corresponds relatively well with the observations from the Hornsundneset Formation. It is suggested here that the Sergeijevfjellet Formation was related to a somewhat similar palaeogeographic setting as for the Hornsundneset Fm., with a main source area to the west, and probably a basin which was restricted northward by the Wedel Jarlsberg Block.

A lateral change of sedimentary facies was probably present during deposition. Braided streams dominated the western proximal area, wheras meandering streams and shallow water deltas developed eastward.

It is important to bear in mind that, due to overthrusting during the West Spitsbergen Orogeny (Tertiary), the rocks now exposed on Hornsundneset probably were located some 30 km southwest of their present position, during Carboniferous time (Birkenmajer 1981).

BLADEGGA FORMATION

INTRODUCTION

The prominent conglomerates which are exposed in the area south of Inner Hornsund, and which are situated in a stratigraphic position between Sergeijevfjellet Fm. and Hyrnefjellet Fm. are here defined as the Bladegga Formation. These conglomerates have earlier been interpretated to be a lateral equivalent to the lower clastic unit of the Treskelodden Fm. on Treskelodden (Birkenmajer 1964). However, little attention has previously been paid to these sediments, not least because most previous work on the Carboniferous succession has been concentrated on the north side of Inner Hornsund.

The Bladegga Formation is exposed at several localities south of Inner Hornsund, but only the two northernmost exposures, at Bautaen and Bladegga, have been visited by the author (Fig. 2.2).

The outcrops at Bautaen are very steep and difficult to approach. It is impossible to establish a continuous profile from this exposure as both the lower and upper part of the formation are missing. The Bladegga locality is, however, much better suited as type locality, due to the fact that it is possible to measure a complete section here. An objection against the choice of Bladegga as type locality is that it is far away from the coast, and difficult to reach.

STRATIGRAPHIC AND TECTONIC SETTING

The Bladegga Formation overlies the Sergeijevfjellet Formation (Namurian), and is concordantly overlain by the Hyrnefjellet Formation (? Bashkirian-Moscovian). No fossils were found in the formation, and the age is difficult to establish. The age of the overlying Hyrnefjellet Formation is also uncertain. It is, however, likely that it span the Bashkirian-Moscovian border (Gjelberg and Steel 1981).

The tectonic and structural setting of the formation is briefly illustrated in Fig. 2.3, in section B and C, which cross the Bautaen and Bladegga localities respectively. At both locations the bedding is vertical or nearly vertical, due to folding and faulting related to the West Spitsbergen Orogeny.

GENERAL DESCRIPTION OF THE TYPE PROFILE

The lowermost part of the Bladegga Formation consists of a 69 m thick unit of white quartzitic (m-f) sandstone (Fig. 2.12). These sandstones are strongly silica-cemented and both grain size and sedimentary structures are difficult to distinguish. Occasional imprints of plant fragments are present in the sandstones.

The overlying 13 m of the formation consist of well-stratified, planar or wedge-shaped fine quartzitic conglomerates (maximum particle size 2 - 3 cm), and pebbly sandstones (Fig. 2.12). The set thickness ranges between 10 and 30 cm, and most of the sets are rather massive internally, though a few sets show tendencies to low-angle, cross-stratification. Some sets are normally graded with a zone of well-washed, granule-size conglomerate on the top (Fig. 2.13c). In general these conglomerates are well-sorted and mineralogically (and partly texturally) mature. It is, however, anomalous that a relatively large percentage of the fragments are

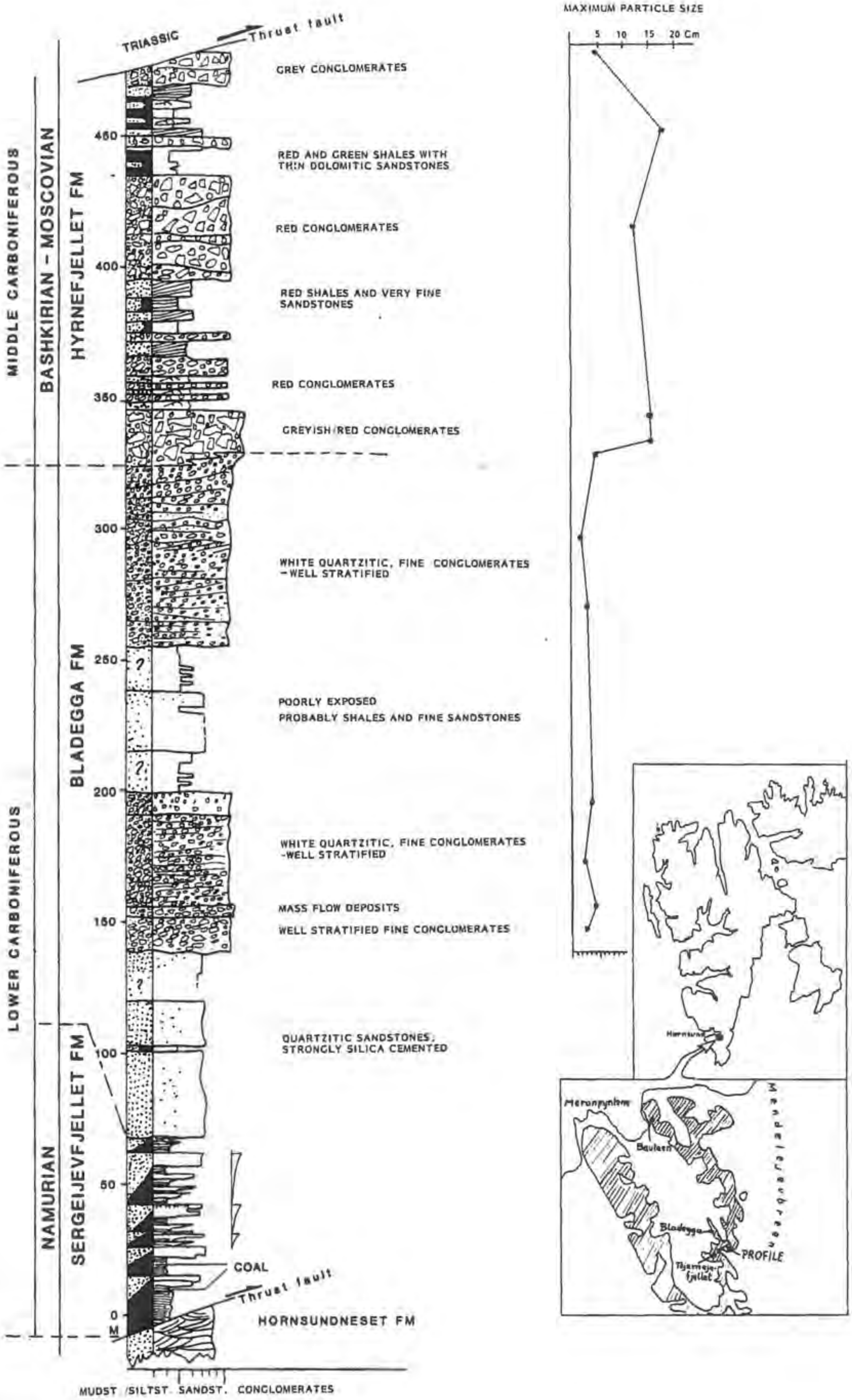


Fig. 2.12. Stratigraphic section from the Sergeijevfjellet, Bladegga and Hyrnefjellet Fms. at Bladegga.

subangular. The subangular fragments are mainly restricted to clasts of chert and vein quartz, the other clasts (mostly quartzitic sandstone and quartzites) are usually well rounded. A few thin sets of dis- organized matrix-supported conglomerates are inter- stratified with the dominating, well organized sets. Texturally immature sets dominate the overlying 5 m of the formation (Fig. 2.12). The set thickness in this zone ranges between 10 - 50 cm and the maximum particle size is about 3-4 cm.

The next 35 m of the formation consists largely of well stratified, well "washed" conglomerates similar to those described from the lower part, with occasional sets of massive sandstone interstratified.

The next 100 m of the formation are poorly exposed (Fig. 2.12), but probably consist mainly of shales and fine sandstones (as seen from occasional exposures).

The uppermost 60 m of the formation consist mainly of the same types of well stratified, well sorted conglomerates as those described above (Fig. 2.12).

The transition to the overlying Hyrnefjellet Formation occurs over a zone of some tens of metres, and is marked by the increasing occurrence of red, texturally immature, relative coarse conglomerates.

THE BAUTAEN LOCALITY

The Bladegga Fm. conglomerates which make the remarkable mountain "Bautaen" show many similarities with those of the type profile, but there are some differences. The lowermost 160 m of the Bautaen Section consist mainly of clast-supported, well washed, quartzitic conglomerates with well rounded pebbles. The maximum particle size is larger than on Bladegga. The next 30 m of the sequence are more sandy and consist of an alternation of well-stratified conglomerates and sandstones. Then follows a zone (20 m thick) of thinly stratified sandstones, with coal lenses and partings of organic-rich mudstones. This zone is probably laterally equivalent to the poorly exposed zone in the middle part of the type profile. The uppermost 140 m of the section again consist of conglomerates, similar to those described from the type profile, but probably with higher content of angular fragments. (The thicknesses mentioned above are all estimated and subject to significant error.)

OVERALL INTERPRETATION AND PALAEOGEOGRAPHY

Detailed sedimentological work has not been carried out from Bladegga Fm., and the interpretation given below is based on brief field studies.

It is suggested, mainly because of the complete lack of any marine facies or facies associations, that the formation mainly represents a continental depositional environment. It is also suggested that the well "washed" conglomerates and sandstones were deposited by fluvial processes. Two main types of waterlaid deposits have been distinguished, and according to the terminology of Bull (1972) these are: 1) Stream-channel or stream-flood deposits and 2) Sheetflood deposits (Fig. 2.13). The stream-channel deposits dominate the formation, and are generally represented with the relatively thick (10 - 50 cm) sets of conglomerates and pebbly sandstones. These sediments correspond well with the stream-channel deposits described and illustrated by Gloppen and Steel (1981). The sheetflood deposits are less common in the Bladegga Formation and are composed of an alternation of coarse and fine-grained sediment sheets. The sets are thin (often only a few cm) but laterally extensive (Fig. 2.13). Similar sediments have been described by Gloppen and Steel (1981).

The disorganized, matrix-rich beds which make only a small part of the formation, are thought to be mass flow deposits, probably mainly of subaerial origin. However, some sets are comparable to subaqueous mass-flow deposits (Fig. 2.13), described from the Adriabukta Fm. (see page 107) and in the literature (eg. Walker 1978, Larsen and Steel 1978, Nemec et al. 1980, Gloppen and Steel 1981). Most characteristic of these are that the sets are relatively thick compared to the maximum particle size, and that they lack the well "washed" and reworked upper part which is commonly seen in the subaerial deposits.

The Bladegga Formation most likely represents alluvial fans, mostly occupied by poorly channelized braided streams (probably with very shallow channels). The sandstones in the lower part of the formation may represent a distal development of the same fan system. The few palaeocurrent data recorded from the Bladegga conglomerate (at Bladegga) suggest that the source area was located to the east. It is also suggested that the Wedel Jarlsberg Block (Fig. 1.5) which probably was a non-basinal area during most of the Lower Carboniferous, still was positive during deposition of the Bladegga formation, and probably a source area for some of the coarse clastics of the Bladegga Formation. Unfortunately palaeocurrent data are few.

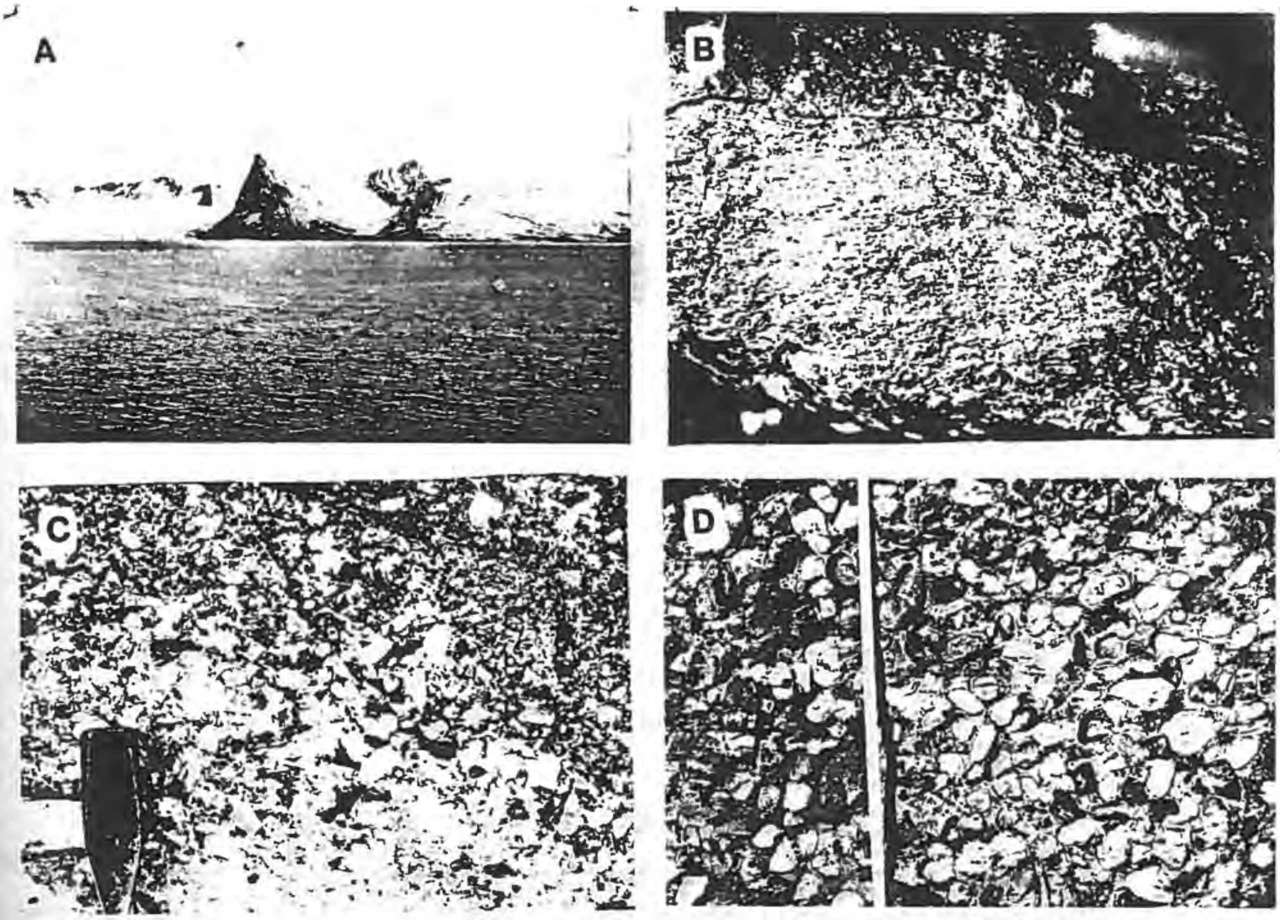


Fig. 2.13 A; The Bladegga/Bautaen locality. The prominent mountain in the middle part of the picture is Bautaen which is made up of vertically standing conglomerates of the Bladegga Fm. The type locality, Bladegga, is seen in the background to the left of Bautaen. B; Thickly bedded, fine grained conglomerates in the Bladegga Fm. These conglomerates may represent subaqueous debris flows deposits. C; "Well washed" thinly stratified conglomerates of the fluvial , probably sheetflood type. D; Typical Bautaen Cgl.

HYRNEFJELLET FORMATION

AGE AND STRATIGRAPHY

The Hyrnefjellet Formation was given formal status as a formation by Cutbill and Challinor (1965), but it was already defined as a stratigraphic unit by Birkenmajer (1960) who used the term Hyrnefjellet Beds and who gave a detailed description of the sediments.

The age of the formation has been difficult to establish as it contains no fossils. Birkenmajer (1964) suggested that the tectonic movements, prior to the deposition of the Hyrnefjellet Beds, which resulted in an angular unconformity between the Hyrnefjellet Fm. and the underlying Adriabukta Fm. (on the north side of Inner Hornsund) probably were related to the Erzgebirge phase (boundary of Namurian and Westphalian).

Fedorowski (1964), Liszka (1964) and Birkenmajer and Fedorowski (1980) all found a Lower Permian fauna in the conformably overlying Treskelodden Fm., but all of their samples were from the Upper part of the formation and the unfossiliferous lower "clastic horizon" of the Treskelodden Fm. may according to Birkenmajer (1964) be of Upper Carboniferous age, whereas he tentatively suggested a Middle Carboniferous age for the underlying Hyrnefjellet Formation.

Since a lateral equivalent to the overlying Treskelodden Formation has been found to contain fossils (fusulinids) of Gzelian age (Nysæther 1977) it is concluded that the Hyrnefjellet Formation most likely represents a Middle Carboniferous (Bashkirian-Moscovian) age. This implies that the stratigraphic scheme of Cutbill and Challinor (1965) for the Hornsund area probably is wrong. They suggested an early Permian (Artinskian) age of this formation as well as for the entire overlying

Treskelodden Formation. Recent studies have shown Hyrnefjellet Fm. to be more than 3 times thicker than what Cutbill and Challinor believed.

This new suggested stratigraphy is much more in agreement with the Carboniferous stratigraphy elsewhere on Svalbard, (see beow).

The Hyrnefjellet Formation overlies the Adriabukta Fm. with an angular unconformity of between 20 and 50^{o} in the exposures south of Hyrnefjellet (Birkenmajer 1964) whereas it directly overlies the Precambrian, Sofiebogen Formation (Hecla Hoek) farther north at Kopernikusfjellet (Birkenmajer 1964). On the south side of Inner Hornsund there is probably a concordant contact between the Hyrnefjellet Formation and the underlying Bladegga Fm.

The contact with the overlying Treskelodden Fm. appears to be conformable over most of the area, and is marked by an upward replacement of dominantly red lithologies (Hyrnefjellet Fm.) into grey and yellow sandstones and conglomerates (Treskelodden Fm.).

The tectonic and structural setting of the Hyrnefjellet Formation at three of the studied localities (Hyrnefjellet, Meranpyntne and Bladegga) is briefly illustrated in Figure 2.3..

FACIES DESCRIPTION

The following gives a general description of the lithologies or combinations of lithologies present in the Hyrnefjellet Formation. Most of the recorded data come from the type locality along the shore of Adriabukta (Fig. 2.2). However, Meranpyntene have recently been discovered to be an important locality as the development here is thicker and quite different from that in Adriabukta. Beside these two localities, data were also recorded from Treskelen, Bladegga and Austjøkultind (ca. 12 km SSE of Inner Hornsund).

Conglomerates are quantitatively very important in the Hyrnefjellet Formation and constitute approximately 48% of the type profile (Fig. 2.14). At Maranpyntene up to 90% of the formation are conglomerates (Fig. 2.15).

Facie assemblage CU - Unsorted, disorganized conglomerates This facies assemblage is very common on Meranpyntene, but is also present at all the other studied localities. The conglomerates are generally very disorganized, internally structureless and with an unsorted often matrix-supported texture. The composition of the conglomerates also unveils their immature nature, as a large portion of clasts consist of sandstones and conglomerates, probably of early Carboniferous (Culm) or Devonian age, but also fragments (conglomerates and sandstones) which were poorly consolidated during deposition, probably more or less of syn-depositional origin were frequently recorded. The following three lithofacies have been included in Facies CU:

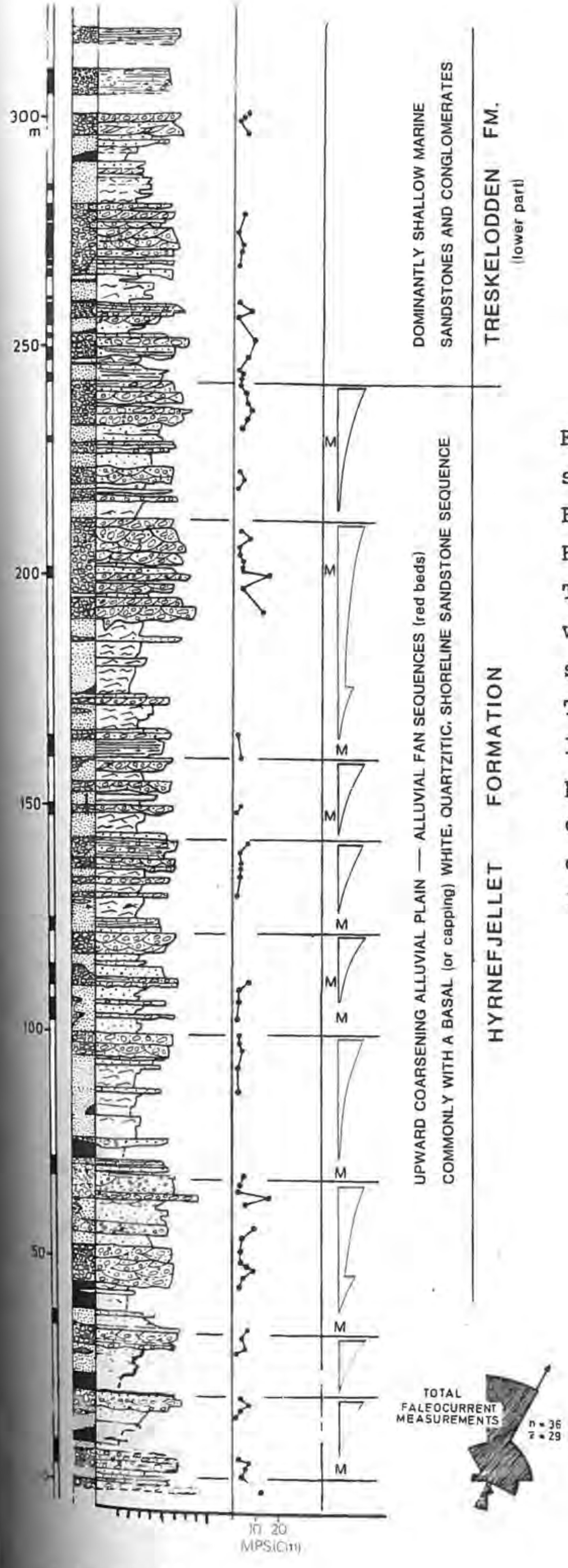


Fig. 2.14 Stratigraphic section from the Hyrnefjellet Fm. at the south side of Hyrnefjellet (Type profile). The profile represents the western limb of the anticline shown in Fig. 2.3, section AA. The black intervals in the left column indicate the presence of sandstones and conglomerates of foreshore origin. (Gjelberg & Steel 1981).

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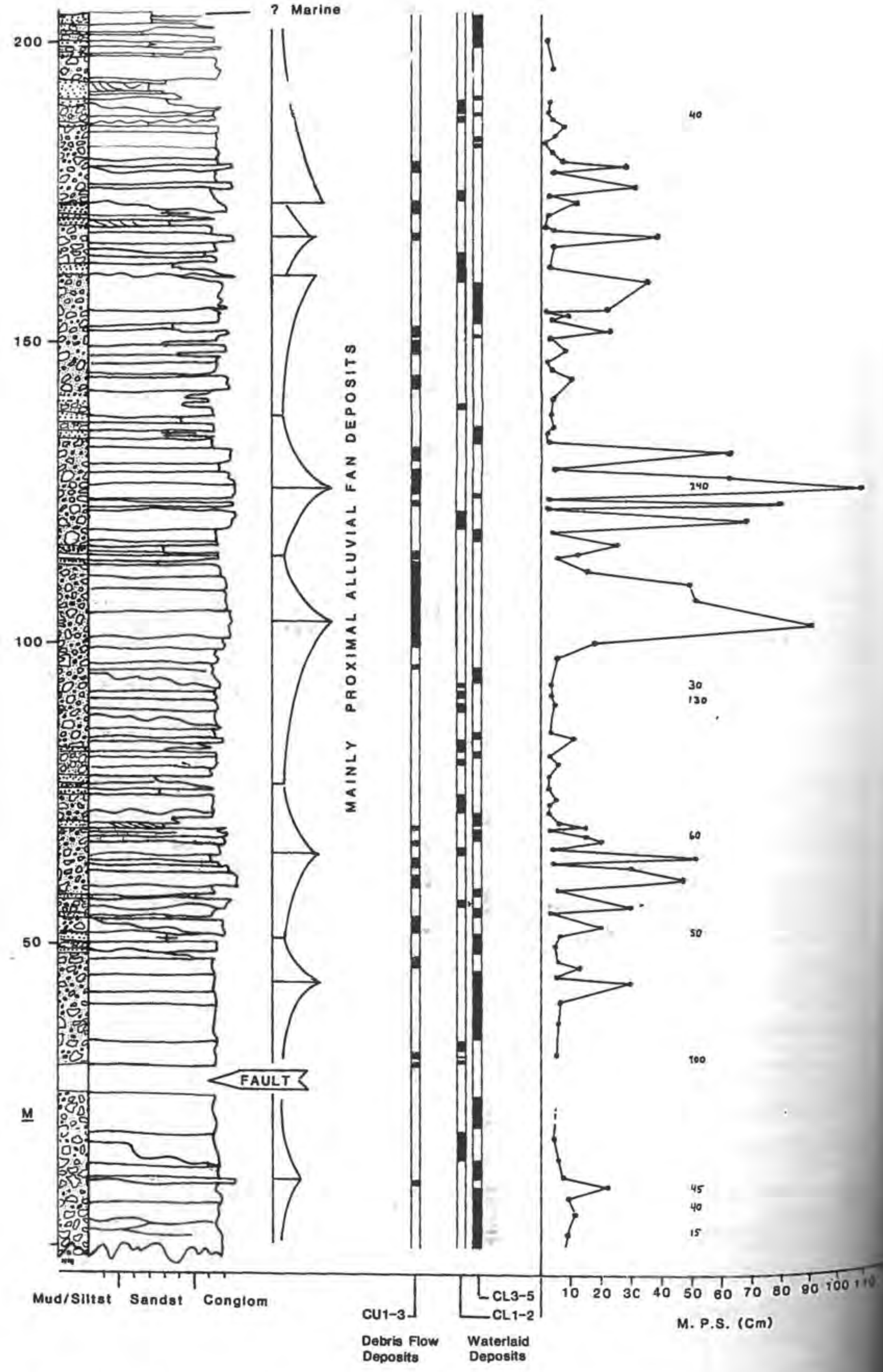

Fig. 2.15 Stratigraphic section from lower middle part of the Hyrnefjellet Fm. on Meranpyntene, Inner Hornsund. The small numbers in the right column represent the diameter of some outsize clasts.

Facies CU1 - Unsorted; internally structureless, matrix-supported red conglomerates with floating outsize pebbles. The matrix is unsorted, red sandstone and the matrix varies considerably, as all transitions from pebbly sandstone (with outsize pebbles) to partly clast-supported conglomerates were recorded. Individual sets are usually less than one metre thick, and the maximum particle size is generally 20-30% of the set thickness. On Meranpyntene, strongly contorted giant sets, with clasts more than 2 m in diameter, are present. Some representative illustrations of these lithofacies are shown in Fig. 2.16.

Facies CU2 - Thick, unsorted, clast-supported conglomerates, infilling scour and channels with strongly erosive bases. The texture of these conglomerates is not unlike that of type CU1, but the matrix content is usually less.

Facies CU3 - Fine-grained, red, disorganized (massive) conglomerates with some sets of inverse grading developed. The texture of this conglomerate is comparable with those described above, however, the grain size is less.

Interpretation of facies assemblage CU - Facies CU1 and CU2 are interpretated as typical subaerial debris flows deposits. This interpretation is made on the basis of literature descriptions and illustrations of both ancient and recent forms of such deposits (eg. Bluck 1967, Bull 1972, Collinson 1972, Steel 1974b, Larsen and Steel 1978, Gloppen and Steel 1981). The extreme clast sizes present on Meranpyntene suggest a very proximal development, influenced by rock fall processes. Facies CU2 has been developed by gradual infilling of debris flows into previously eroded channels. The reason that these conglomerates have less matrix may be that some water was concentrated in the channel during deposition, resulting in a more fluid character of the flows (Steel 1982, pers. comm.). Facies CU3 is also interpretated as debris-flow deposits, however, on a much smaller scale, probably a more distal development.

Facies assemblage CL - Laminated conglomerates of fluvial origin - Sediments of this facies assemblage are commonly present in all localities of Hyrnefjellet Formation and dominate often thick intervals (Fig. 2.15). Characteristic for all facies of this assemblage is that they are relatively well sorted (clast supported) and well stratified. The following 5 lithofacies have been distinguished:

Facies CL1 - These conglomerates are moderately/well sorted, clast-supported and posess relatively thick sets of cross-stratification (0,5-3 m). Maximum particle size average 3 cm but clasts up to 30 cm were recorded.

Facies CL2 - This facies was only recorded from two localities on Meranpyntene. It consists of a complex infilling of deeply eroded channels. The infilling sediments generally consist of well sorted, well laminated conglomerates and sandstones arranged in giant foresets (up to 4 m thick). The foresets build out from one of the channel-sides, probably as a result of lateral accretion. Figure 2.17 shows the most obvious example of this facies.

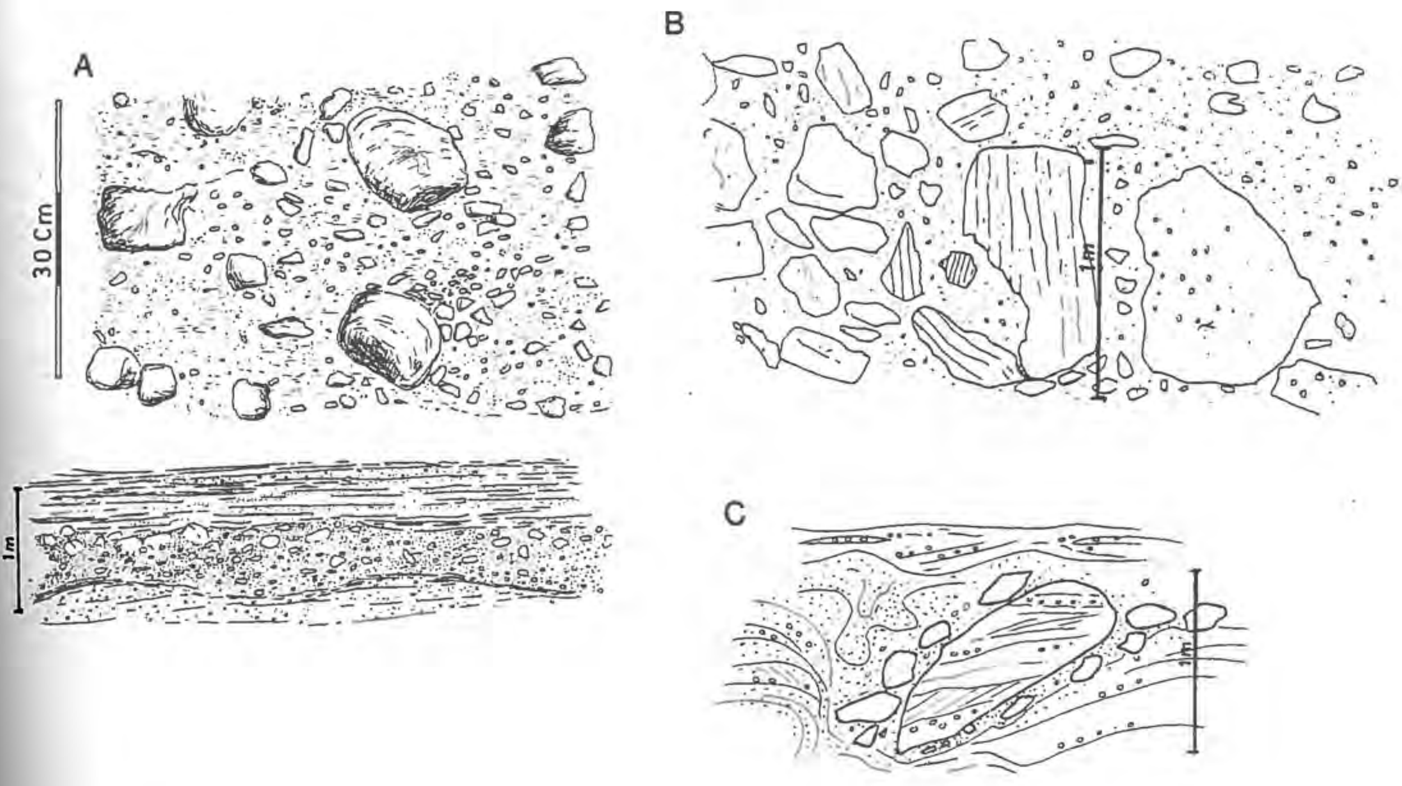

Fig. 2.16 Some representative examples of Facies CU1
Note the disorganized, unsorted character of the sediments.

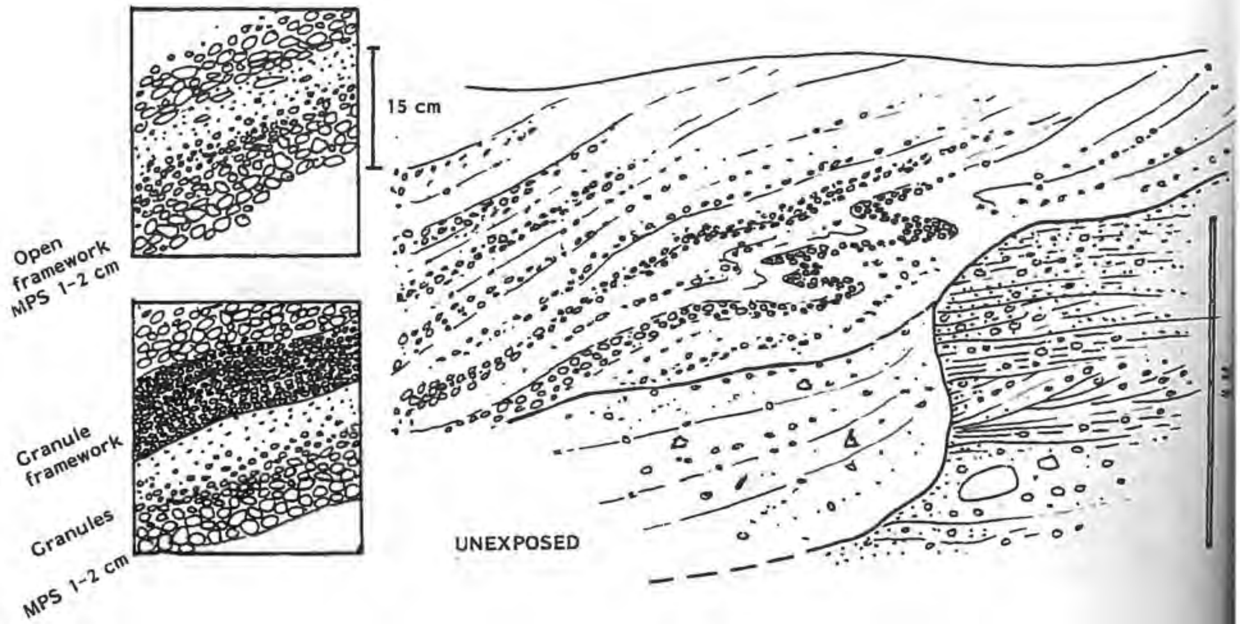

Fig. 2.17 Facies CL2 (see text for explanation and description).

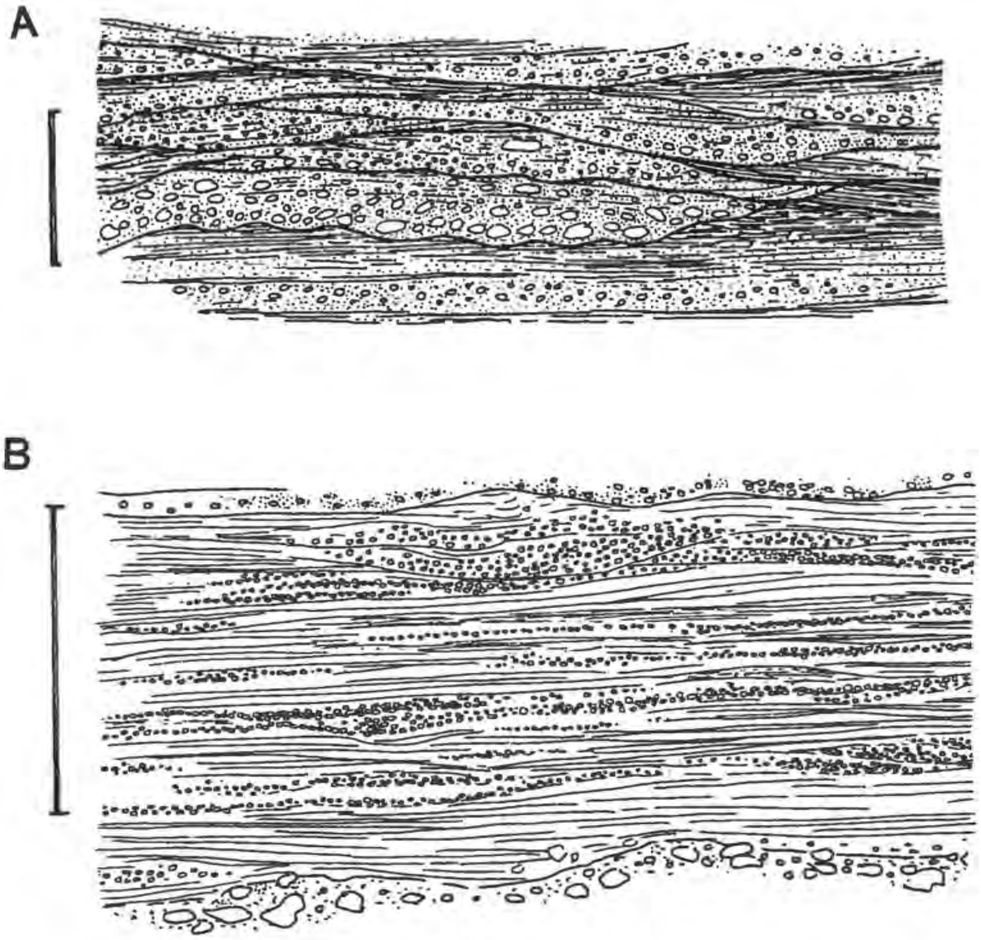

Fig. 2.18 A: Example of Facies CL3 (stream channel deposits) B: Example of Facies CL5.

Facies CL3 - An example of this facies is shown in Fig. 2.18. It consists of clast-supported, red conglomerates or pebbly sandstones in horizontally or cross-laminated sets varying from 20-100 cm in thickness. The lower boundary of individual sets is often marked by curved erosion surfaces, which may be interconnected so that they form lenticular bedforms (Fig. 2.18 A). Individual sets are commonly fining upwards from relatively coarse conglomerates at the base to sandstone and pebbly sandstone at the top.

Facies CL4 - An association of massive and normally graded, fine-grained conglomerates and granules are characteristic of this facies. Set thickness ranges from 10-15 cm. Texturally these conglomerates are very similar to those present in the foresets of Facies CL2, but they are not confined to any channel forms. A few sets of inversely graded granule conglomerates are associated with this facies.

Facies CL5 - This facies is dominated by red sandstones and thinly stratified (2-10 cm) fine-grained conglomerates, and is characterized by an alternation of coarse and fine-grained sheets of sediment (Fig. 2.18 B). Individual sets may be laterally persistant whereas others wedge out rather quickly and form elongated lenses.

Interpretation of facies assemblage CL - The well "washed" character of these conglomerates together with the fact that they are closely associated with subaerial debris-flow deposits indicate that they were deposited from a turbulent medium with relatively low apparent viscosity and in a subaerial environment. Both Facies CL1 and CL2 show most of the characteristics of the stream-flood deposits described from the Scottish Old Red and New Red Sandstones (Bluck 1967, Steel 1974b), and from recent fans (eg. Bull 1964, Bluck 1964). Facies CL1 and CL2 are relatively common on Meranpyntene (Fig. 2.15), but rare in the type profile, which represents a more distal development (see below).

Facies CL3 occurs more frequently in the type profile than on Meranpyntene and Bladegga. The sediments of this facies most likely represent fluvial processes confined to shallow channels. The origin of the sediments is

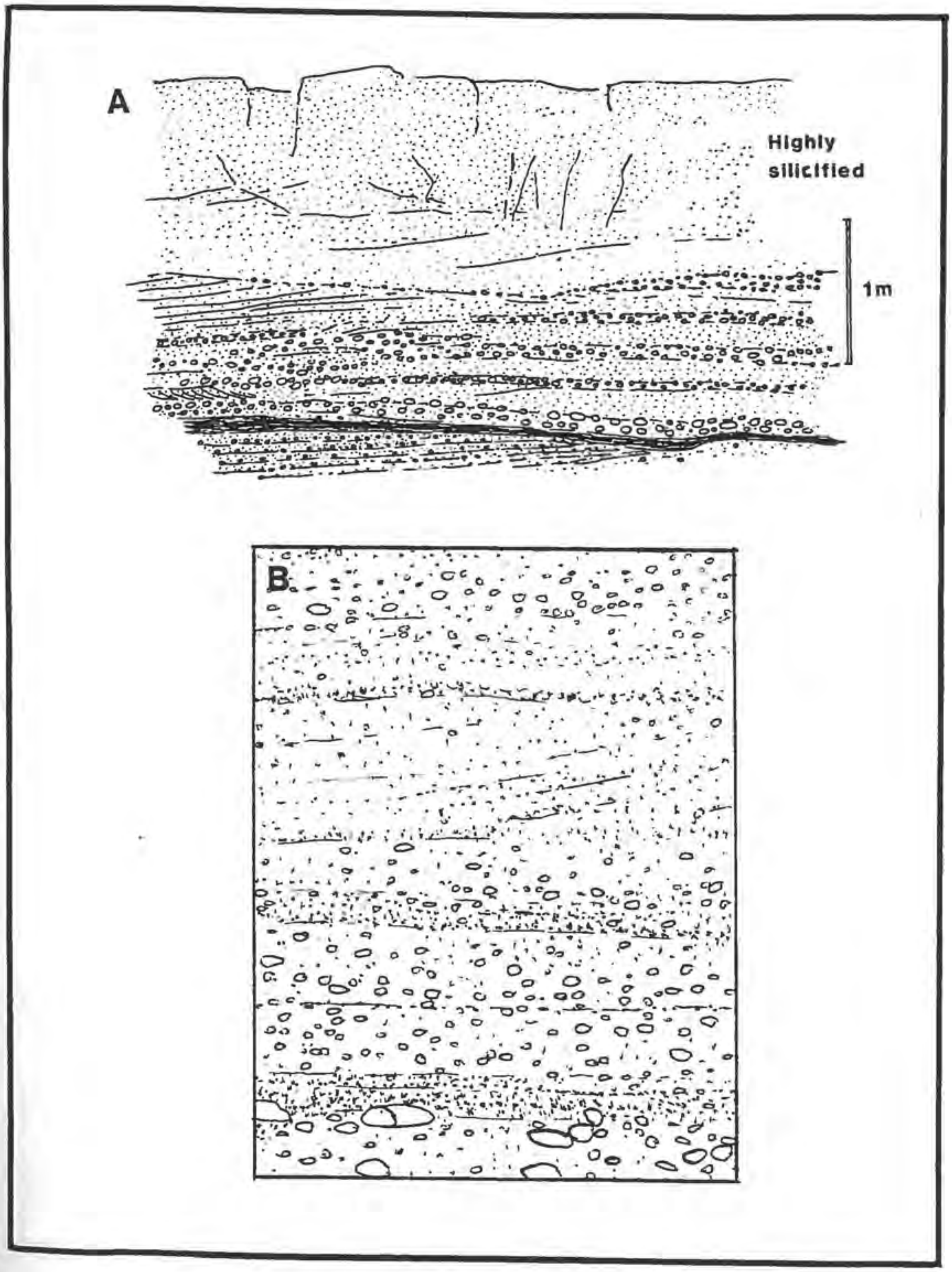

Fig. 2.19 A: Example of Facies SCL of the Hyrnefjellet Fm. The lithologies are texturally mature and of an orthoquartzitic composition. The facies probably represents foreshore or beach environment.
B: Details from the conglomeratic part of the sequence.

consequently fairly similar to those of facies CL1-2. The main differences are related to set thickness and maximum particle size.

Facies CL4 and CL5 are stratigraphically closely associated to the debris-flow and stream-flood deposits, and it is suggested that they represent sheetflood deposits similar to those described and illustrated by Gloppen and Steel (1981). The sets of Facies CL4 are much thicker than those of Facies CL5, and are mainly located in the proximal, Meranpyntene profile. The coarsening upwards nature of some sets assigned to this facies, probably reflect a progradational upbuilding of the sets. (The coarsest portion of bedload sediments are deposited in the upstream end of sheet-floods.)

Facies SCL - Evenly laminated, well sorted ortho-quartzitic sandstones and conglomerates This facies resembles facies CL4 and CL5, but differs because of the typical ortho-quartzitic composition which gives the sediments a bluish/grey colour that makes it easy to distinguish from the redish/grey, polymict, alluvial conglomerates. The facies is characterized by an alternation of well stratified or well laminated quartzitic sandstones, pebbly sandstones and fine-grained quartz conglomerates (Fig. 2.19). The conglomerates are well stratified, well sorted, and clasts are well rounded. Some sets of planar and trough cross-stratified sandstones are present in this facies, but most commonly the sandstones are apparently massive. The facies usually occurs as a capping of well defined coarsening upwards sequences. No fossils were recorded.

Interpretation of Facies SCL - This facies is very like (both texturally and structurally) sandstones and conglomerates of Facies association LD2 of the Landnørdingsvika Fm. (Gjelberg 1981b), interpretated as conglomeratic foreshore deposits, and none of the observed data contradict a similar interpretation. Most of the lithologies of this facies are strongly silica-cemented (often giving the rocks a characteristic bluish/grey colour). The reason for this strongly facies-related cementation is uncertain, but it may be due to an early cementation stage, strongly related to depositional environment.

Facies assemblage S - (Red/brown sandstones) - Two different types or assemblages of red sandstones were recognized, Facies S1 and Facies S2.

Facies S1 - Red/brown sandstones - Red or brownish/red sandstones are commonly associated with the fanglomerates in the Hyrnefjellet area. These sandstones are usually fine-grained, poorly sorted and contain mica, iron oxides and a clay mineral admixture. Current ripple lamination together with irregular lamination are the most common sedimentary structures recorded, but a large part of the sandstones appears massive. Some of the interstratified coarser sandstone sets (medium) are sharply based and trough cross-stratified. Thin drapes of red siltstone and mudstone are very common within the sandstones. Subaerial indications such as wrinkle marks and desication cracks are abundant. No fossils or trace fossils (except for some plant root imprints) were found.

Facies assemblage S2 -(Red sandstone of tidal origin) - Red (redish/grey) sandstone at Treskelen (on the east side of the anticlinal) has a relatively thick development (Fig. 2.21) and contains a wide variety of sedimentary structures. Trough cross-stratification of different scales and shapes, planar cross-stratification with multi-directional orientation of foresets, epsilon cross-stratification, ripple lamination (also climbing ripple lamination), scour and fill structures and soft sediment deformation structures (Birkenmajer 1964, p.95) are all present. Thin mudstone and siltstone drapes are commonly present in the sandstones. Individual sequences of this sandstone succession (2-3 m thick) are often fining upwards and may be capped with fine-grained units of flaser and lenticular stratification (Fig. 2.21). Indications of subaerial exposure and/or very shallow water conditions, such as mudcracks, root impressions and wrinkle marks are commonly present in the fine-grained units.

Interpretation of Facies assemblage S - The red/grey sandstones (Facies S1) which are closely associated with the fluvial conglomerates (see above) are generally interpretated as sheet-flood deposits, developed on flood-plains/coastal-plains in front of alluvial fans. This interpretation is consistent with the frequently interfingering with this facies and conglomerates of distal alluvial fan types.

Facies assemblage S2 is very like some of the sandstones of Facies association LC1 of the Landnørdingsvika Formation (Bjørnøya), interpretated as tidal sand flat and tidal channel deposits (Gjelberg 1981b), since most of the criteria used to interprete Facies association LC1, also are present here, a similar interpretation is suggested.

Facies assemblage F - Fine-grained lithologies - These sequences (up to 7 m) of red brownish/red mudstones and siltstones, massive and/or laminated, interbedded with thin sandstone sets, are present at several localities of the formation (eg. type profile). Lithologically this facies is somewhat similar to the red mudstones described from the Landnørdingsvika Fm. (Gjelberg 1981b), but usually they occur in different sedimentological associations. Here the mudstones often form the lower part of well-defined coarsening upwards sequences. There is often a gradual transition from the red mudstones at the base to the red sandstones in the middle part of the sequences. (The upper part of the sequences is mainly occupied by fanglomerates often capped by foreshore deposits.) No fossils or trace fossils were recorded in this facies.

Interpretation of facies F - The thick, red mudstones most likely represent a continental depositional environment as there are no indications of marine or marginal marine influence (eg. fossils or trace fossils). The stratigraphic position of this facies, at the base of coarsening upwards sequences (this will be discussed more in detail below), may suggest that it represents flood plain or coastal plain depositional environments developed in distal regions of arid or semiarid alluvial fans (Gjelberg and Steel, 1981).

VERTICAL DEVELOPMENT AND FACIES SEQUENCES

The following gives a general description of the vertical evolution of the formation based on the exposures at Adriabukta ("type profile") and on the exposures on Meranpyntene. The description and discussion of the various types of facies sequences are made very briefly.

Meranpyntene Section

A typical section from the Meranpyntene is shown in Fig. 2.15. This figure shows, however, only 200 m of the Hyrnefjellet Formation which probably has a total thickness close to 1000 m in this area. The stratigraphy is difficult to establish at the locality, due to complex tectonic setting. However, it seems likely that the section gives a representative picture of the formation.

The vertical arrangement of facies is chaotic and shows an apparently random alternation of waterlaid and massflow deposits. There is, however, a poorly developed cyclicity in the section (Fig. 2.15), which is established mainly through the study of maximum particle size. The cycles range between 10 and 30 m in thickness and are characterized by gradual coarsening upwards of the conglomerates, followed by a fining upwards (Fig. 2.15). A somewhat similar development was also found from the central Sørkapp Land area (Bladegga and Austjøtultind) but here the thickness of the formation is much less (< 100 m) and the maximum particle size rarely exceeds 20 cm in this area.

The types of sediments which are present on Meranpyntene and in central Sørkapp Land are characteristic for fans that have accumulated in the arid and semiarid parts of the world (eg. Bull 1972, Gloppen and Steel 1981) consequently it is suggested that the Meranpyntene conglomerates represent such alluvial fan systems. The extremely large clasts (> 4 m in diameter) which occur in the formation indicate that the sediments represent a relative proximal development on the fan system. This is consistent with the fact that the alluvial fan facies associations completely dominate the Meranpyntene section, with no interfingering of other facies.

The type profile

The development of the Hyrnefjellet Fm. in the Hyrnefjellet area (type profile) differs much from that on the Meranpyntene. 245 m of the formation is exposed from the core of the anticline (Figs. 2.1, 2.14) and westward along the shore of Adriabukta. The total thickness, however, is slightly more as the base of the formation is not exposed in this section.

A distinct cyclicity is present in the formation (Fig. 2.14). This cyclicity is made by superimposed well defined facies sequences. Individual sequences show a characteristic coarsening upwards which often starts with red mudstones and siltstones of alluvial/coastal plain origin, and which grade into red sandstones probably of similar environmental conditions as the mudstones. The upper part of the sequence is generally dominated by red conglomerates of the alluvial fan association. Though the coarsening upwards character is the dominating feature of the sequences, there may be a slight tendency for fining upwards in the uppermost part (Fig. 2.14). Figure 2.20 shows some representative upwards coarsening sequences from the type profile. Another important feature of the cyclic development is the vertical position of the well-washed, quartzitic sandstone (and conglomerate) facies of foreshore origin. This facies caps individual coarsening upwards sequences (Fig. 2.14).

Each cycle is interpretated in terms of gradual alluvial fan gravel outbuilding over an alluvial coastal plain, followed by sudden transgression in which the alluvial fan surface was reworked to form a thin quartzitic beach capping. Clastic marine sediments increase in volume upwards, and the overlying Treskelodden Formation has generally been deposited in the littoral zone (Siedlecka 1968).

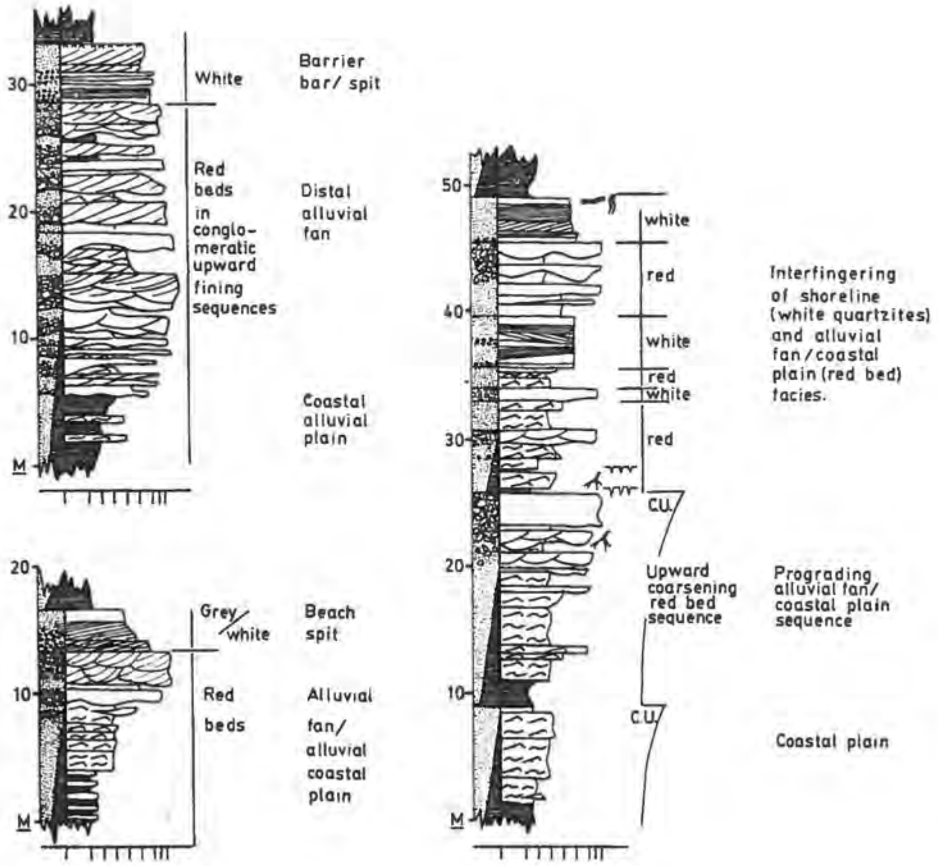

Fig. 2.20 Some details of facies sequences from the Hyrnefjellet Formation showing the typical coarsening upward nature at the sequences and the capping of (beach reworked) grey sandstone and conglomerate. (From Gjelberg and Steel 1981).

The Treskelen profile

The exposures of the Hyrnefjellet Formation which outcrop along the west side of Treskelodden (Treskelen) have been described and interpretated by Siedlecka (1968), who concluded that the sediments show the features of rapid, non-continous deposition and that they mainly were accumulated in a continental environment. On the basis of thin section studies Siedleska was able to distinguish three different parts of the formation: 1) Lowermost (c-

42 m) - with quartz and quartz-chlorite cement. Typical continental sediment without any sign of marine action - 2) Upper (23 m) - with silica-carbonate cement and with increasing carbonate content towards the top - 3) Uppermost (ca. 4 m) - with silica-sulphate cement (barite) without carbonates. Increasing amount of sulphates towards the top.

The occurrence of sulphate and carbonate cement in the upper part of the Hyrnefjellet Formation is according to Siedlecka (1968) genetically connected with the first ingression of the sea upon the area previously characterized by continental sedimentation. She also suggested that "This palaeogeographic change was the formation of a small shallow bay which was quickly cut off from its parent basin, thus changing into drying lakes of rapid increasing salinity", and that the partly unconsolidated and partly lithified sediments were saturated by marine water causing precipitation of salts first and foremost carbonates.

Detailed sedimentological investigations carried out from one part of the Treskelen section which probably corresponds to the lower-middle part of Siedleska's profile (see Siedleska 1968. Fig. 1), is shown in Fig. 2.21. An interpretation of this section, based on the facies interpretation given above suggests that the section represents depositional environments dominated by tidal flats (see also Klein 1967, 1972 and Reineck, 1972) and beach ridges or spits (eg. Davies et al. 1971). Such thick accumulations of marginal marine sequences were not recorded from the type profile, where such deposits only forms relatively thin units separated by alluvial sediments. Consequently the Treskelen development is more distal than the type profile. The original horizontal separation between these two localities (before the folding) was about 700 m, and according to the overall interpretation of the formation (see below) this implies that the "Treskelen development" occurred

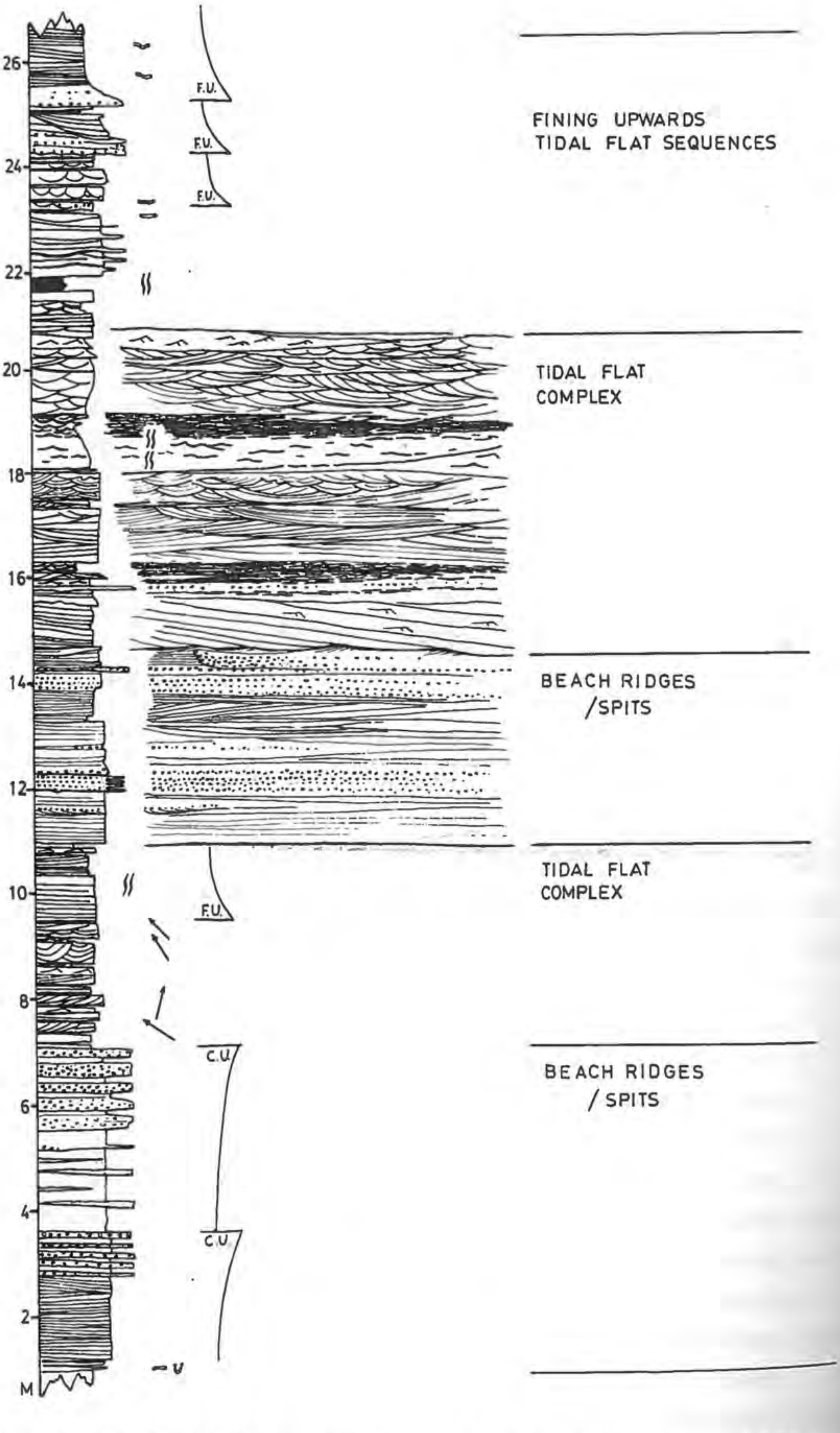

Fig. 2.21 Detailed stratigraphic log from the middle part of the Hyrnefjellet Formation at Treskelen, Inner Hornsund

700 m farther out in the basin, which explains the more distal facies development in this section.

During Statoil's Svalbard expedition in 1982 one thin dolomite bench containing microcodium was recorded from the upper part of the Treskelen profile. (Ron Steel pers. comm.). This is the only carbonate bench recorded from the Hyrnefjellet Fm. However, the microcodium indicates a shallow water and, at least, partly emerged environment of deposition.

OVERALL INTERPRETATION AND PALAEOGEOGRAPHY

Very few palaeocurrent data were obtained from the Hyrnefjellet Formation. However, the few data recorded from the alluvial sediments, together with the general regional patterns of development of the formation suggest that a tectonically active fault of N-S or NW-SE extension formed the western boundary of the basin. It is also most likely that this fault zone was located close to the present exposures (especially close to Meranpyntene) as seen by the coarse sediments and the relatively proximal types of alluvial fan facies.

Distinct thrust faults orientated approximately in north-south direction are present in the Inner Hornsund area (see Fig. 2.2). One of these faults occurs just west of the present exposures and it is probable that this fault was active already in Carboniferous time and formed the western margin of Inner Hornsund Trough (Gjelberg and Steel 1981). This fault was later reactivated during the transpressional regime of the West Spitsbergen Orogeny and forms today a typical thrust fault with upthrusting of the Hecla Hoek and Devonian basement from the west (Fig. 2.3).

A very dramatic change in thickness and sedimentary facies appears in the Carboniferous succession from the north side to the south of Inner Hornsund (Fig. 2.22). This seems, at least for the Lower Carboniferous succession, to be due to synsedimentary faults running more or less parallell to the east-west extension of Hornsund. This fault or fault zone is thought to represent the southern boundary of the Wedel Jarlsberg Block (see page 94). Whether this fault zone was active during deposition of the Hyrnefjellet formation is difficult to deduce as the dramatic thickening observed across Inner Hornsund may be a result of several

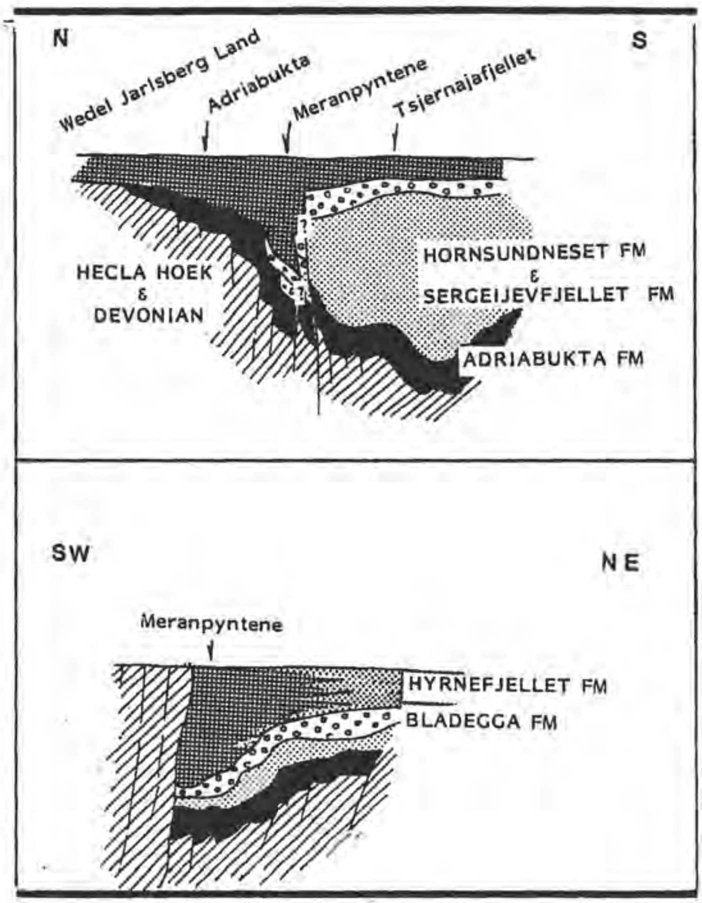

Fig. 2.22
Interpretative reconstruction of two cross sections from the Inner Hornsund area by Middle Carboniferous time. The upper section represent a line in north-south direction across the Inner Hornsund. the lower section goes in SW-Ne direction just south of Inner Hornsund.

factors: 1) Vertical, synsedimentary movements along east-west trending faults may have caused significant thickness variations along N-S axis of the basin. 2) Strike-slip movements along such east-west trending faults during or after deposition may have "displaced" the position of thick proximal and thinner distal developments relative to each other in such a position that the thickness variation appears much more dramatic than it originally was. 3) A bend or curvature of the important N-S trending fault line, similar to that present at Meranpyntene (Fig. 2.2), may have caused the development of deep sedimentary basins, if strike-slip movements took place along the fault, (eg. Crowell 1984, Steel and Gloppen 1980). Which of the above factors has been dominant is difficult to deduce, and it may be a result of a combination of more than one factor. However, the third explanation seems to be the most actual since such curvature of the fault is present in the area (Fig. 2.2), and since sinistral movements seem to have taken place between Greenland and Laurasia in Middle/Late Carboniferous time (Russell and Smythe, 1983, Harland et.al. 1984, Håkansson and Pedersen 1982). This topic will be discussed in more detail below (see page 270).

Cyclicity - A direct correlation between the deposits on the north side and the south side of Inner Hornsund is not possible on the basis of the present data. The cyclicity observed in the type profile and in the Meranpyntene profile is mainly of the same scale (20 - 60 m), but differs in that the "Meranpyntene cycles" show a thicker fining upwards unit in the upper part. It is not fully understood what physical processes caused the generation of such cycles, but is conceivably the result of either direct local/regional tectonics, climatic changes or of eustatic sea level variation. In the latter case either glacial or other changes may be ultimately responsible. Each of these possibilities is discussed below.

Steel (1976) described somewhat similar cycles from the Devonian basins of western Norway, where the coarsening-upwards was interpretated in terms of progradation of alluvial plain and alluvial fan facies in response to rapid lowering of the basin floor, due to tectonic down-throw. The overall cyclicity of the basin fills was thought to be a result of repetition of such tectonic events (see also Steel et al. 1977 and Steel and Gloppen 1980). A similar interpretation seems to be usable also for the cycles in the Hyrnefjellet Fm. The position of the beach reworked material (spit bars) on the top of individual coarsening upwards sequences may be explained in a similar fashion as the alternation of alluvial fan conglomerates and prograding shoreline sequences in the Landnørdingsvika Formation (Gjelberg 1981b, p. 60). The beach capping overlying many of the alluvial sequences may well reflect sudden, periodic tectonic downthrow of the basin area, resulting in a relative rise of sea level. Immediately overlying such beach units, resultant from sudden transgression, there often occurs a new progradational outbuilding of alluvial fan lobes. This renewed progradation may have been caused as a result of the increased topography due to the faulting, followed by the flushing out of accumulated weathered debris. It is hence probable that both the sudden transgression and the accompanying outbuilding of alluvial fan lobes are a direct response to tectonic events (Fig. 2.23A).

The fact that many of the cycles of the Meranpyntene section are fining upwards in the upper part is in significant contrast with the cycles in the type profile which in most situations are only coarsening upwards. This may be explained by the fact that the top of the cycles in the more distal regions of the fans have been reworked by shoreline processes, which partly have destroyed the primary alluvial fan sequences.

There is another possible explanation for the development of such cycles, based on the effect of climatic changes: The

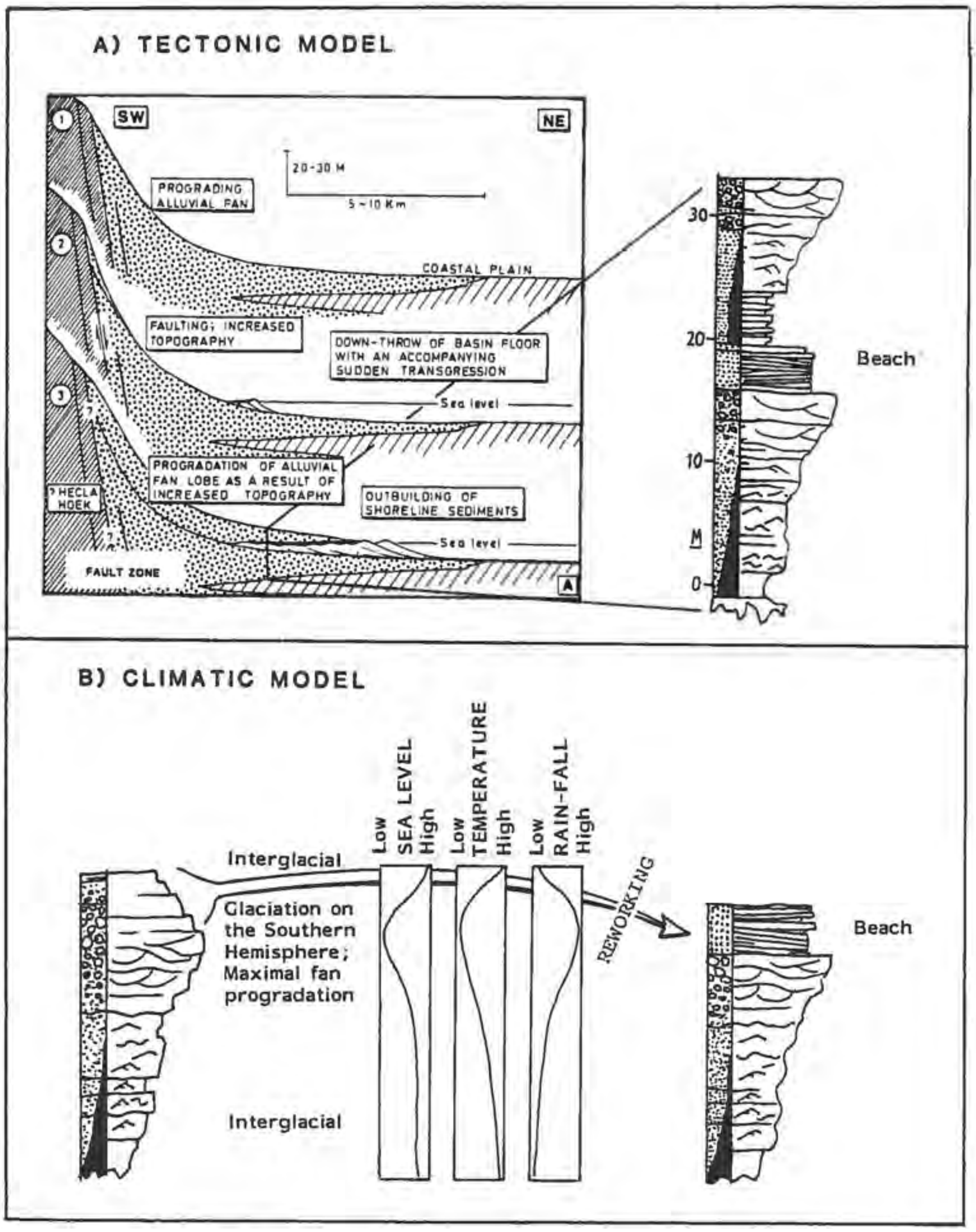

Fig. 2.23 Two alternative explanations for the development of the cyclisity in the Hyrnefjellet Fm, based on tectonic and climatic changes, se text for explanation.

palaeo-latitude for Spitsbergen during Middle Carboniferous time was approximately 30^{o}N (Irving 1977, Steel and Worsly 1984, about the same latitude as North Africa today). During most of Carboniferous time there were periods of extensive glaciation in the vicinity of the south palaeopole. Periods of extensive glaciation would cause eustatic sea level fall, which would, more or less, coincide with the cooler weather periods. The effect of a glaciation around the south pole on the climate (especially precipitation) in the area near 30^{o}N in Carboniferous time is difficult to deduce, and probably the best way to approach this problem is to look at the climatic response in arid-semiarid regions to quartenary glacial cycles. A tentative correlation made by Tricart (1956), between pluvials of Africa and periods of glaciation, suggests that two geographical types of pluvials have to be distinguished: "those of middle latitudes, which coincide with glaciations (North Africa, western United States, Iran etc.) and those of low latitudes, which on the contrary, fall within the interglacial periods".

Further studies during the last years seem to confirm this statement (eg. Street and Grove 1979, Talbot 1980, Street 1981). Since "Spitsbergen" was located in the middle latitudes during Carboniferous time it is possible that the maximal fan lobe progradation was related to increased precipitation which again coincided with periods of glaciation, producing a coarsening upwards cycle. The interglacials would coincide with high eustatic water level which could explain the beach capping in the upper part of sequences. If this was the case, a combination of fluctuation in sea level and precipitation could produce cycles as illustrated in Fig. 2.23B.

Cyclicity which probably developed as a result of eustatic sea level changes is known from other

Lower-Middle Carboniferous deposits in North Atlantic regions. Ramsbottom (1979) recognized a hierarcy of biostratigraphically based units in the Carboniferous of NW Europe, with the major transgressive events being traceable to United States and Russia. It is possible that the wave-reworked intervals of the Hyrnefjellet Fm. represent periods of eustatic high water stand. The tectonic influence on the development was, however, very strong, and it is suggested here that the eustatic effects were subordinate to local and regional tectonism. It is, on the other hand, believed that the overall, eustatic rise of sea level which occurred throughout Westphalian time is reflected with a gradual increase of marine deposits upwards in the Middle Upper Carboniferous succession.

Whether the cycles are a product of tectonic pulses or long term rythmic global climatic variations is not yet understood, and this may be a subject for further study. It is, however, clear that tectonic movements along near-by faults had a significant influence on the sedimentation of the Hyrnefjellet Fm., as seen by the great thickness of the coarse-grained succession and by the frequent occurrence of out-size clasts (rock fall) in the proximal areas. Since it is suggested that tectonic activity often occurs in pulses (Steel et al. 1977) the tectonic model may be preferred. Such an interpretation is also consistent with the interpretation of the cyclic development near the margin of other Carboniferous basins of Svalbard (eg. Billefjorden Trough) where our understanding of the basin evolution is much better.

SUMMARY OF THE LOWER - MIDDLE CARBONIFEROUS DEVELOPMENT IN THE SØRKAPP LAND AREA

Figure 2.24 illustrates the development of the Lower-Middle Carboniferous succession along a line of WSW and ENE extension, going through Hornsundneset and approximately parallel to the southern side of Hornsund. The Adriabukta Fm. (Visean-Namurian) rests unconformably on Devonian and Hecla Hoek strata and consists of alternating grey shales, sandstones and conglomerates succeeded by grey and black shales. These sediments accumulated in standing water which probably was rather deep, while the quartzitic conglomerates and sandstones represent subaqueous mass flows and turbidites derived from the east (Fig. 2.24).

The overlying Hornsundneset Fm. consists mainly of thick (> 1000 m) quartzitic sandstones deposited by eastward flowing braided streams, as a widespread series of fluvial-dominated, alluvial fan systems. There are also local coal seams. It was earlier thought that this thick sandstone succession was confined to the west of the Hornsund High, but it is now known to be present also in Inner Hornsund. We suggest that the Hornsundneset Formation prograded eastward over the Adriabukta Formation.

The Sergeijevfjellet Formation (> 200 m) overlies the Hornsundneset Formation and consists of alternating fluvial sandstones and floodbasin black/grey shales and coal. The overlying grey conglomerates (see Fig. 2.14 and 2.20) have been defined as a new formation, the Bladegga Fm. This formation consists of more than 200 m of texturally mature quartzite conglomerates, and were derived from the east, probably mainly as humid alluvial fans.

The Hyrnefjellet Formation consists of more than 500 m (probable up to 1000 m) of texturally immature conglomerates and sandstones, and represents a relatively abrupt change (over about 5-10 m of strata) to red bed conditions in the area, despite a general similarity in lithology to the underlying Bladegga conglomerates.

The succession is characterized by repeated upward-coarsening sequences in which red, texturally immature sediments (mudstones and sandstones grading upward to conglomerates) are overlain by texturally mature quartzitic sandstones and thin conglomerates. Each cycle is interpreted in terms of gradual alluvial fan gravel outbuilding over an alluvial coastal plain, followed by sudden transgression in which the alluvial fan surface was reworked to form a thin quartzitic beach capping. Figure 2.20 shows some of the most representative upward coarsening sequences. Clastic marine sediments increase in volume upwards, and grade into the overlying Treskelodden Formation. This is closely analogous to the time trends discussed for Bjørnøya (Gjelberg 1981b). Direction of outbuilding was to the east and northeast, and the presence of extremely coarse grained mass flow conglomerates (clasts > 2 m diameter) on Meranpyntene suggests a fault line just west southwest of Adriabukta. This important middle Carboniferous rift zone has been termed the Inner Hornsund Trough.

In both general and specific terms, the Hornsund Lower-Middle Carboniferous succession is similar to that of Bjørnøya. The continental and coal-bearing grey strata of Hornsund are similar to Røedvika-Nordkapp sequences of Bjørnøya while the Hyrnefjellet and Landnørdingsvika Formations correspond. The red bed sequence in both areas was controlled by short term tectonic movements, repeated marine transgressions and alluvial fan outbuilding, and also by longer term regional sea level rise. The latter produced the transition from thoroughly continental to thoroughly marine sediments.

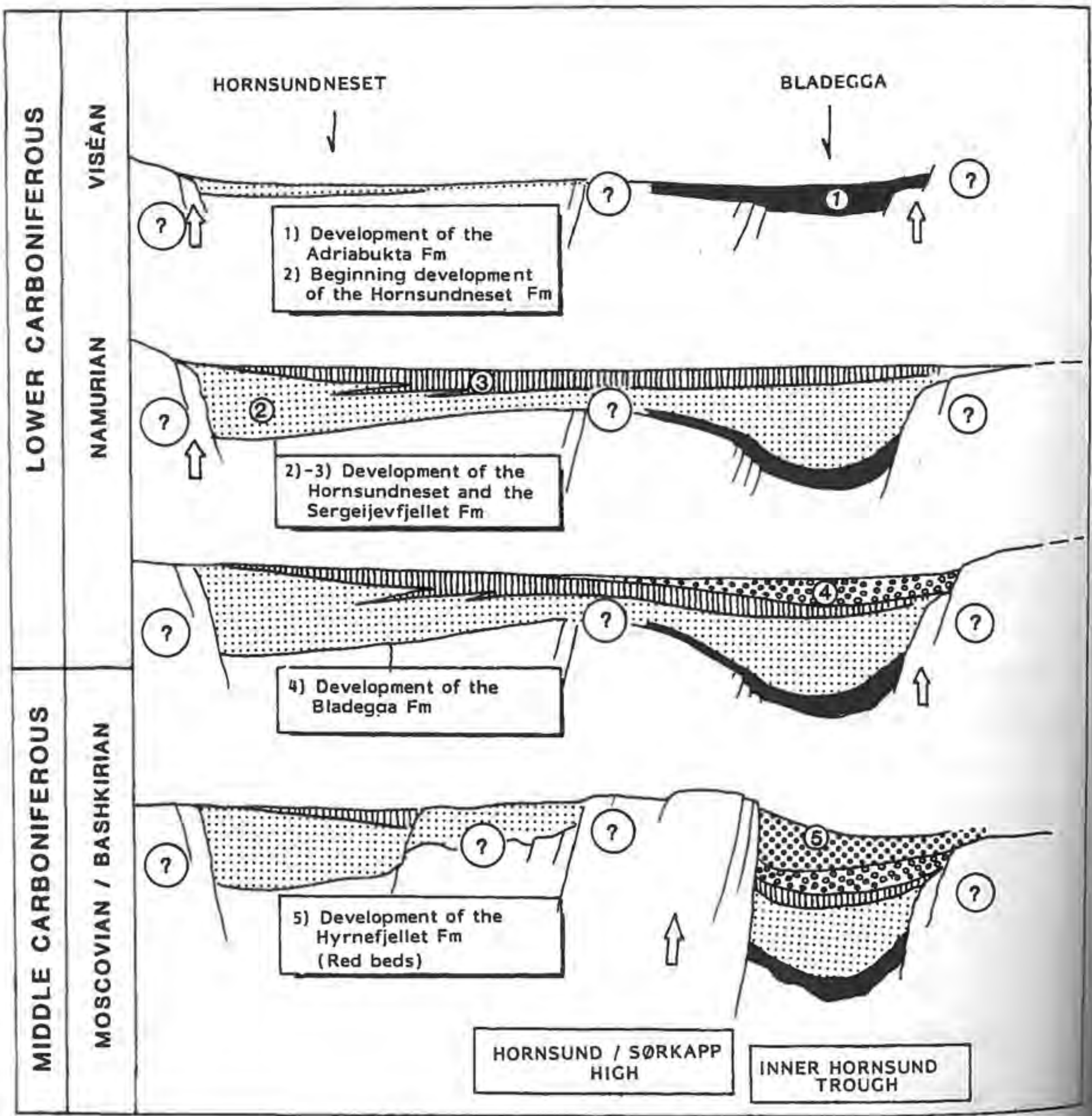

Fig. 2.24 Development of Lower-Middle Carboniferous basins on Sørkapp Land across a W-E line.

The Bashkirian basins on Spitsbergen probably developed in a strike-slip tectonic regime. However, the regional tectonics for the area will be discussed in the summary (Part IV).

III. 3

LOWER-MIDDLE CARBONIFEROUS
(Namurian - Bashkirian)

SUCCESSION ON WESTERN SPITSBERGEN
("ST. JONSFJORDEN TROUGH")

INTRODUCTION

This chapter summarises the Lower-Middle (Bashkirian) Carboniferous succession on western Spitsbergen, north of Wedel Jarlsberg Block, together with an interpretation of the depositional environments and a brief reconstruction of the palaeogeographic setting. The investigations have been concentrated on two areas: 1) Nordenskiöld Land and 2) Inner St. Jonsfjorden area. In addition some other important localities have also been dealt with, either from literature descriptions or from short visits in the field.

PREVIOUS WORK

The existence of widespread Lower Carboniferous "Culm" sandstones on the west coast of Spitsbergen has long been recognized (eg. Nathorst 1910) but the first major contributions are those of Holtedahl (1911, 1913) who visited a large number of localities between Kongsfjorden and Bellsund, and established the broad divisions of the Carboniferous stratigraphy.

A detailed description of the Upper Palaeozoic stratigraphy of the Kongsfjorden region (Brøggerhalvøya) was given by Orvin (1934). An outline of the geological history of Spitsbergen, presented by Orvin (1940) summarized all available data and briefly illustrated the lateral variations in the Carboniferous rocks. A review of the Carboniferous and Permian rocks of the west coast of Spitsbergen was published by Dineley (1958), who also defined the Trygghamna and Vegard Formations on Oscar II Land. Cutbill and Challinor (1965) revised the stratigraphic scheme of the Carboniferous and Permian of Svalbard and defined the Billefjorden Group with 9 formations. The Orustdalen in central western Nordenskiöld Land was chosen as type locality for the extensive Lower Carboniferous, quartzitic sandstones occuring along the west coast of Spitsbergen, in which also the Trygghamna Fm. of Dineley (1958) was included. Other important contributions to the Lower-Middle Carboniferous geology of western Spitsbergen have been given by Winsnes (1966), Flood (1968), Barbaroux (1968), Challinor (1967) Flood et al. (1971), Fairchild (1982).

Tectonic aspects of the investigated area have been discussed by Weiss (1953), Lowell (1972), Challinor (1967), Harland and Horsfield (1974) and Hjelle et al. (1979).

LOWER CARBONIFEROUS OF NORDENSKIOLD LAND

The Lower Carboniferous on the Nordenskiöld Land was investigated during the summer 1977. Two sections were studied, one located near Kapp Lineé at the mouth of Isfjorden, the other on the north side of Bellsund (Figs. 3.1 and 3.2). These sections have been investigated in some detail, and they consequently represent the most detailed description and interpretation of the Lower Carboniferous succession on the west coast of Spitsbergen.

The Middle Carboniferous (Bashkirian) red bed development is poorly represented on Nordenskiöld Land and in the investigated coastal areas no red beds are exposed at all. It is, however, known that some 20-30 m of red beds are preserved in the interior of the Nordenskiöld Land (Netland 1981), and in the Kleivdalen area. These sediments generally consist of red mudstone/siltstone interstratified with red sandstones.

STRATIGRAPHIC SETTING

The Lower Carboniferous - Bashkirian succession of Nordenskiöld Land consists of three formations: the Orustdalen Formation, the Vegard Formation and the Petrelskardet Formation (which is very poorly developed in this area). The Orustdalen Formation (Cutbill and Challinor 1965) rests unconformatly on phyllites, quartzites, carbonates and tillites of The Upper and Middle Hecla Hoek succession (Hjelle 1962). the contact between the Carboniferous and Hecla Hoek has been described from a few localities by Flood (1968), who recognized extensive solution channels in The Hecla Hoek carbonates (karst) which have been filled with sand and gravel of Lower Carboniferous age.

The contact between the Orustdalen and the Vegard Formation is supposed to be conformable, with no appreciable break in deposition between the two Formations. The nature of the contact to the overlying red beds is not known as this is very poorly exposed in the area. The fossiliferous Upper Carboniferous Nordenskiöldbreen Formation rests unconformably on the Lower-Middle Carboniferous succession, probably with an angular discordance.

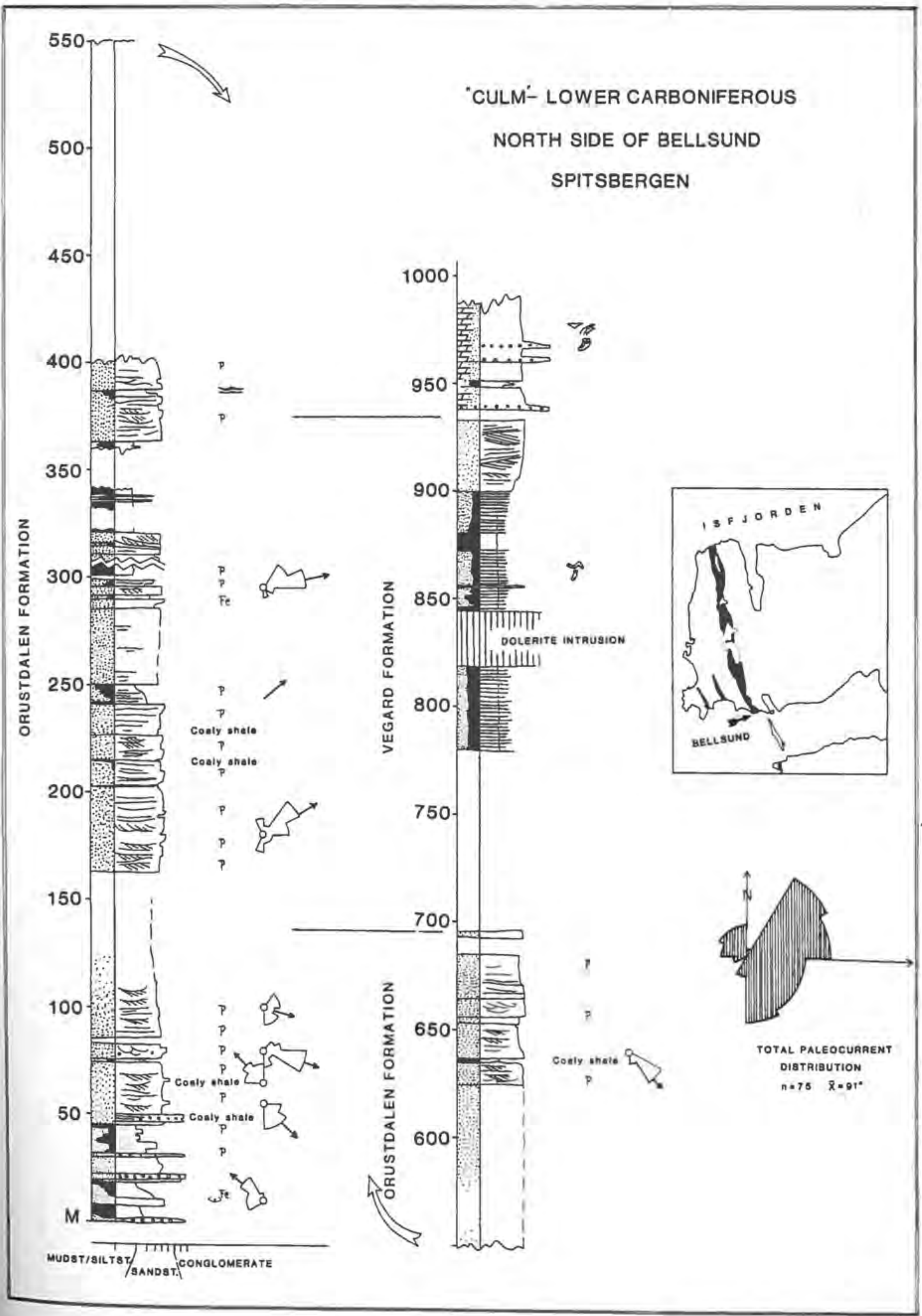

Fig. 3.1 Stratigraphic section of the Lower Carboniferous Orustdalen and Vegard Formations on the north coast of Bellsund.

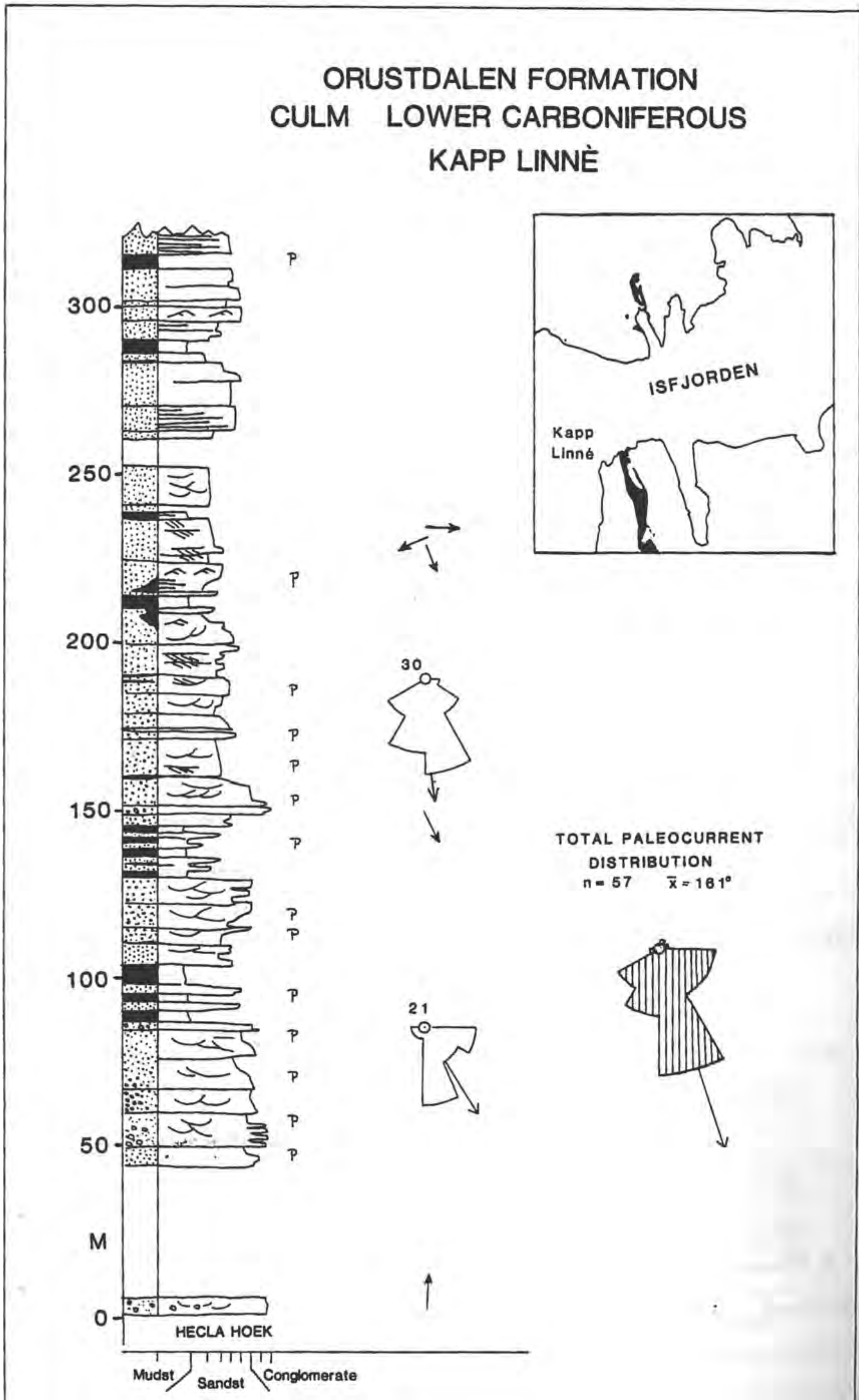

Fig. 3.2 Stratigraphic section from the Orustdalen Formation at Kapp Linné. From Gjelberg 1984 Dr. Sciant Thesis

TECTONIC SETTING

The Lower-Middle Carboniferous succession on Nordenskiöld Land is mainly exposed along a narrow line from Linnévatnet to Bellsund (Fig. 3.1), as this zone represents the western boundary, limb of the big synclinarium preserving the Upper Palaezoic - Cenozoic succession on Spitsbergen (Fig. 1.3). Beside this, two exposures are preserved as outliers on the south-western corner of Nordenskiöld land. These outliers are preserved due to Tertiary normal faulting, probably developed during the transtensional phase (se page 88). the dip of the Carboniferous strata is almost exclusively towards east and northeast, and varies considerably due to smaller folds superimposed on the main geosynclinarium limb. Overturned Carboniferous strata were recorded from the north side of Bellsund.

LITHOFACIES

This section consists of a general description of all the main lithofacies recognized from the investigated Lower Carboniferous succession on Nordenskiöld Land. Most of the "Culm lithofacies of Svalbard can be compared with those described by Miall (1977) from modern and ancient braided streams.

Conglomeratic lithofacies.

Massive conglomerates (Facies Cm). - This facies comprises pebble-conglomerates in which crude horizontal stratification may or may not be present. The conglomerates, which often overly erosion surfaces, are mainly clast-supported, but pebbles may also be scattered in a coarse sandy matrix. Impersistent lenticles of shale and massive or cross-stritified sandstone may be interstratified in the conglomerates. Typical thickness for induvidual units varies between a few cm to more than 1 m.

Lateral grain size variation may be apparent, and pebble-size conglomerates may completely convert into sandstone over a lateral distance of a few metres. Grading of any type is not common, but sets with poorly defined fining upwards character are present. Clasts are poorly imbricated, The lower part of Fig. 3.3 shows a typical example of Facies Cm. The white pebbles are generally quartzites and vein quartz, which dominate the composition of the conglomerates, together with chert fragments.

Fig. 3.3. Typical conglomerates from the Orustdalen Fm. Both massive or crudely laminated conglomerates (Facies Cm) and cross-stratified conglomerates (Facies Cc) are seen. From the mouth of Isfjorden near Kapp Linné. The hammer is ca 30 cm long.

Associated lithofacies are most commonly massive and cross-stratified sandstone. Facies Cm often occur in rapid alternation with massive sandstone.

Cross-stratified conglomerates (Facies Cc) - These conglomerates are distinctly stratified; usually broad, shallow troughs, but also planar cross-stratification is relatively common. The conglomerates may be clast-supported or pebbles may be supported by a coarse sandy matrix.The set thickness of such lithofacies rarely exceeds half a meter. The base of individual sets is sharp and often erosive. This lithofacies may occur as a single set, but most commnly it forms cosets, often more than one meter thick. The clast size of the conglomerates is usually less than 2 cm, and a remarkable large portion of the clast population are of granule size. An exception is the basal conglomerate, which is relative coarse (5-7 cm).

Interpretation of the conglomeratic facies.

These conglomerates, most likely represent fluvial depositional environments due to their general association with subaerial indicators (such as in situ plant roots), and their sedimentary structures and texture which indicate high energy turbulent agents. The high proportion of sand matrix in these conglomerates (often matrix-supported) is generally thought to have been carried in suspension whilst the pebble fraction was moved by rolling (Harms et. al. 1975, fig. 7.3).

Massive gravel or conglomerates have frequently been described from both modern and ancient braided stream deposits (eg. Bluck 1974, Boothroyd and Nummedal 1987, Miall 1977, Steel 1974b, Rust 1978 and most likely represents lognitudinal bar formation.

Low-angle trough and planar cross stratified conglomerates are most commonly known from pebbly braided streams (eg. Doeglas 1962, Steel 1974b, Allen 1974, Cant 1978, Rust 1978, Botthroyd and Nummedal 1978, Bluck 1980), though similar structures may develop in relatively coarse-grained meandering streams (eg. Bluck 1971).

The trough cross-stratified conglomerates are generally thought to occur as a result of minor channel or scour fill (Miall 1977), but similar structures may form by migration of undulatory bars or dunes (Smith 1970). Cross-stratified gravel in some valley sandur deposits in Iceland were according to Bluck (1974) formed by 1) lateral fill into slough 2) megaripples 3) ripple topped bars and 4) accreting bar tail margin.

Sandstone lithofacies

Sandstones of all grain size, included pebbly sandstone (<30% pebbles) are included in this group of lithologies. The following facies division is based on the types of structures present in the sandstone.

Planar cross-stratified sandstone (Facies Sp) - The lithology of this facies varies from fine to very coarse, grey, quartzitic sandstone. Planar-tabular cross-stratification, often with sharp base and top is the main sedimentary structure. Cross strata may be solitary or cosets of superimposed planar cross-strata (omikron cross-strata of Allen 1963). As many as twenty sets may be superimposed within a single occurence of the facies. Set thickness varies from a few cms to 1,5 m but usually single sets are less than 1 m thick. Reactivation surfaces are relatively common.

Trough cross-stratified sandstone (Facies St) - This facies consists of trough cross-stratified, grey quartzitic sandstone which varies in grain size from fine to very coarse. The coarsest sandstones are often pebbly. Trough cross-stratification may occur as solitary scoops eroding into the underlying sediments (Theta cross-stratification of Allen 1963) or as cosets of cross-cutting troughs (festoon cross bedding). Set thickness ranges from a few cm to about one meter, but most commonly set thickness does not exceed half a metre. Cosets of this facies may reach a considerable thickness, and units, mainly composed of this facies, have been recorded up to 5 m thick.

Low-angle cross-statified sandstone (Facies Sl) - This facies is characterized by very low-angle cross-stratified sandstone ($<10^{o}$), usually of fine and medium grain size. The sets are often formed as broad shallow troughs or lenses, and may occur in cosets. There seems to be a gradual transition between some sets of Facies Sh and Facies Sp, where Facies Sl represent the transition.

Minor channels and scour-filled sandstone (Facies Ss) - Characteristic of this facies is relatively large assymetric, sand filled scours (or small channels). The scours may be filled with fine to coarse sandstone, stratified at a very low angle or almost parallel to the shape of the scour. Plane parallel lamination, ripple lamination and cross stratification may be present in the scour fillings.

Horizontally-laminated sandstone (Facies Sh) - This facies consists of horizontally-stratified fine to very coarse sandstone, often with well developed lamination in which parting lineation may be present. The thickness of this facies ranges from a few centimeters to cosets more than a meter thick.

Ripple or small-scale,cross-laminated sandstone (Facies Sr) - Ripple cross-stratification has been recorded from sandstones which vary in grain size between very fine and coarse. A great variety of ripple-generated structures are present; they include solitary ripples (rare), cosets of small scale (<4 cm thick) trough and planar cross-statification, and climbing ripple lamination. This facies is often associated with Facies Sp and St.

Massive sandstone (Facies Sm) - Sandstone of this facies occurs very commonly in the "Culm" of Svalbard and consists of massive sandstone where any type of sedimentary structures are indetectible. Sandstones of all grain size occur within this facies, but most commonly the sandstones are coarse, often pebbly. The facies is often associated with the conglomeratic facies Cm and Cc.

Many of the sets assigned to this facies probably should belong to one of the other sanstone facies described above and below, but because of intense silica-cementation primary sedimentary structures are completely indetectible, in the weathered surfaces.

Contemporaneous deformed sandstone (Facies Sd) - Sandstone of this facies ranges from very fine to coarse in grain size, and is characterized by soft sedment deformation. Deformation structures comprises mainly soft sediment, folding (included convolute lamination and deformed cross-strata), but also soft sediment mixing (Lowe 1975). The thickness of such deformed zones varies from a few centimeters to several decimeters.

Interpretation of the sandstone facies

Planar cross-stratified sandstone (Facies Sp) may generally be produced by: Migrating sandwaves (Bluck 1974), by migrating steep, accreting bar margins of lingoid bars (Miall 1977, Bluck 1974), and by migrating small deltas of sand (Bluck 1974).

Trough cross-stratification (Facies St) is mainly produces by migrating dunes or megaripples in the lower flow regime (Simons and Richardson 1961).

The generation of minor channel and scour fill structures (Facies Ss) is, as the name indicates, a result of erosion of a sediment surface, followed by sediment infilling. The larger structures were probably formed by channel erosion into unconsolidated sediments, followed by infilling when the stream power declined. Scour and fill structures on a small scale seems to be eroded out by occasional vortexes. Similar structures have been described by Singh (1977).

Most of the horizontally stratified sandstones (Facies Sh) and especially those where parting lineation is present, represent "plane beds" of the upper flow regime.

Plane horizontal stratification (or lamination) occuring in coarse and very coarse sandstone may represent "plane beds" of lower flow regime (Southard and Boquchwal 1973).

It is also suggested that "wash-out" megaripples generated in the transition between lower and upper flow regime may be preserved in the sequence as very low-angle (nearly horizontal) statification. There is probably a gradual transition from very low angle stratification to high angle cross-stratification, where Facies Sl (low angle cross-stratification) represents the transitional facies (see also Jopling 1965).

The ripple laminated bedforms (Facies Sr) are produced by migrating ripples in the lower part of the lower flow regime, indicating relatively low stream-power.

Contemporaneous deformed units are supposed to be a result of liquefaction and fluidization (water escape structures) of sediments with a loose, unstable packing (Lowe 1975). Many of the apparently massive sandstones may also be related to such intense soft sediment deformation.

A hydrodynamic interpretation of the massive sandstones is not possible, and in many cases the massive appearance probably is related to diagenetic effects which strongly influence the way the rocks weathers (e.g. quartz overgrowth).

It is most likely that the sandstones of the Billefjorden Group on Nordenskiöld Land mainly represents a fluvial depositional environment, due to the inferred hydrodynamic conditions, the more or less unidirectional current patterns, the presence of subaerial indicators such as numerous plant fossils (included in situ plant roots) and the absence of marine fossils or trace fossils.

Fine-grained facies

Fine-grained sediments such as mudstone and siltstone occur frequently in the succession and comprise an important part of the Vegard Formation, but also in the Orustdalen Fm, these sediments are localy important.

Interstratified sandstone, siltstone and mudstone (Facies Fil) - This facies is characterized by coarsely interstratified sandstone, siltstone and mudstone often in an vertically disorganized way. The sandstones are usually fine-grained and the thickness of individual sets vary from some cm to a few dm often with a lensoidal geometry. The sandstones may be ripple-laminated and locally trough cross-stratified, but in most situations primary sedimentary structures were not recorded. The interbedded, grey and dark-grey siltstones and mudstones, which often are rich in organic material, may be massive or laminated. Plant fossils are common, both as carbonaceous films and root imprints. Thin coal seams and zones of siderite concretions are present within the mudstones.

Rhythmic interstratification of sandstone and mudstone(Facies Fi2) - Sandstones and fine grained sediments occur in a remarkable rhythmic interstratification in the Vegard Fm on the north side of Bellsund, where a more than 100 m thick accumulation of this facies is present (Fig. 3.10). The sandstone sets in this locality vary from a few cm to a few dm in thickness and are most commonly massive and plane, horizontally laminated in the lower part and ripple laminated in the upper part, often with mudstone drapes. The grain size of the sandstones are usually very fine and fine and may decrease upward within the sets. Individual sets are sheetlike and extensive. The base of the sandstones may be burrowed, and plant fragments are common.

The interstratified mudstones/siltstones are usually thinner than the associated sandstones, and are laminated or massive. Plant fragments and thin coal-streaks are common.

Thick mudstone-siltstone beds (Facies Fm 1) - These sediments generally consist of grey and black, massive and laminated mudstone and siltstone.

Plant fossils and coal-streaks are common. Thin coal seams and zones of clay ironstone nodules may be present. This facies may reach a thickness of nearly 10 m, and is best developed in the Vegard Formation, where it is closely associated with Facies Fi1.

Thin mudstone-siltstone drapes (Facies Fm 2) - Relatively thin mud-drapes are very commonly associated with most of the sandstone facies, and consist of massive or laminated, grey or dark-grey, often coaly, mudstone or siltstone. Plant fossils and root horizons are commonly found within such sediments. Thin sets of pebble and granule congolomerates have also been frequently found associated with this facies.

Interpretation of the fine grained facies

The interstratified sandstone/mudstone-siltstone facies (Facies Fi1) reflect an environment where the stream energy was low for long periods of time, and where fine grained sediments in the clay and silt fraction were deposited from suspension. These calm periods were frequently interupted by periods of more active currents, where sand was transported over relatively long distances probably as bedload (traction current). The water depth was mainly shallow, as indicated by in situ plant roots. This facies is commonly associated with fluvial channel sandstones, and most likely represents depositon on flood plains, in shallow abandoned channels or lakes. Bothroyd and Ashley (1975) and Steel and Aasheim (1978) showed that such deposits are common in the more distal parts of a braided-stream system.

The interpretation of the rhythmic interstratified facies (Facies Fi2) present in the Vegard Formation on the north shore of Bellsund is difficult, mainly because of the limited data record. (The present data were collected during a few hours of field-work in 1977). An attempt at more extensive investigation failed in 1981, because of difficult snow and ice conditions. It is, however, suggested on the basis of general sedimentological considerations that these sediments are thinly bedded turbidites. The nature of the water body, or basin, in which the sedimentation took place is little known, but it seems likely that it was relatively shallow as indicated by associated facies with in situ plant roots and coal (Facies Fi1 and Fm1). No marine fossils have been found in, or associated with this facies.

The thick accumulations of mudstone/siltstone/(Facies Fm1), reflect deposition from suspension during long periods of time. In most situations this facies is associated with fluviale sandstones and in such situations it probably represents flood basin or abandoned channel environments. However, similar sediments are also associated with Facies Fil (see above) and in such cases probably represent a more extensive and permanent waterbody.

Thinner mudstone sets or drapes interstratified in the fluvial sandstones reflect deposition in sporadic, standing water bodies under low flow stage.

ORUSTDALEN FORMATION: FACIES SEQUENCES AND OVERALL INTERPRETATION

The general fluvial origin of the Orustdalen Formation has already been established (see above). In order to detect any preferential vertical arrangement of lithofacies, Markov Chain Analysis has been carried out. 336 lithofacies transitions in the Orustdalen Formation, from the two sections on Nordenskiöld Land and from the Trygghamna have been analysed. In order to reduce the number of states some of the most related facies (described above) have been combined (Fig. 34).

Few strong Markov properties have been found, but the analysis reveals soms weak properties which are summarized in Figure 3.4. Fining upward sequences form conglomerate to mudstone, (which may be recognized in the field) are also seen from the Markov Chain Analysis. The thickness of such sequences varies from less than a meter to several tens of meters. The most common upward transitions go from conglomerates and massive, pebbly sandstone at the base of the sequences, trough and planar cross-stratified sandstone in the central parts, and terminate in ripple laminated sandstone and mudstone. Such fining upward sequences are comparable with sequences described from the Battery Point Fm (e.g. Cant and Walker 1976). Cant (1978) compared this Battery

Point sequences with the recent South Saskatchewan River and found certain similarities in facies development. Based on this, the following interpretation may be suggested for some of the fining upwards facies sequences of the Orustdalen Formation: The trough cross-stratification in the lower part of the facies sequences corresponds to deposition of dunes in the deeper channels. Cosets of superimposed planar cross-beds resemble the stratification of complex sand flats. Solitary planar cross-sets may be related to slipface-bounded bars in the channels. The ripple cross-laminated sandstone and mudstones present in the upper part of sequences (Fig. 3.4) corresponds mainly to deposition in shallow areas of the river and in adjacent flood basin.

Miall (1977) distinguished between several types of repetitive vertical sequences, or cycles, in a braided stream environment: 1) A flood cycle: a superimpositon of beds formed at progressively decreasing energy level. 2) A cycle due to lateral accretion: a cycle generated by side or point-bar growth is possible, as in a meandering river environment. 3) A cycle due to channel aggradation: this cycle would represent the fill of a channel or a local channel system. Waning energy level would occur during sedimentation, followed by channnel abandonment as a result of avulsion. 4) A cycle due to channel re-occupation: an abandoned partially filled channel may be re-occupied by avulsion.

Cycles of all these categories are probably present in the formation, but insufficient lateral exposure make it often difficult to make a shaded distinction. Flood cycles are most easily recognized in the fine grained association as superimposed small-scale, fining upward sequences. Fining upward sequences due to lateral accretion of channels may be distinguished if lateral accretion surfaces or ϵ-cross-stratification are preserved. However, the exposures are not good enough for such observations.

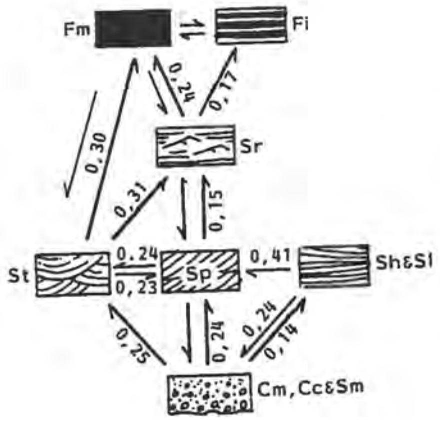

Fig. 3.4 Markov properties for facies or combination of facies in the Orustdalen Fm. The arrows indicate the most probable upward transitions from one lithology to another. The number represents the probability for such an upward transition

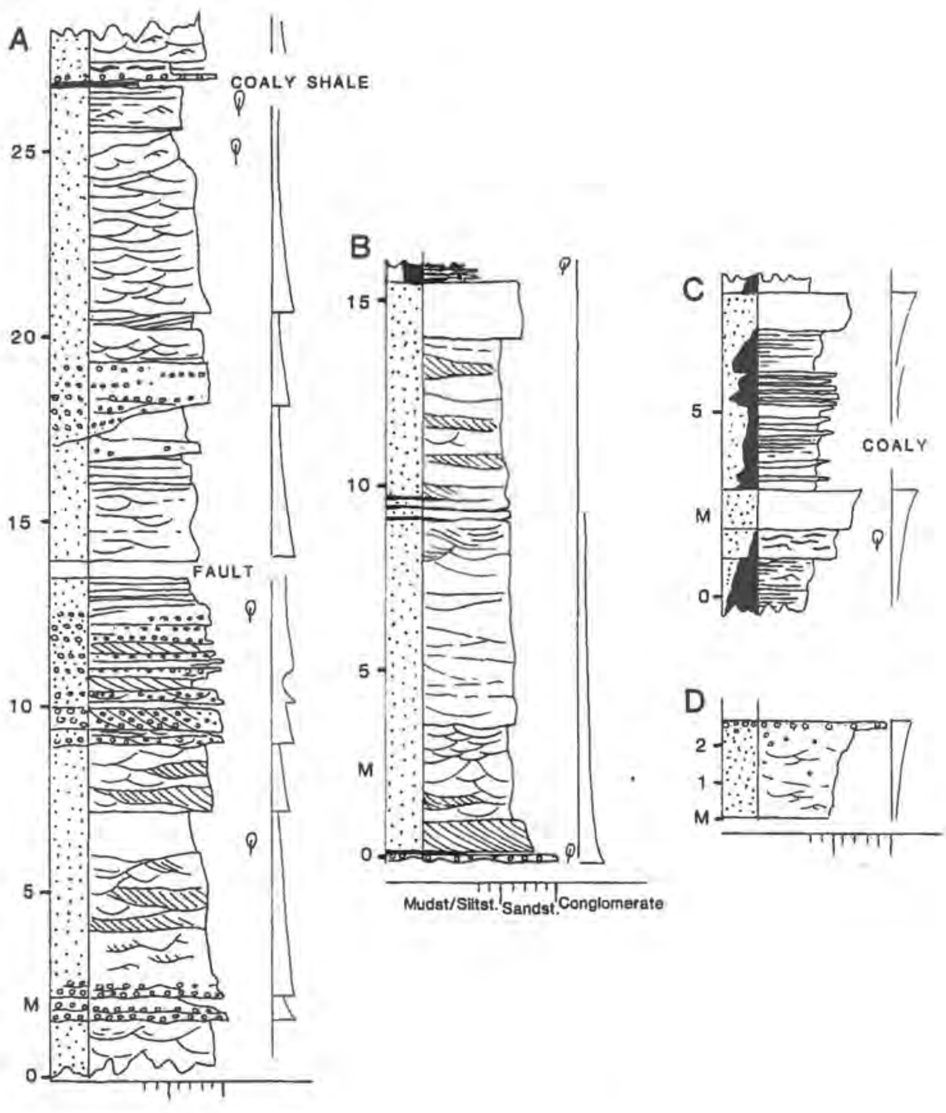

Fig. 3.5 Typical sequences from the Orustdalen Fm. on Nordenskiöld Land. A and B represents typical fining upward sequences, whereas C and D shows some of the few coarsening upwards sequences recorded in the formation

In addition, far more detailed sedimentological work is needed in order to identify and understand the nature of individual sequences.

Some representative sequences from the formation are shown in Figure 3.5. Section A and B shows typical fining upward cycles. Section A represents the relatively coarse grained lower part of the formation, whereas section B occurs in the middle part.

Some examples of coarsening upward sequences are present in the formation. Such sequences (< 5 m thick) commonly consist of mudstone/siltstone in the lower part, whereas cross-stratified, massive or ripple laminated sandstone dominate the upper part (Fig. 3.5). These sequences are often associated with fine grained sediments probably of flood plain or flood basin origin, and are comparable with crevasse splays, like those recognized from the Hørbyebreen Formation (See Fig. 3.5). It is also possible that progradational infilling of reoccupied abandoned channels may generate sequences of similar shape and scale (see also Miall, 1977). Bluck (1980) recognized coarsening upward sequences in the Old Red Sandstone of Scotland, which have been generated by migrating medial bars. Some of the coarse grained, coarsening upward sequences of the Orustdalen Formation probably represent similar development, especially those closely associated with active channel sedimentation.

The cyclic development of the Orustdalen Formation is not easy to recognize in the field, and in most localities the vertical arrangement of facies is rather complex and apparently random. This seems to be due to the many curved, often interconnected erosion surfaces, which only rarely allow fully developed facies sequences to be preserved.

It is difficult to prove that all of the fining upward sequences of the Orustdalen Formation represent sandy braided streams rather than meandering streams. There are no absolute criteria for distinguishing the deposits of distal braided and meandering fluvial systems (Rust 1978), and in many situations the absolute nature of the palaeochannel pattern may be relatively unimportant.

Palaeoccurent analyses indicate that the drainage direction of the braided stream systems responsible for deposition of the Orustdalen Formation was towards east and south (Figs. 3.1 and 3.2). The thick accumulations of braided stream sediments probably represent extensive sedimentary cones (or coalescing humid alluvial fans), mainly derived from a major source area west of the present coast of western Spitsbergen. The fan geometry is difficult to prove. However, palaeocurrent pattern together with the overall distribution of the sediments along west Spitsbergen suggest such environmental and morphological development.

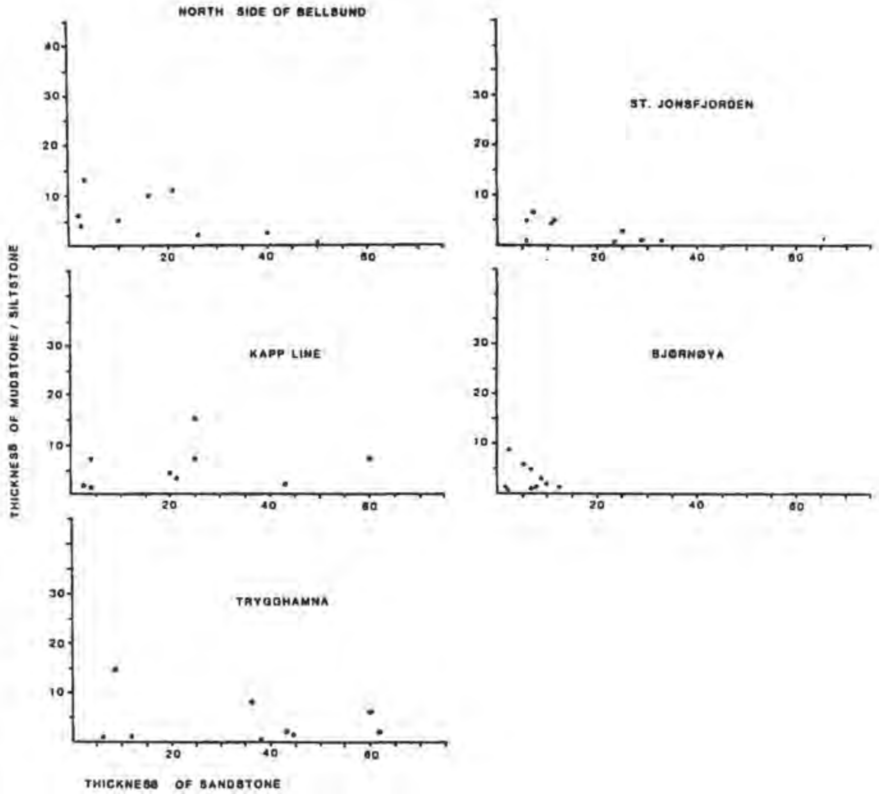

Fig. 3.6. The relation between the thickness of sandstone units and mudstone/siltstone units in some Culm profiles on Svalbard.

As a result of extensive amalgamation of channel sandstones near the axis of the cones, thick units of coarse sediment tend to accumulate here. This occurs at the expense of fine-grained, flood plain sediments, which have a much higher preservation potential on the flanks of the cones. An inverse relationship should therefore be expected between coarse and fine grained units in a vertical section through such sediments, supposing that the axis of the cone system shifts laterally through time. Such a relationship has been recorded from most of the "Culm" sections on Svalbard (Fig. 3.6), and hence supports the suggestion of a cone system where the active stream channels tend to migrate laterally across the cone surface (see also Bluck 1980).

The vertical evolution of the Orustdalen Formation shows in general an overall fining upwards tendency which culminates in the fine-grained Vegard Formation above. However, more detailed investigation shows that it may be subdivided into two fining upward megacycles (Fig. 3.7). The lower megacycle is up to 360 m thick and represents a gradual development from dominantly coarse - medium sandstone and conglomerate to fine sandstone and shale. The second megacycle consists generally of medium and fine sandstone in the lower part (no conglomerates) and grades upward into the fine grained deposits of the Vegard Formation. This large-scale cyclicity has been recorded from most localities in central western Spitsbergen (Fig. 3.7) and there is also some tentative indications that similar development is present in the Hornsundneset Fm. It is therefore most likely that this development is related to wide-spread features such as climatic changes, regional tectonism, extensive isostatic movements (eg. affecting the source area).

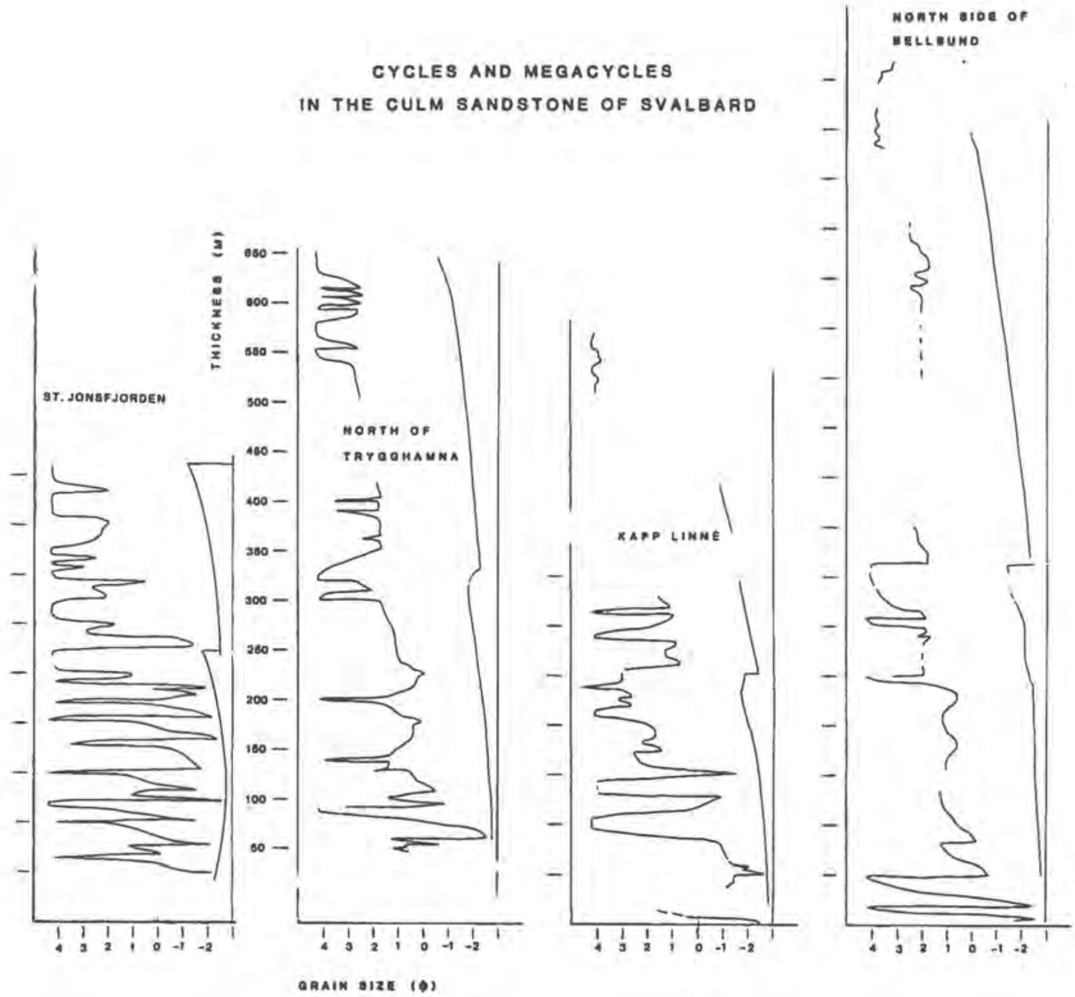

Fig. 3.7. Cycles, and megacycles from the "Culm" (Namurian) sequences at different localities on Spitsbergen.

VEGARD FORMATION: OVERALL INTERPRETATION

On Nordenskiöld Land the Vegard Fm. is generally poorly exposed, and the only investigated section is located in Diabasbukta on the northern shore of Bellsund. Unfortunately, the base of the formation is not exposed here. The lower half of the section, which also includes a 26 m thick dolerite sill (Fig. 3.8), shows a sedimentary development dominated by well stratified fine sandstone and siltstone/mudstone, mainly of Facies Fi1, and probably represents a flood plain or flood basin environment. The lower part of the upper half consists mainly of Facies Fi2, (Figs 3.9, 3.10) tentatively interpretated as thinly bedded turbidites (see above). The turbidites becomes thinner upwards, and are replaced by interstratified mudstone and siltstone. These fine grained sediments make the base of a well defined coarsening upward sequence which is overlain by quartzitic sandstones and which defines the top of the section (Fig. 3.8). This sandstone may (according to R. Steel and E. Johannessen pers. komm. 1982) represent a tidal environment. This because they, during the Statoil's Svalbardexpedition (1982) discovered a distinct horizon of skolitos in the upper part of the unit. This corresponds well with the observations farther north, at St. Jonsfjorden, where marine trace fossils occur in the middle part of the Vegard Fm. This represents one of the first marine incursions prior to the Middle Carboniferous of central western Spitsbergen.

The development of the upper part of the Vegard Formation at Bellsund most likely reflects deposition into an extensive basin which had sufficient subaqueous gradien to generate gravity currents. The coarsening upward sequence at the top of the formation probably represents a progradational (deltaic) infilling of such a basin.

Very few palaeocurrent measurements have been gained from the formation and a palaeogeographic reconstruction is difficult. There is, however, some few indications that the progradational (deltaic) sequence at the top built out towards north (Fig. 3.8).

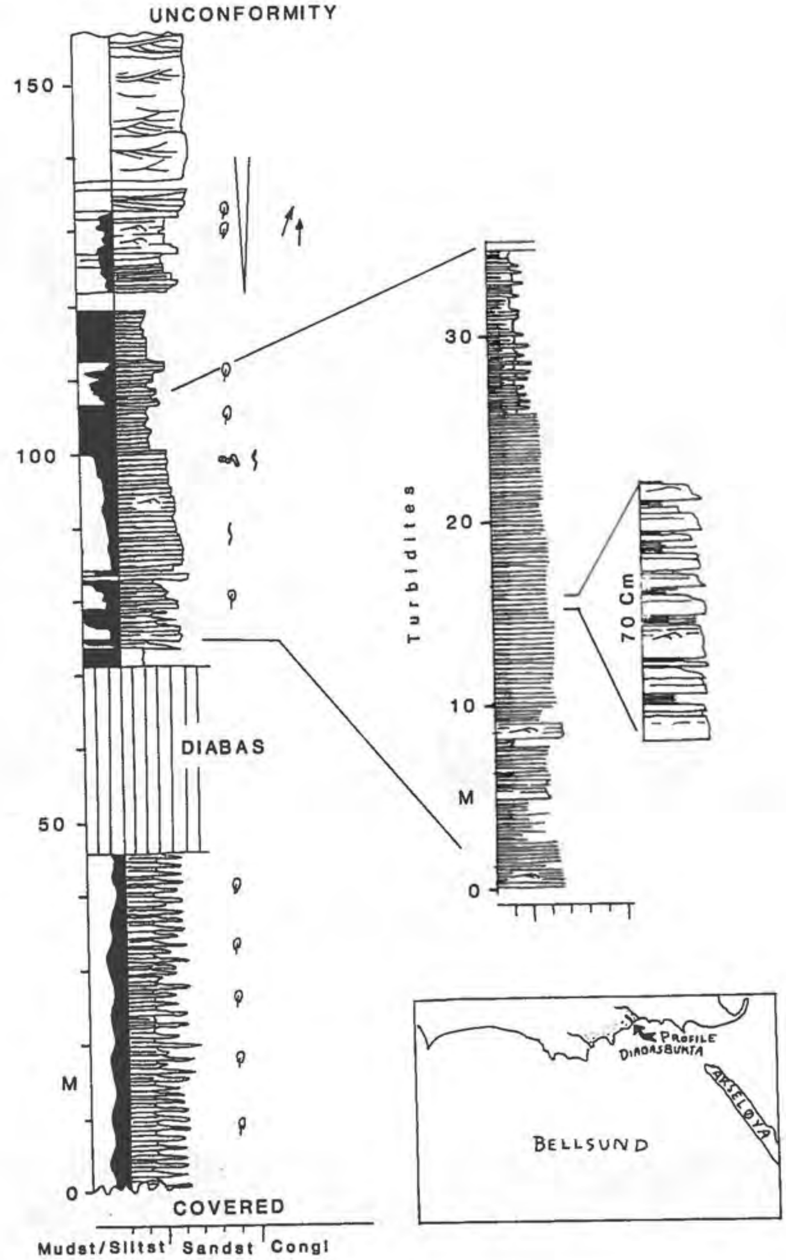

Fig. 3.8 Stratigraphic section from the Vegard Formation on the north side of Bellsund

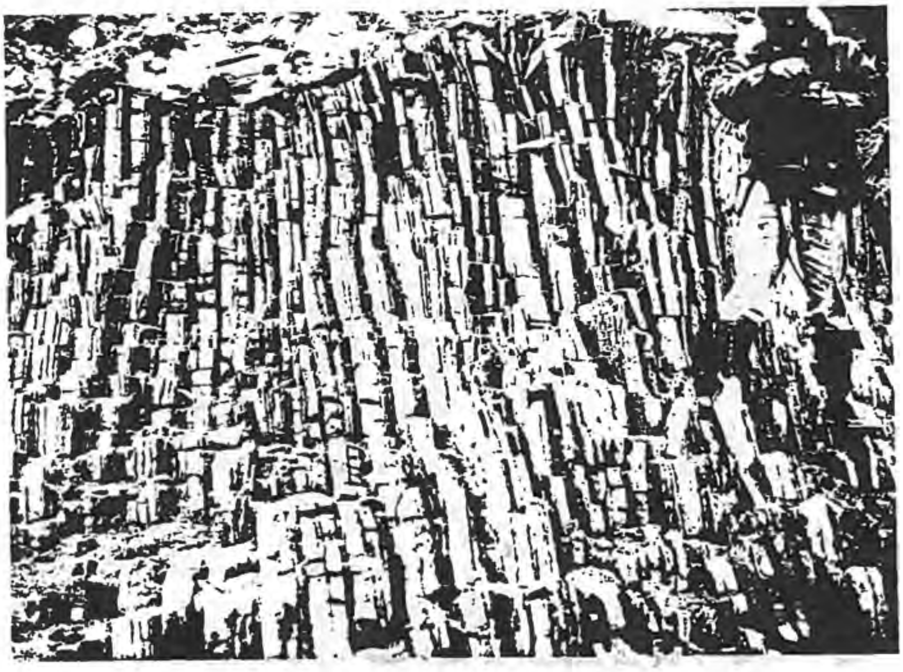

Fig. 3.9 Thinly bedded turbidites from the Vegard Formation (Namurian), north side of Bellsund.

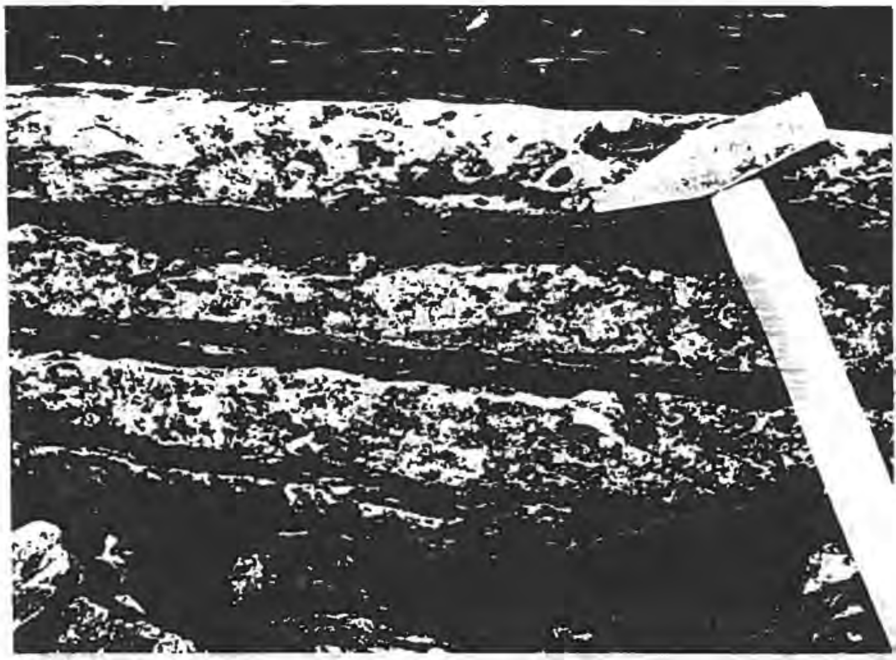

Fig. 3.10 Details from the thinly bedded turbidites illustrated above.

OTHER LOWER-MIDDLE CARBONIFEROUS LOCALITIES IN THE BELLSUND AREA

REINODDEN

In addition to the exposures north of Bellsund, (described above), there are also some other localities where the Lower-Middle Carboniferous succession is exposed on the western part of Spitsbergen. The best known of these localities is Reinodden on the southern shore of Bellsund. This outcrop was examined by Orvin (1940) and described by Winsnes (1966). The beds are inverted and strongly faulted. The thickness of the Lower Carboniferous (Billefjorden Group) is > 700 m. The succession starts with a unit of black shale, which probably corresponds to the Adriabukta Fm. (Yen Sun, 1980). These rocks have not been described in any published work yet, probably because the exposures until recently have been covered by ice from the glacier. Overlying these black shales occurs a thick succession of grey quartzitic sandstone which shows no significant different development from the Orustdalen Formation elsewhere on Spitsbergen. The upper part is more shaley and probably represents a lateral equivalent to the Vegard Formation north of Bellsund.

The Middle Carboniferous (Bashkirian) succession which unconformably overlies the Billefjorden Group (Dineley 1958) consists of some 250 m of red and grey conglomerates, sandstones and shales, interstratified with some thin limestone beds (Winsnes 1966). This red bed succession was named the Reinodden Formation by Cutbill and Challinor (1965). The exposures of the formation are rather poor and not suitable for detailed facies analysis.

MIDTERHUKEN

The Orustdalen Formation is also exposed at Midterhuken on the peninsula between Van Mijenfjorden and Van Keulenfjorden. Here the contact with the underlying Hecla Hoek basement is exposed and also the angular unconformity with the overlying Drevbreen Beds (Nysæther 1977, Tangen 1980, Nettland 1981). The locality has not been visited by the author.

WEDEL JARLSBERG LAND

Beside the Reinodden locality no other Lower Carboniferous exposures are known on Wedel Jarlsberg Land. Middle Carboniferous red beds (conglomerates, sandstone, shale and limestone) are, however, exposed at several localities (Rozycki 1959).

INNER ST. JONSFJORDEN AREA, OSCAR II LAND

INTRODUCTION

This investigation of the Lower-Middle Carboniferous succession of the St. Jonsfjorden area is based on five days of field work on Vegardfjella in innermost St. Jonsfjorden. Vegardfjella represents a mountain ridge about 8 km long (Fig. 3.11) on which the highest summit, Tårnkanten, reaches an altitude of about 850 m. The exposures are locally good, but large areas of the mountain are coverd by scree. The best exposures commonly occur in steep and almost unaccessible parts of the mountain.

The field work was concentrated on measuring vertical stratigraphic sequences in order to understand the depositional environment and the development of the depositional basin which has been defined as the St. Jonsfjorden Trough by Cutbill and Challinor (1965). The inner St. Jonsfjorden area is very important in understanding the regional Carboniferous geology of Spitsbergen as a more or less continual lower-middle Carboniferous succession is present in the area.

STRATIGRAPHIC SETTING

The Lower-Middle (Tournaisian-Bashkirian) Carboniferous succession of the inner St. Jonsfjorden area unconformably overlies the tillite conglomerates of probably Vendian, volcanogenic origin (e.g. Hjelle et al. 1979, Harland et. al. 1979). The succession is conformably overlain by the Nordenskiöldbreen Formation (Cyathophyllum Limestone of Dineley 1958), which largely consists of limestone and shale, and generally represents a carbonate shelf environment. The investigated succession consists of four formations: Orustdalen Fm., Vegard Fm. (The Billefjorden Group), Petrelskardet Fm., Tårnkanten (Gipsdalen Group). This stratigraphy was defined by Cutbill and Challinor (1965), however, the first stratigraphic subdivision was made by Dineley (1958).

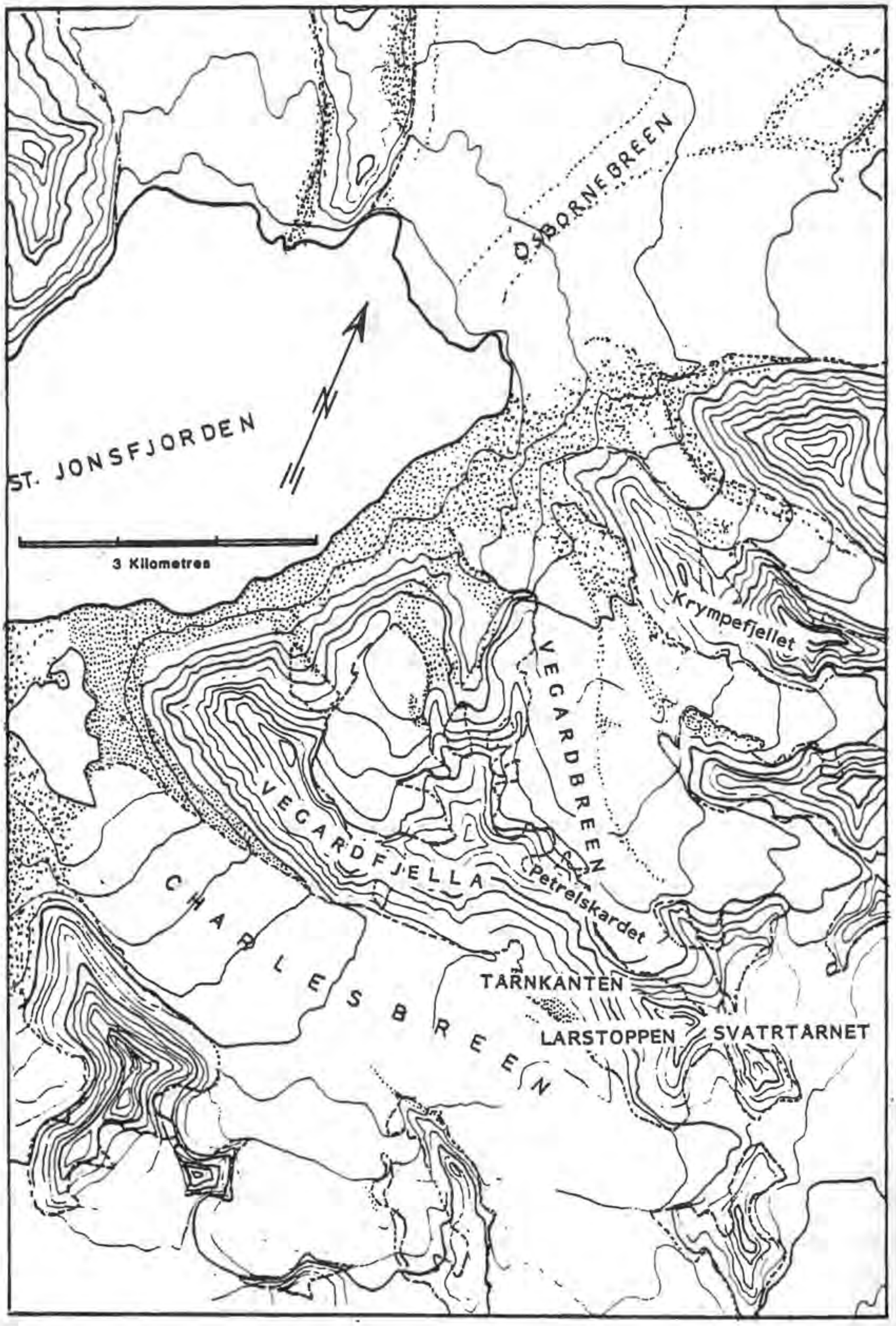

Fig. 3.11. Topographical map of the Inner St. Jonsfjorden area.

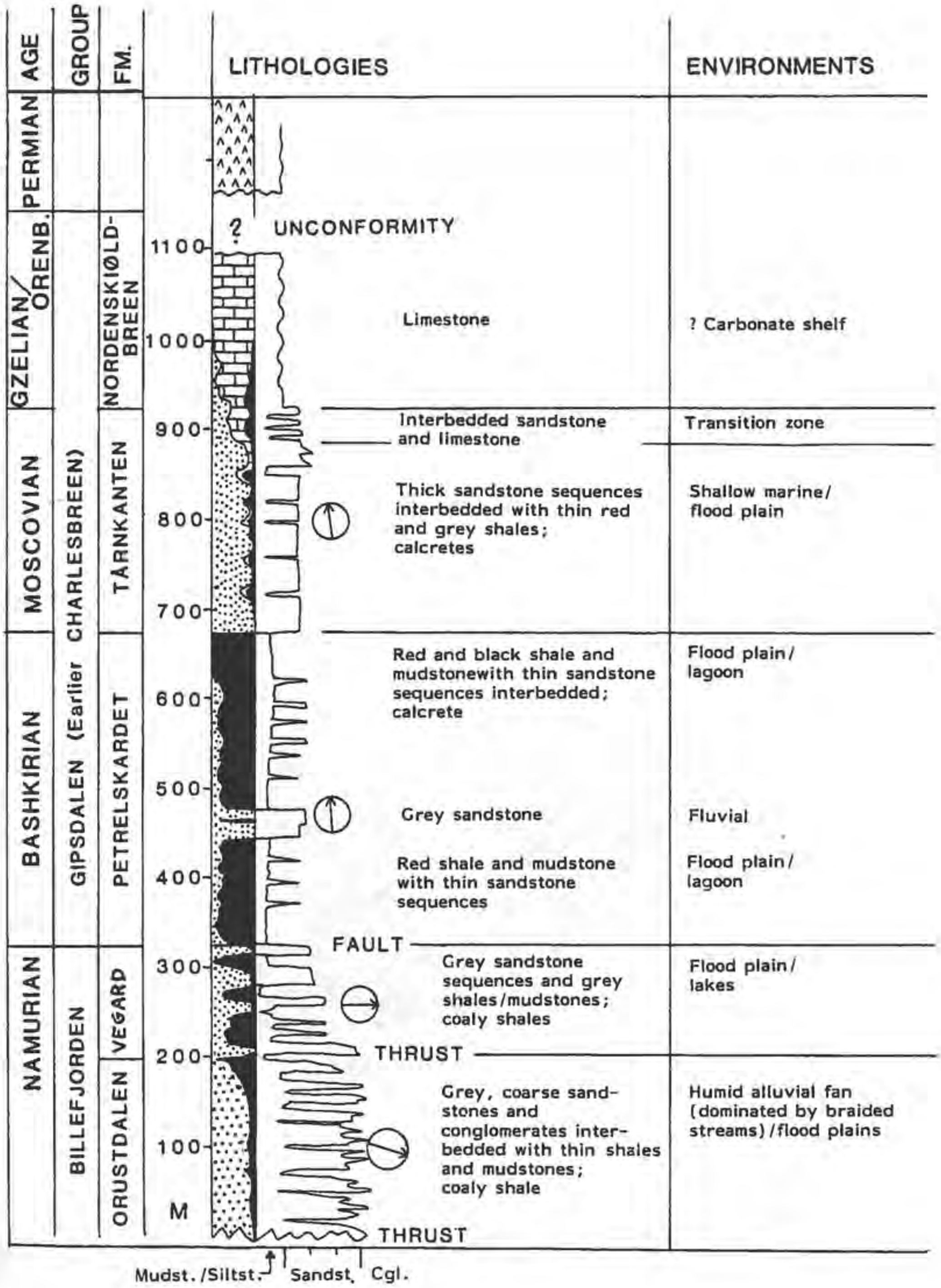

Fig. 3.12. Generalised stratigraphic column of the Carboniferous succession of the Inner St. Jonsfjorden area.

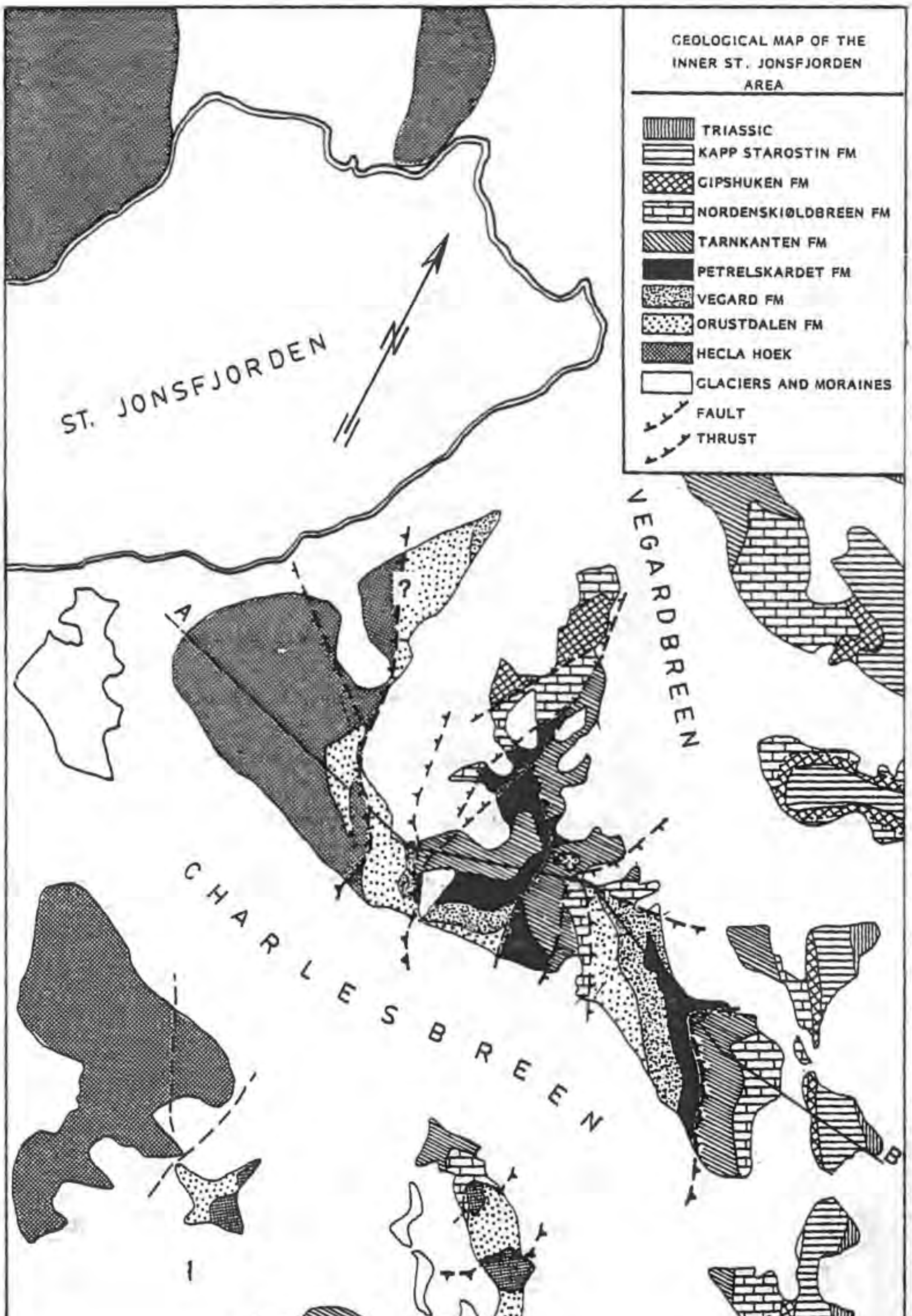

Fig. 3.13. Geological map of the Inner St. Jonsfjorden area. Line A-B represents the cross-section shown in Fig. 3.14.

A generalized stratigraphic column from the investigated succession is shown in Fig. 3.12. This figure also includes a brief interpretation of the depositional environments.

TECTONIC SETTING

Most of the tectonic deformation in the investigated area probably occurred during the Tertiary, West Spitsbergen Orogeny. Low to moderately westward-dipping faults and regional folds with NNW-SSE axial trends are the main elements of tectonic architecture (Hjelle <u>et</u>. <u>al</u>. 1979). The boundary between the Hecla Hoek and the Upper Palaeozoic succession on the western part of Vegardfjella is largely a NNW-SSE trending thrust fault with moderate to steep westward dip (Figs. 3.13, 3.14). Another thrust fault, also dipping westward occurs only a few hundred metres east of this "boundary fault" (Fig. 3.13). The central parts of Vegardfjella form a large open anticline disected by normal faults, which probably represent some of the youngest tectonic events in the area.

In the eastern part of Vegardfjella two important thrust faults with an approximately eastward dip are present (Fig. 3.14). This observation is in sharp contrast with most other observations from the West Spitsbergen Tertiary Orogenic belt which generally shows westward dipping thrust faults (eg. see Lowell 1972).

ORUSTDALEN FORMATION: FACIES SEQUENCES AND OVERALL INTERPRETATION

The best exposures of the Orustdalen Formation (Namurian) are located on the northwestern edge of Vegardfjella (Fig. 3.13), and occur in a vertical and overturned position (Fig. 3.14). A section about 200 m thick has been measured from this locality (Fig. 3.12). This section is, however, not complete as the lower part is missing due to tectonism, and the contact between the Hecla Hoek and the Orustdalen Fm. is a fault plane at this locality (Fig. 3.14). However, there is an outlier of the Orustdalen Fm. just west of the investigated locality (Figs. 3.13, 3.15) in which the primary contact between the Hecla Hoek and the Lower Carboniferous may be present together with the lowermost 20-30 metres of the Orustdalen Formation. Unfortunately, this locality is poorly accessible. The boundary to the overlying Vegard Formation is difficult to define in this area as the transition from the sandy Orustdalen Fm. to the more shaley Vegard Fm. appears to be rather gradual.

The Orustdalen Formation consists of 16% mudstone, siltstone and shale, ca. 30% conglomerate and up to 54% sandstone. The lithofacies present in the formation are similar to those present at other localities of the Orustdalen Fm. (eg. Trygghamna, Kapp Line and on the north side of Bellsund).

The lower part of the Orustdalen Fm. consists largely of sandstone facies with occasional thin conglomerates interbedded. Fine grained lithofacies (mudstone, siltstone, shale) are present also in the lower part of the formation though they are scarce (Fig. 3.15). Both conglomerates and the fine grained facies become more abundant upwards, and the uppermost part of the formation consists largely of conglomerate and mudstone in alternation (Fig. 3.15).

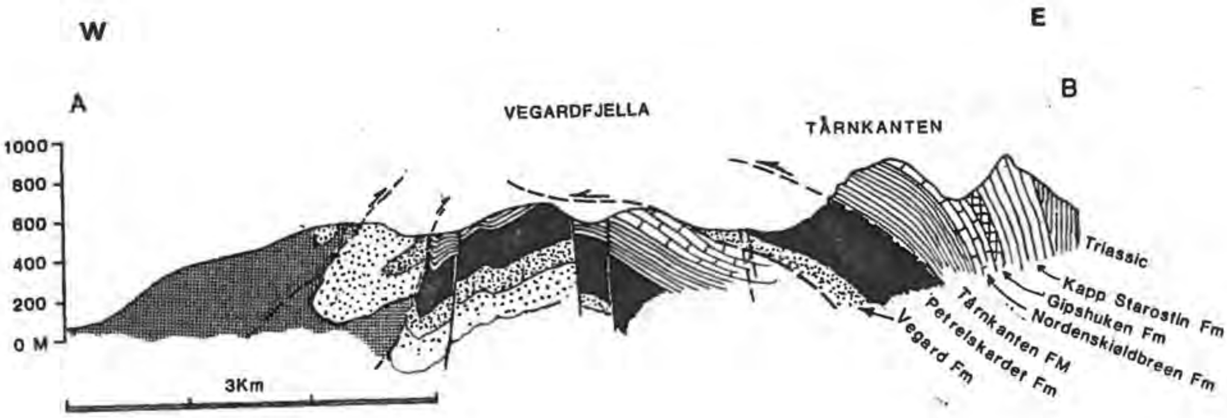

Fig. 3.14. Cross-section along the Vegardfjella. Two important zones of thrust faulting occur in the area: In the western part of the mountain there are two westward dipping thrust faults, one of which make the boundary between the Hecla Hoek and the Carboniferous successions (Fig. 2). In the eastern part of the mountain there is another zone of thrust faulting but here the fault planes dip approximately eastward.

The vertical arrangement of lithofacies appear to form a complex and apparently random sequence. However, fining upward sequences ranging from a few metres and up to 12 metres thick are present throughout the formation, and most of the fine grained facies represent the termination of such fining upward sequences (Fig. 3.15). A few, relative thin, coarsening upwards sequences (about half a meter thick) are present in the middle part of the sequence. The formation contains abundant plant fossils and coaly shales are present at several levels. No indications of marine influence were recorded.

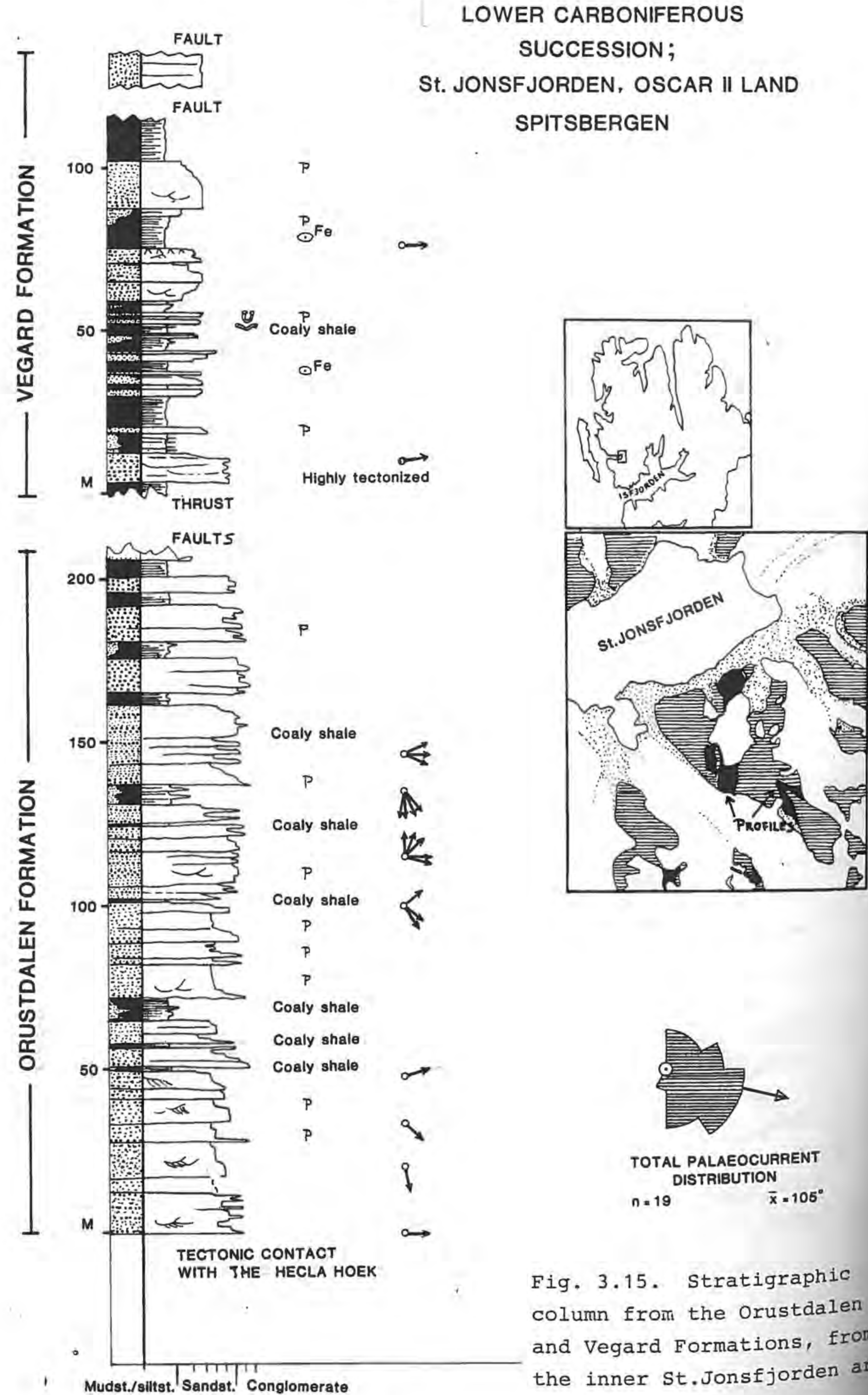

Fig. 3.15. Stratigraphic column from the Orustdalen and Vegard Formations, from the inner St.Jonsfjorden area.

Fig. 3.16. The outcrops of the Orustdalen Formation on the western part of Vegardfjella. The dark rocks represent the upthrusted Hecla Hoek formation.

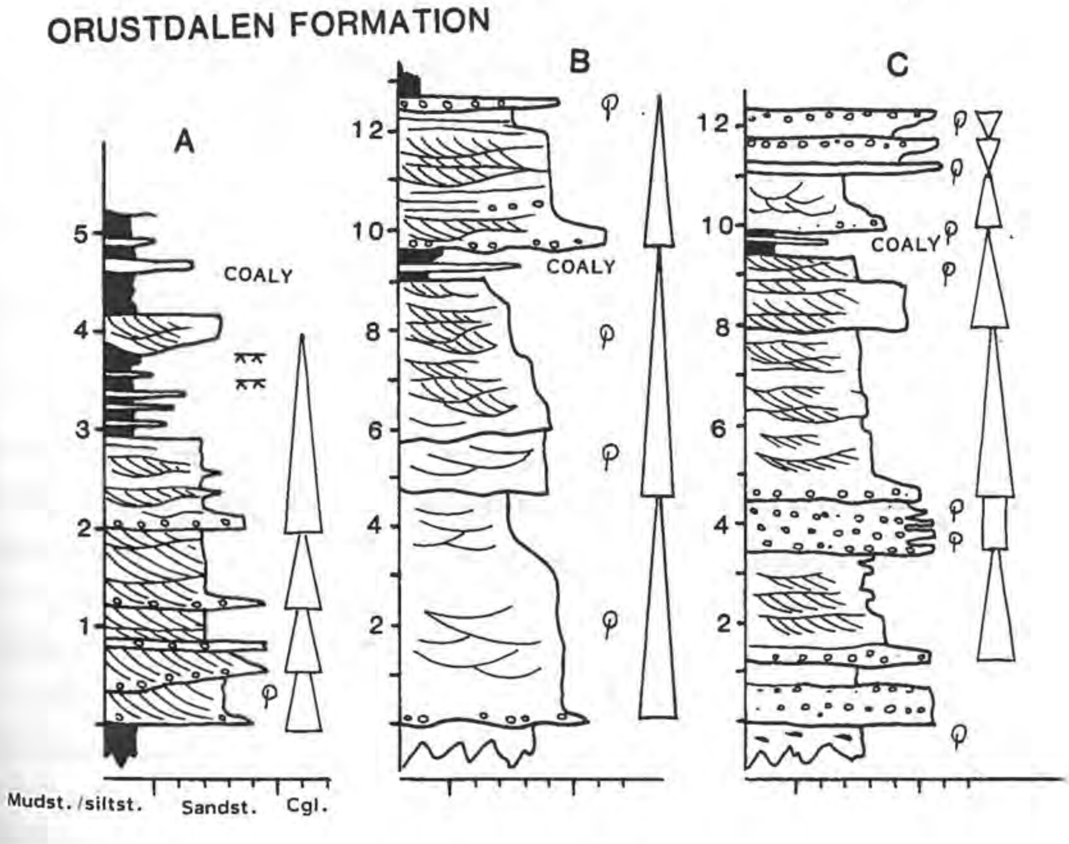

Fig. 3.17. Typical sequences of the Orustdalen Formation as it appears in the inner St. Jonsfjorden area.

The Orustdalen Formation in the inner St. Jonsfjorden area is broadly similar to the Orustdalen Formation elsewhere on western Spitsbergen, though it tends to be more conglomeratic than at the localities around Bellsund and Isfjorden. The conglomerates at St. Johnsfjorden are, however, relatively fine grained with a maximum particle size usually less than 2 cm. The St. Jonsfjorden section also differs from the section north of Bellsund in that large, relative deep channel-fill bedforms are less common.

The formation is interpreted in terms of braided stream deposits. This interpretation is consistent with the interpretation of the Orustdalen Formation at other localities along the west coast of Spitsbergen, where there are similar depositional patterns and suites of sedimentary structures. The sandstones and conglomerate facies were, in general, deposited within the belts of active braided stream channels, whereas the fine grained facies represent the flood areas. The complexity of the coarse grained units reflects the complex relationship of channels, migrating sand flats and bars in such an environment. The rapid lateral shifting and lateral migration of channels tends to produce a complex stratigraphic sequence with many marked curved erosion surfaces.

It is suggested here that the Orustdalen Formation in the St. Jonsfjorden area represents an accumulation of humid fan or sediment cone systems similar to those recognized from the Nordkapp Formation on Bjørnøya (Gjelberg 1981b), from the Hornsundneset Formation and from the Orustdalen Formation in the Bellsund and Isfjorden area. The cyclicity of fining upward sequences observed within the formation (Fig. 3.17), may reflect the lateral migration of the channel belt from one side of the cone to the other . (See also page 182). Bluck (1980) concluded that the preservation of such cycles is favoured by wide floodplains with few streams and a rate of lateral migration which is not great compared with the rate of alluviation or subsidence. He also showed that there is an inverse relationship between the thickness of coarse and fine members. Such a relationship was recorded from the Orustdalen Formation (Fig. 3.6).

Palaeocurrent analysis from all localities of the Orustdalen Fm. indicate that the source areas were west of the present outcrops. The palaeocurrent data from the St. Jonsfjorden section are, however, unreliable due to the strong tectonic movements in the area, especially close to the thrust faults, where it is very difficult to find out how much and in what direction the succession has been rotated from its primary position.

VEGARD FORMATION: FACIES SEQUENCES AND OVERALL INTERPRETATION

The Vegard Formation was defined by Dineley (1958), who described the formation as "thinly bedded pinkish quartzose sandstones and thin shales" which forms a passage some 125 m thick into the overlying Gipsdalen Group (Charlesbreen Group of Dinely 1958).

The best exposures of the formation occur on the eastern part of Vegardfjella at the base of Tårnkanten (Fig. 3.15), where a sequence about 130 m thick has been measured. The sequence is, however, not complete as it is limited by faults both at the base and at the top. The formation is rather poorly exposed, especially due to the strong tectonism of the area. It consists of about 50% sandstone, 48% siltstone and mudstone (with some sandstones interstratified) and about 1% conglomerate. Most of the lithofacies are similar to those of the Orustdalen Formation.

Insufficient exposure makes it also very difficult to interpret the formation. It is, however, likely that most of it represents continental depositional environments, as suggested by abundant plant fragments and lack of marine indicators. The only observation which could suggest elements of marine or marginal marine conditions are the U-form burrows in the middle part.

The lowermost part of the Vegard Formation consists of a very coarse sandstone and conglomerate sequence (8 m thick), which is very similar to the coarse units of the Orustdalen Fm. The overlying 50 m of the formation are largely of fine grained facies with relatively thin (1 - 3,5 m) sandstone sequences interbedded. The upper half of the formation contains three thick sandstone sequences (17, 12 and 10 m) and two thick sequences of shale and mudstone (about 14 m thick).

Both coarsening and fining upward sequences are present in the Vegard Fm. (Fig. 3.18). The thickness of the coarsening upward sequences range between 3 and 11 m, while the fining upward sequences range from 3 to 12 m. A detailed description of facies sequences is not attempted here due to the poor exposures.

The Vegard Formation shows similarities with some other Upper Palaeozoic formations of Svalbard. Most comparable is probably the Vesalstranda Member of the Røedvika Formation (Bjørnøya) which was deposited in lakes and large floodplains, occupied by high sinuosity streams (Gjelberg 1978). It is suggested that the Vegard Formation represents similar depositional environments, and that the fining upward sequences may represent point bars of high sinuosity rivers, whereas the relatively thick coarsening upwards sequences were generated due to delta progradation into lakes or lagoons. The fine grained facies generally represent floodbasins, distal

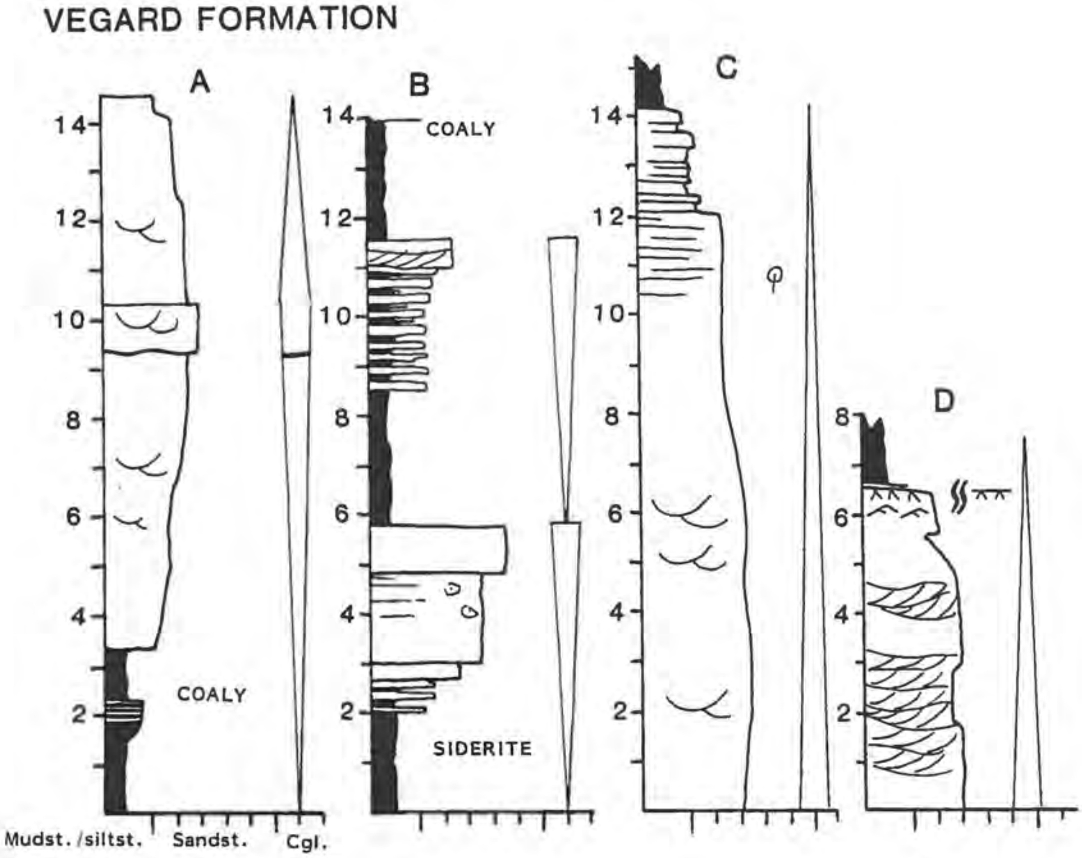

Fig. 3.18. Some sequences from the Vegard Formation on the eastern part of Vegardfjella.
Sequence A most likely represents a progradational infilling of a lake, where the fining-upwards upper part represents the distributary or, crevasse channel. The coarsening upwards sequence in section B are probably crevasse splays. The upper sequence represents a more proximal development than that below. Sequences C and D are point bar deposits of high sinuosity streams.

lakes and probably lagoonal environments. The 8 m thick coarse sandstone sequence at the base, however, is most likely to be braided stream deposits and probably belongs to the same humid fan system as the Orustdalen Fm. It is also a possibility that some of the thinner sandstone sequences may be the product of sandy sheet floods of wide lateral extent (Reading 1978, p.54), related to the same fan or sediment cone system.

PETRELSKARDET FORMATION;

The best exposures of the Petrelskardet Formation (Bashkirian) occur along the west side of Tårnkanten (Fig. 3.19) where a more or less complete section is exposed. Most of the other outcrops (which occur on the central part of Vegardfjella) are incomplete and unsuitable for any detailed investigations. The exact base of the Petrelskardet Formation is not exposed on Vegardfjella, but it is suggested that there is a conformable contact to the underlying Vegard Formation (see Dineley 1958). The contact to the overlying Tårnkanten Formation (Moscovian) is probably also conformable as no major time-break appears between the two formations. The stratigraphic contact between the formations is, however, not exposed at the type locality due to small thrust faults (Fig. 3.14).

The Petrelskardet Formation is about 360 m thick and consists mainly of red and black/grey shales, interstratified with thin, red, grey and white sandstone benches. The only promiment sandstone horizon occurs near the middle of the formation (Fig. 3.19).

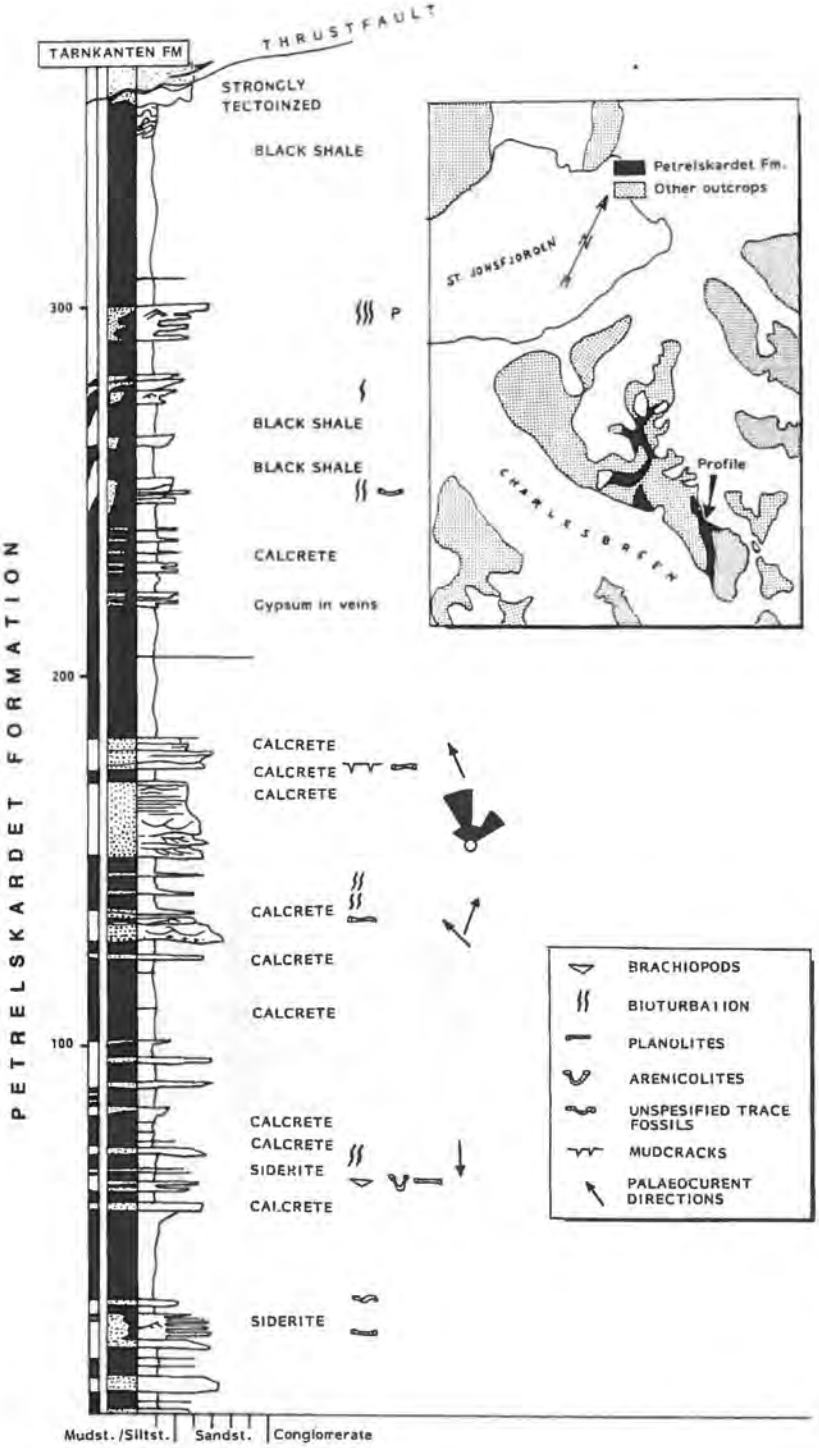

Fig. 3.19. Generalized stratigraphic section from the Petrelskardet Formation (Bashkirian), Inner St. Jonsfjorden area. The black zones of the left column indicates where red beds are present.

The following distribution of lithologies is present in the type profile: sandstone; 19%, grey and black siltstone/mudstone/shale; 30%, red siltstone/mudstone/ shale; 51%. The lithofacies present are similar, both with respect to structures and textures, to lithologies described from other Middle Carboniferous red bed formations on Svalbard. An exception here is, however, the very thick accumulations of black shale present in the upper part of the formation.

Facies sequences

Four different types of facies sequences (or facies associations) have been distinguished from the type profile:

Facies sequence	P1	(Channel sandstone)
" "	P2	(Red, fine grained; floodplain and coastal plain deposits)
" "	P3	(Black shale and fine grained sandstone; lagoon, bay or lakes?)
" "	P4	(Prograding infilling of lagoon or lake)

Facies sequence P1 - This facies sequence consists of grey and white, strongly silica-cemented, quartzitic sandstone which generally varies between very fine and medium in grain size. Dominating sedimentary structures are in order of importance: Trough cross-stratification, plane horizontal and low angle stratification, ripple lamination and planar cross-stratification. However, thick intervals appear massive. Individual sequences (usually a few m thick) are often fining upwards from a sharp erosive base, and may be stacked vertically to form thick complex units or horizons of sandstone, up to 20 m thick (Fig. 3.20).

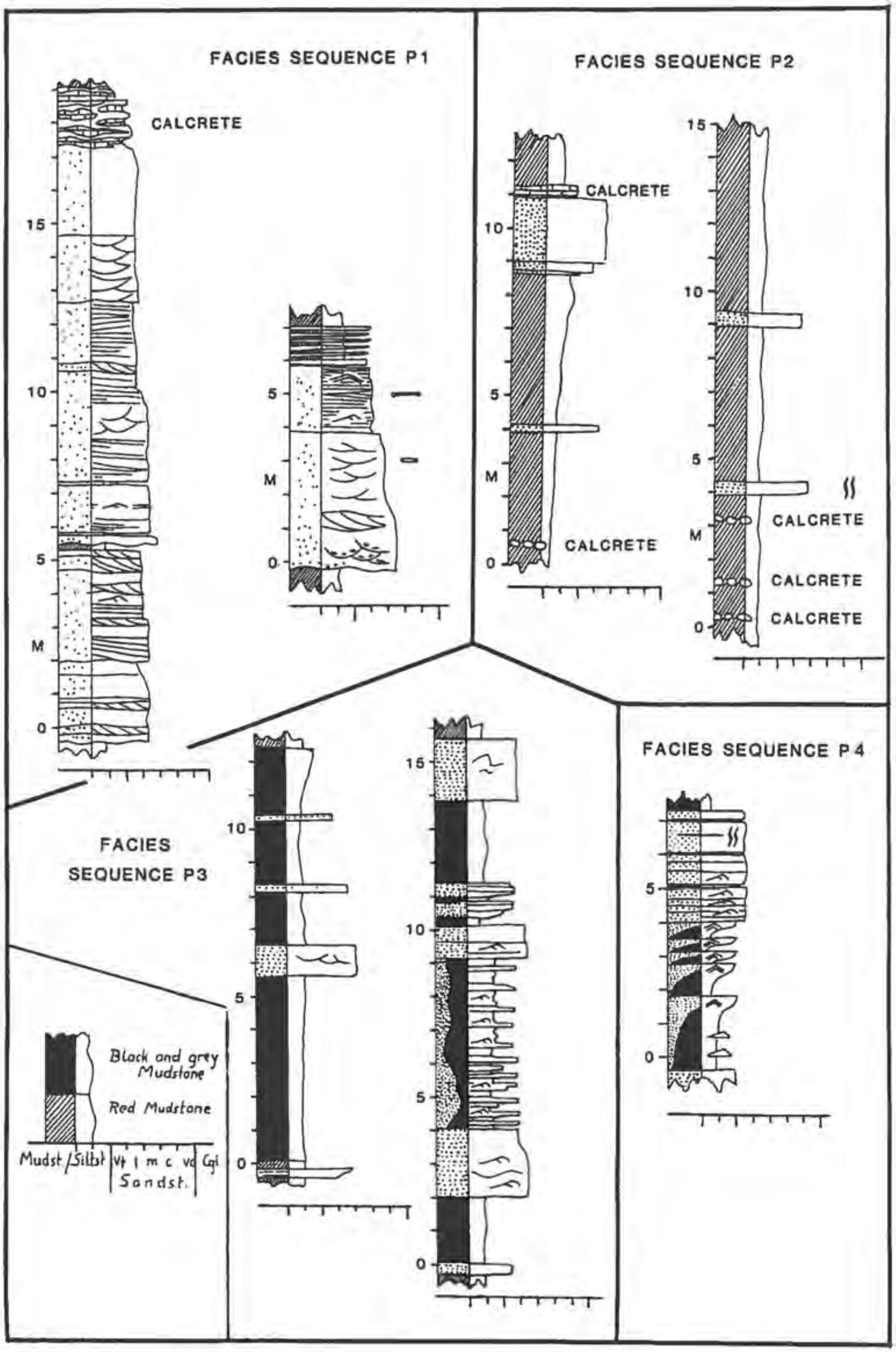

Fig. 3.20. Facies sequences from the Petrelskardet Fm., St. Jonsfjorden.

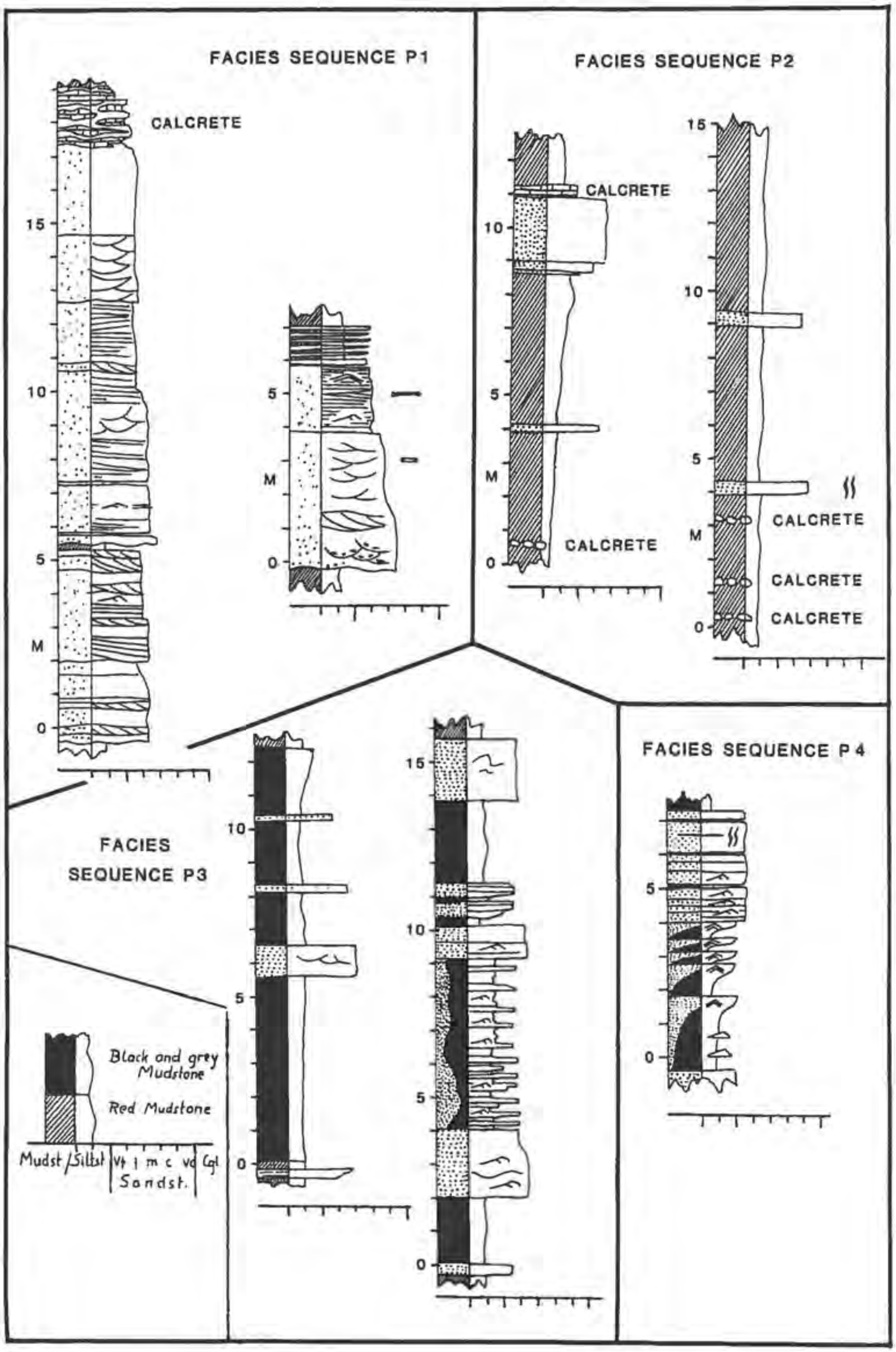

Fig. 3.20. Facies sequences from the Petrelskardet Fm., St. Jonsfjorden.

Bedding plane trace fossils (planolites) and mudcracks are present in the upper part of individual sequences.

Calcretes (more than 2 m thick) are present near the top of the prominent sandstone unit, where quartzitic sand have been replaced partly by calcite to form irregular bands and nodular horizons.

Facies sequence P2 - These sequences are similar to the fine grained red bed sequences present in both the Landnördingsvika Fm. and the Hulteberget Member. They are characterized by thick units (up to 70 m) of red, blocky mudstone and siltstone interstratified with relatively thin (up to 4 m thick), red and fine grained sandstones. The sandstones are very often massive, but occasional zones of trough cross-stratification and ripple lamination are present. Well defined coarsening upward units from red mudstone to red siltstone were recorded from the fine grained sediments. Some selected stratigraphic sections from this facies association are shown in Fig. 3.20.

Calcrete is present within most of the red beds, and occurs mainly as horizons of carbonate nodules. The calcrete horizons appear to be randomly distributed within the red shales, with no obvious cyclicity. However, it is strongly restricted to the red beds. Some of the thickest and best developed calcretes are often located on the top of relative thick sandstone benches. Common for most of these calcrete horizons are that they show similar characteristics as those described by Steel (1974 a) and interpretated as fossil caliche. Most of the caliches from Petrelskardet Fm. are, according to Steel's classification, immature. However, those developed on the top of prominent sandstone sequences may be classified as mature.

Biogenic structures are very rare within the red beds, but a few of the thin, interstratified sandstones are bioturbated.

Facies sequence P3 - Black and grey shales, mudstone and siltstone interstratified with thin (< 2 m), grey sandstone benches are the dominating lithologies of this facies sequence (Fig. 3.20). The fine grained lithologies are blocky or laminated, and may show a slight tendency to coarsening upwards from mudstone to siltstone. The sandstones often appear massive, but intervals of ripple lamination and low-angle trough cross-stratification are present. Some of the sandstones represent the upper part of relatively thin coarsening-upward sequences.

Biogenic structures are very common in the sandstones, and trace fossils such as arenicolites, planolites and other, unspecified, types were recorded. Imprints, probably of brachiopods were seen in one of the sandstone benches. A few zones of siderite concretions occur within the fine grained sediments.

Facies sequence P4 - The only exposures of this facies sequence are located within massive black shales in the upper part of the formation. The sequence is 7 m thick, coarsens upwards (Fig. 3.20) and consists of very fine sandstone, interstratified with mudstone and shale. The lower part consists of stacked, small-scale, coarsening upward sequences of mudstone, siltstone and very fine sandstone, usually with wave ripple lamination. The upper part of the facies sequence consists mainly of sandstone interstratified with thin mudstones. The top is strongly bioturbated.

Interpretation of the facies sequences

Facies sequence P1 most likely represents a fluvial depositional environment. This suggestion is consistent with the fact that typical subaerial indicators (such as mudcracks and calcrete) are closely associated with the sediments. Primary sedimentary structures indicate that deposition took place under relatively high energy conditions (eg. plane lamination of upper flow regime), and palaeocurrent analysis suggest a relative unidirectional palaeocurrent flow. Whether the sandstones represent meandering or distal braided rivers are not clear from the present data.

Facies sequence P2 represents similar depositional environments as the thick fine grained red beds associations of the Landnördingsvika Fm. (Gjelberg 1981b) and the Hulteberget Member (Ebbadalen Fm.), which most likely developed as floodplains or coastal plains in front of arid or semiarid alluvial fans (Gjelberg 1981b, Gjelberg and Steel 1981, Aakvik 1981). The relative thin sandstones interstratified probably represent episodes of severe flooding, resulting in deposition of extensively distributed sand in front of the fan system (see also Collinson, 1978).

It is difficult to give an exact interpretation of Facies sequences P3 and P4, especially due to the very small lateral extension of the exposures. It is, however, likely that the sediments represent reducing conditions, which were in sharp contrast to the red bed development of Facies sequence P2. The only indications of marine influence to the system are represented by the imprints of brachiopods and U-formed trace fossils (arenicolites). Due to the very close association between Facies sequence P3 and the continental red beds of Facies P2, it is suggested that the black and grey, fine grained sediments were deposited in relatively shallow water, probably in lagoon, bay or lake with low wave and current energy. Facies sequence P4 may represent similar environment of deposition, where the coarsening upwards of the sequence probably reflects a progradational infilling. There is, however, no absolute evidence of its origin, and similar sequences may develop in other environments (eg. as offshore bars, channel reoccupation etc.).

Vertical development and overall interpretation

The lowermost 150 m of the formation consists mainly of Facies sequences P2 and P3 which suggest a depositional environment dominated by alluvial plain, coastal plain and lagoon. Only one sequence of fluvial channel sandstone (Facies sequence P1) occurs within this part. The interval between 150 and 180 m is, however, completely dominated by fluvial sandstones. The upper half of the formation is again dominated by the fine grained, P2 and P3 Facies sequences. The black and grey shales of Facies sequence P3 become more important towards the top of the formation, and the uppermost 70 m are almost entirely of this facies (? lagoon, bay or lake deposits).

There is no obvious cyclicity in the Petrelskardet Formation. This contrasts with the other Bashkirian deposits on Svalbard which usually exhibit a well defined cyclicity. However, detailed sedimentological investigations unveil a tendency for coarsening upwards within the fine grained sediments (eg. from mudstone to siltstone). This coarsening upwards is sometimes combined with a parallel transition in colour, from black/grey shale at the base to red siltstone at the top, and probably represents the progradation of coastal plain (represented by the red beds) into lagoon, bay or lakes (black/grey lithologies). These cycles may very tentatively be interpretated to be tectonically generated, in a similar fashion to the sabkha cycles of the Ebbadalen Formation (see page), which seem to be directly related to the proximal conglomeratic cycles developed close to the Billefjorden Fault Zone (Johannessen 1980). The often sudden incursion of black shales may reflect a sudden lowering of base level (? tectonically), whereas the following progradation of floodplain/coastal plain may be related to increased topography in the source area. There is, however, no absolute evidence for such an interpretation.

A majority of the palaeocurrent data, recorded from the fluvial sequences, show a relatively uniform northward drainage direction.

OTHER LOCALITIES ON OSCAR II LAND

A detailed reconstruction of the palaeogeography of the St. Jonsfjorden Trough during early-middle Carboniferous time is difficult, due to insufficient lateral control. Besides the Inner St. Jonsfjorden and Trygghamna localities no other exposures on Oscar II Land have been visited by the author. Information is, however, available from other works, both published and unpublished.

BRØGGERHALVØYA

On Bröggerhalvøya the Orustdalen Fm. is exposed at two localities on the south-western coast. Orvin (1934) gave a short description of this section which he identified as Culm, because of the occurence of coal. The section has recently been examined by Fairchild (1982) who presented detailed sedimentological analysis. He found the thickness to be 203 and 224 m, which is much thicker than earlier estimated (Orvin 1934, Barbaroux 1968). The succession which rests unconformably on Hecla Hoek basement consists of quartzitic sandstones, conglomerate and grey/reddish shale. The clast composition is quartzite and black chert (some red and yellow chert appear near the top of the sequences). Fairchild (1982) interpretated these sediments as humid alluvial fans occupied by braided streams which entered tidal-dominated deltas. The fans probably built out from a source area north-east of the present exposures. The identification of tidally influenced sediments represents an important observation as this is the only marine influence so far known from the Orustdalen Fm. It is on the other hand, likely that these exposures represent the upper part of the formation due to the present of red beds just above, and may be a lateral equivalen to the Vegard Fm. farther south. The sea probably entered the area from the north.

Detailed description of the Middle Carboniferous, red bed succession on Bröggerhalvøya was first made by Orvin (1934). He described two sections, one from the edge of Bröggerfjellet and the other from the beach north of Scheteligfjellet. Orvin believed that this section was of Devonian age (due to some poorly preserved fish fossils). However, Cutbill and Challinor (1965) found some Middle Carboniferous brachiopods and foraminifera in sandy limestones on Kiærfjellet. They suggested that these sediments were laterally equivalent to the Devonian sections of Orvin (1934), and defined a new formation, with the Bröggertinden section as type profile. The Bröggertinden Formation (Middle Carboniferous) is about 360 m thick, and consists mainly of red conglomerates (clast size some few cm in diameter), red micaceous sandstones and red sandy mudstones in rapid alternation (Fig. 3.21). It rests unconformably on Hecla Hoek basement and changes upwards into thick limestone units.

It is probable that these sediments represent an arid alluvial fan system which, according to Barbaroux (1967), built out towards the west.

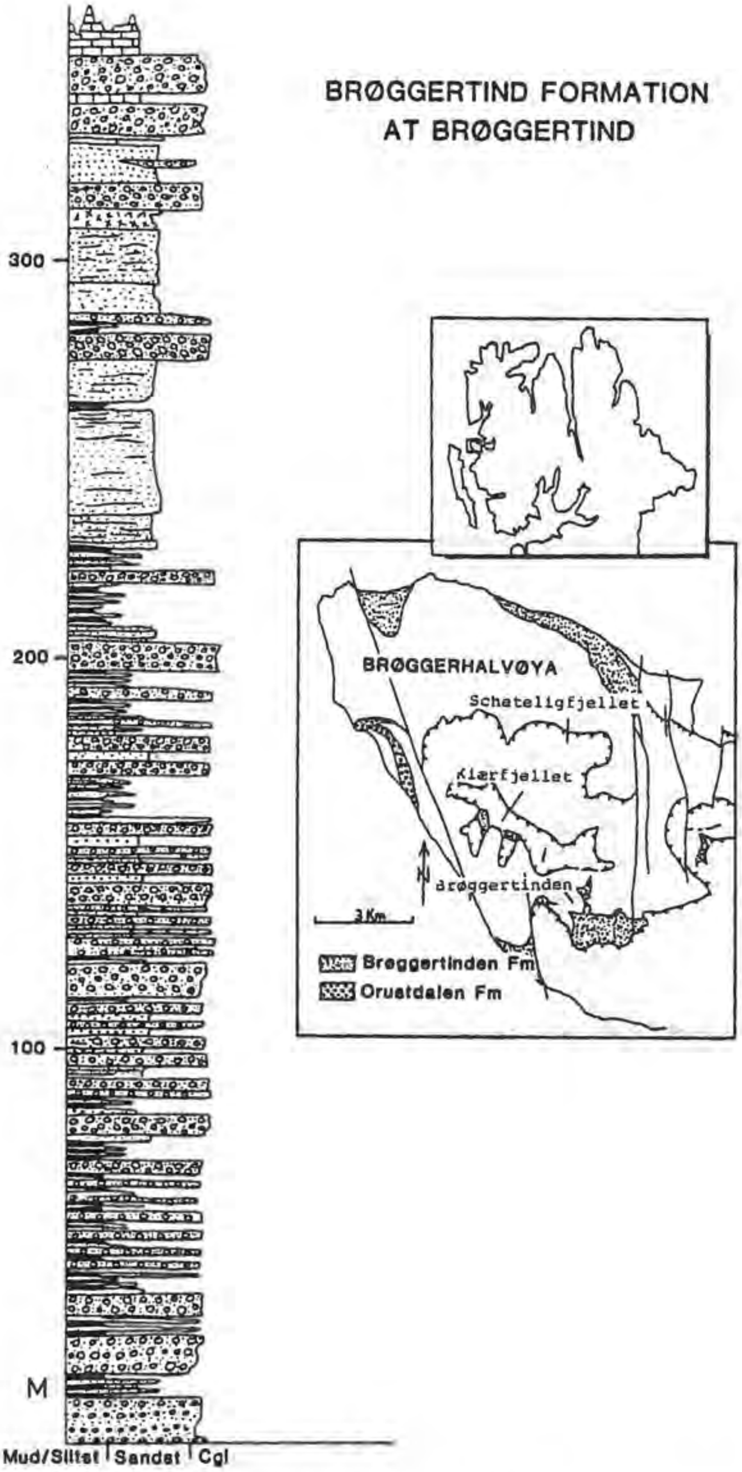

Fig. 3.21. Generalized stratigraphic section from the Bröggertingen Formation (? Bashkirian), Bröggerhalvøya, NW Spitsbergen. From Orvin (1934).

FORLANDSUNDET

The Carboniferous outcrops along the coast between Isfjorden and St. Jonsfjorden (Fig. 3.22) have been mentioned in several publications (eg. Baker, Forbes and Holland 1952; Weiss 1953; Dineley 1958). The beds are intensely deformed but their original sedimentary characters are often discernible (Dineley 1958).

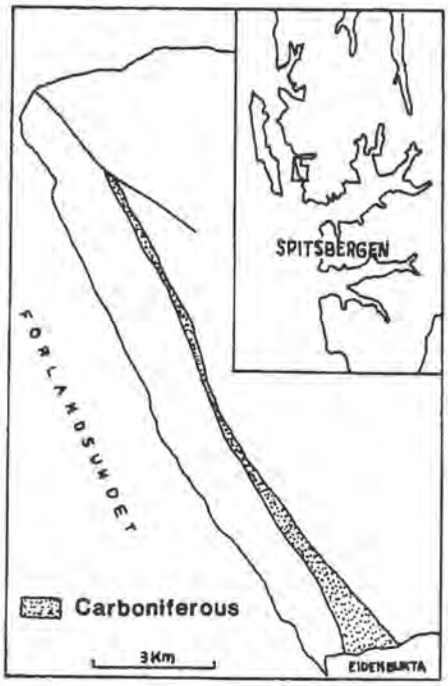

Fig. 3.22.
Carboniferous exposures along the eastern side of Forlandsundet, south of St. Jonsfjorden.

TRYGGHAMNA

The thickness of the Lower Carboniferous succession at Trygghamna may be 700 - 800 m (Dineley 1958). The development of the Orustdalen Formation is similar to the Orustdalen Formation at other localities along the west coast of Spitsbergen, and consist mainly of grey quartzitic sandstones and conglomerates, with thin coaly shales and coals. The formation overlies the Hecla Hoek succession with a coarse basal conglomerate (Dineley 1958). The lithology becomes more sandy upwards and terminates upwards into the dominantly fine grained Vegard formation. The development of the Vegard

Formation is very similar to that in the Inner St. Jonsfjorden area, and probably represents somewhat similar depositional environments. However, no marine or marginal marine trace fossils were recorded.

Fig. 3.23 shows a generalized stratigraphic section from the Billefjorden Group at Trygghamna .

Red beds like those at St. Jonsfjorden (Petrelskardet Formation) succeed the "Culm". A thickness of more than 125 m has been estimated (Dineley 1958; unpublished data from Weiss). It is probable that the red beds on Trygghamna are much more sandy than those at St. Jonsfjorden (see Dineley 1958, Fig. 3).

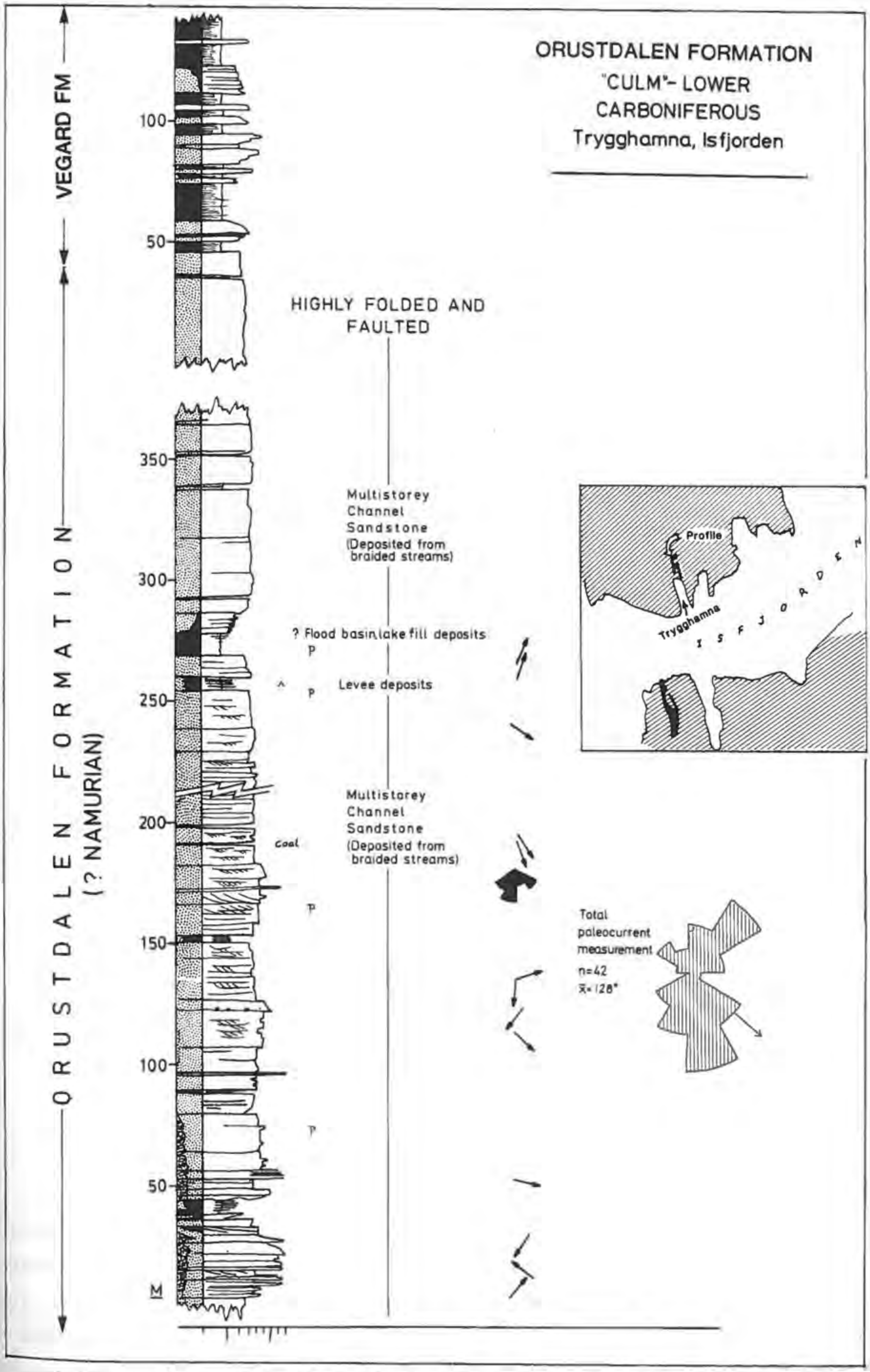

Fig. 3.23. Stratigraphic section from the Orustdalen Formation, north of Trygghamna.

ST. JONSFJORDEN TROUGH, SUMMARY

A reconstruction of the "St. Jonsfjorden Trough" with respect to palaeogeography and sedimentary depositional pattern is difficult due to the considerable distances between the different localities and to the strong, post-Carboniferous tectonic movements in the area. However, taking account of the available geological

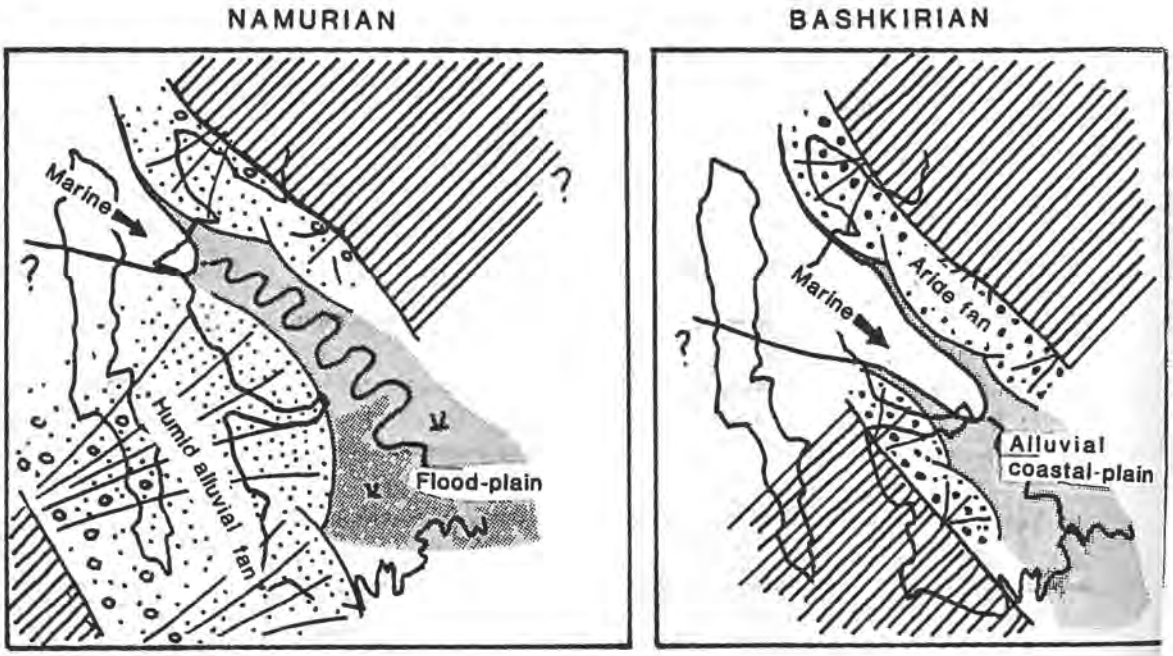

Fig. 3.24. Reconstruction for the Lower-Middle Carboniferous palaeogeography of Oscar II's Land, NW Spitsbergen.

data, the palaeogeographic model tentatively illustrated on Fig. 3.24 is the most probable for Oscar II Land. Two source areas have been suggested, one located just north-east of Bröggerhalvøya, the other was located somewhere near the present west coast of Spitsbergen. The basin margins were generally characterized by coarse clastic sedimentation, whereas fine grained sediments were deposited along the axial tracts. An overall transgression during Bashkirian time (from north?) caused marine conditions to prevail for long periods of time as far south in the basin as the present St. Jonsfjorden area. During Middle-Upper Carboniferous an extensive elevation of the Isfjorden and Nordenskiöld Land area caused only scarce red beds to be deposited or preserved.

* * *

We see that the same large scale trends that are recognized from the other Lower-Middle Carboniferous successions on Svalbard also are present in the St. Jonsfjorden trough. The Lower Carboniferous is characterized by deposition in a rather humid climate, whereas the Bashkirian climate was much dryer. The red beds appear more or less at the same time as a regional marine transgression, inducing marine or marginal marine facies in the stratigraphy which until then had been exclusively characterized by continental sediments.

III. 4

UPPER DEVONIAN - MIDDLE CARBONIFEROUS (Bashkirian) OF CENTRAL SPITSBERGEN

INTRODUCTION

The Carboniferous succession in the Central Spitsbergen area has been the subject of repeated geological investigations, particularly by Cambridge expeditions (see Harland et al. 1974). One of the main reasons for this interest is the economical importance of the coal-bearing strata. The University of Bergen (Svalbard Project) started their sedimentological investigations in the Billefjorden area in 1978, and in successive years have covered both clastic and carbonate parts of the Carboniferous Succession.

Investigation of the Lower Carboniferous succession concentrated mainly on the evolution of the coal basins (Aakvik 1981, Gjelberg, present work), whereas in the Middle and Upper Carboniferous strata emphasis was on understanding the red bed, evaporite and carbonate environments (Johannessen 1980; Johannessen and Steel 1981; Lønøy 1982; Sundsbø 1982; Gjelberg, present work).

Some of the investigations were carried out during the Statoil Svalbard Expedition of 1979 where extensive helicopter use greatly facilitated the work. The investigations covered an area some 60 km long and 40 km wide.

HISTORY AND PREVIOUS WORK

The coal-bearing Lower Carboniferous "Kulm" rocks of Billefjorden were mentioned by Nathorst (1910), and at about the same time coal mining activity started in the Pyramiden area with many conflicting interests. Documentation of these activities has been given by Hoel (1929, 1966, 1967). A short resume taken from Cutbill et al. (1976) is given here:

One of the first areas to be claimed included the Pyramiden and Mimerdalen districts. This area was claimed on behalf of the Swedish A.B. Isfjorden-Bellsund on 12. July 1910. The following year a party of miners from Sweden arrived, and opened a 50 m working into one of the seams, and the coal proved to be of good quality (6,7 - 8%) ash content). Further investigations followed in 1912, 1914 and 1916, during which further excavations were opened and a total of 15 m of coal was reported. However, in 1926, following the clarification of claims made by the Svalbard Commission, the Pyramiden concession was taken over by the Russians, who began serious investigations of the area in 1932, when J.M. Auslander made a geological map of the area. Further investigations were published by Lyutkevich (1937) who recognised the coal-bearing horizons about 25 m apart. The upper unit was reported to be 1-8 m of pure coal (14% of ash content) while the lower unit was about 6 m of coal and shales. These results encouraged Soviet exploitation of the coalfield. Some results of their investigations have been published by Livshits (1966).

The Bunsow Land area was first claimed in 1909 by W.S. Bruce on behalf of the Scottish Spitsbergen Syndicate. The basis of that claim was the extensive gypsum and anhydrites in the area, although he did know of the existence of the coalbearing, Culm sandstones. The Swedish expedition of 1910 also claimed Bunsow Land of behalf of A.B. Isfjorden-Bellsund. Another claim was made in 1911 by the Northern Exploration Company. This confused situation was solved by the Svalbard Commission of 1920-1925 who recognised the priority of the Scottish claim.

The area to the east of Petuniabukta was investigated by Swedish expeditions from the University of Uppsala under Professor Stensiø during the years 1912-1917 (Stensiø 1918).

Cambridge expeditions to Spitsbergen began in 1932. The expeditions of 1938 and 1949 were particularly concerned with Carboniferous studies and the geological work up to and including 1949 was summarised by McWhae (1953) and Gee, Harland and McWhae (1953). Parties from six Cambridge expeditions investigated further the Carboniferous rocks in the area during a period from 1959 to 1965 (eg. Harland 1962, 1963, 1965). Cutbill and Challinor (1965) reviewed the Carboniferous succession and defined the formal stratigraphy of Central Spitsbergen. Detailed geological work on the Middle Carboniferous Ebbadalen Formation was published by Holliday and Cutbill (1972). Harland et al. (1974) reviewed of the development history of the Billefjorden Fault zone, which played a critical role on the location and behaviour of the basins developed in the area during Upper Palaeozoic time. A review of the Billefjorden Group in its type area, with special reference to the coal was published by Cutbill, Henderson and Wright (1976).

The stratigraphy and general development of the area had then been extensively investigated before the University of Bergen started their work in 1978. The main aims of this latest work was to deduce the palaeogeography and development history of the basins, mainly by means of facies analysis. Most of the work is still unpublished, but present as Cand Real Thesis at the University of Bergen (Johannessen 1980 and Aakvik 1981).

A revised geological map of the area is shown in Figure 4.1, and a map with all place names referred to in the text is shown in Figure 4.2.

STRATIGRAPHIC SETTING

A generalised stratigraphic column from the investigated succession is shown in Fig. 4.3. It comprises the three

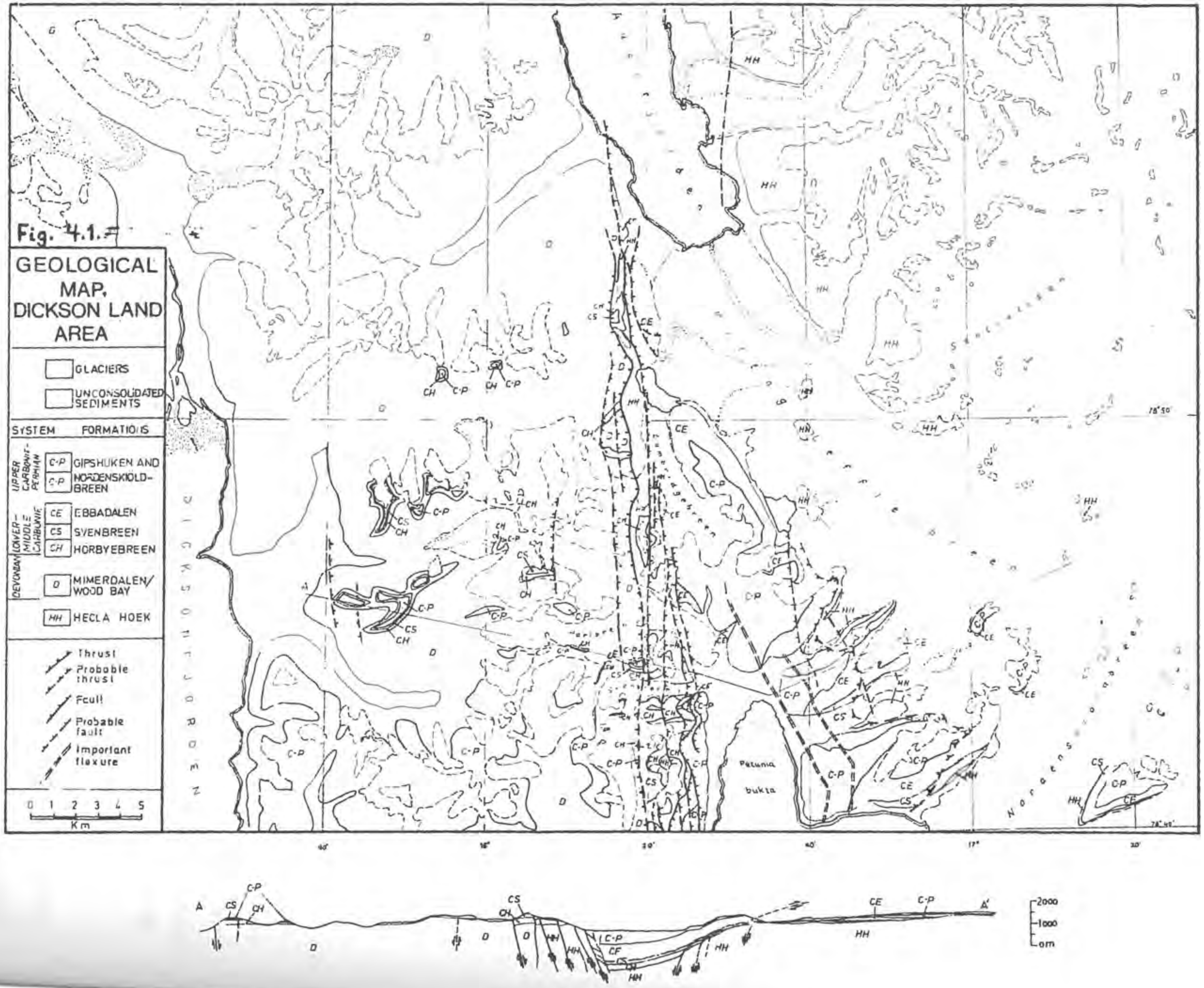
Fig. 4.1.
GEOLOGICAL MAP, DICKSON LAND AREA
GLACIERS
UNCONSOLIDATED SEDIMENTS
SYSTEM
FORMATIONS
UPPER CARBONIFEROUS-PERMIAN
C-P GIPSHUKEN AND NORDENSKIOLD-BREEN
LOWER-MIDDLE CARBONIFEROUS
CE EBBADALEN
CS SVENBREEN
CH HORBYEBREEN
DEVONIAN
D MIMERDALEN/WOOD BAY
HH HECLA HOEK
Thrust
Probable thrust
Fault
Probable fault
Important flexure
0 1 2 3 4 5
Km
DICKSONFJORDEN
Petunia bukta
78°50'
78°40'
40'
50'
20'
17°
2000
1000
0m

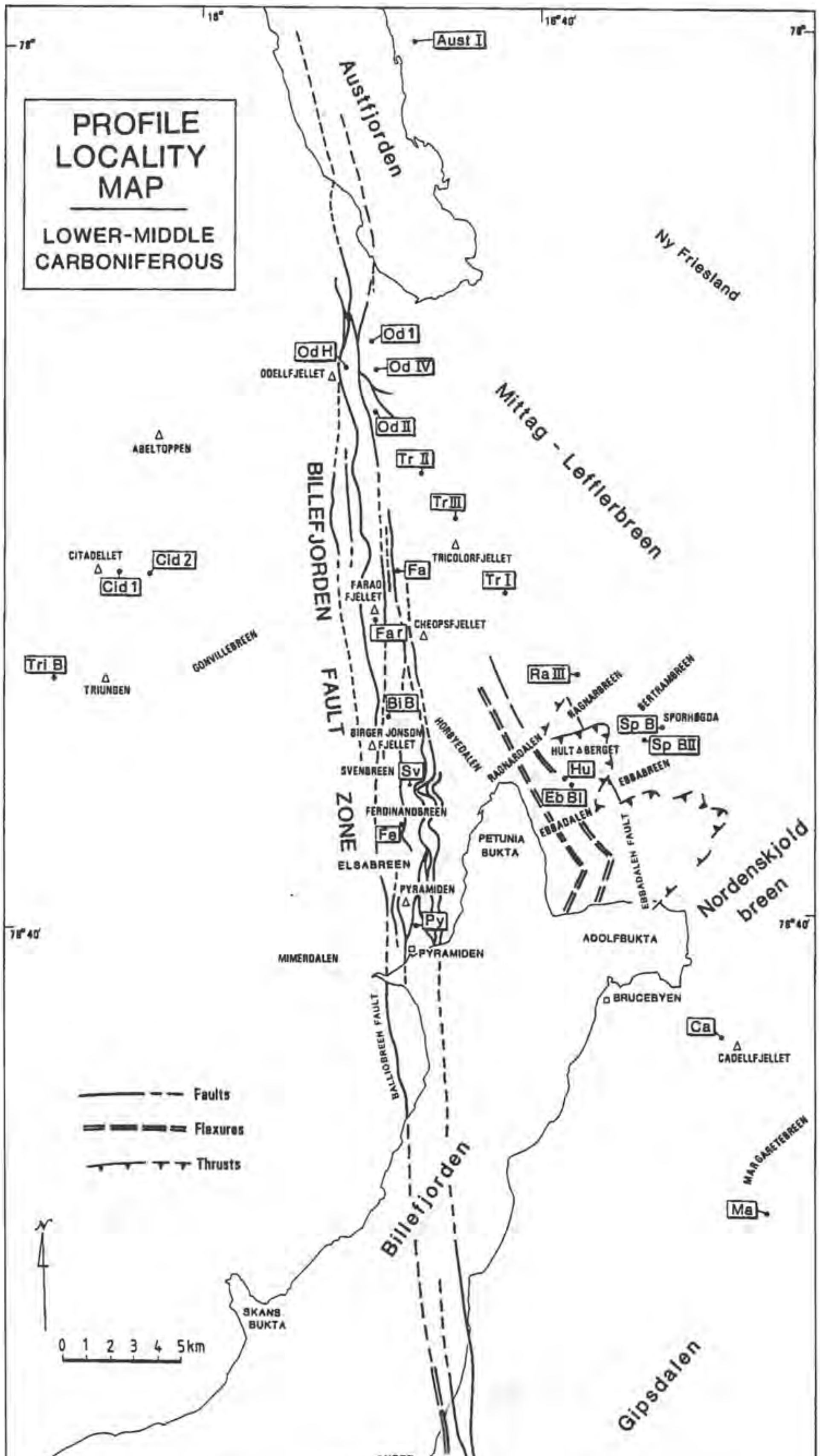

Fig. 4.2. Profile locality map for the Lower-Middle Carboniferous investigations in Central Spitsbergen.

jg840130maa/4

formations; Hørbyebreen Fm. (?Tournaisian-Viscan) Svenbreen Fm. (Namurian) and Ebbadalen Fm. (Bashkirian). Cutbill and Challinor (1965) defined the formations and also gave the Lower Carboniferous succession the status as a group (The Billefjorden Group). The Hørbyebreen unconformably overlies Hecla Hoek and Devonian rocks. Cutbill et al. (1976) suggested that the base of the Svenbreen Formation (Sporehøgda Member) also represents an unconformity. There is, however, no clear palaeontological or palynological evidence for this. On the other hand, two different assemblages of palynomorphs are present in the Group (Playford 1962/1963). The transition between the two assemblages, however, occurs within the Hørbyebreen Formation (Hoelbreen Member) and is not marked by any lithological changes (Cutbill et al. 1976).

Spør John etter kart

The boundary between the Ebbadalen and Svenbreen Formations has been a subject of discussion, (Johannessen 1980 and Aakvik 1981). Holliday and Cutbill (1972, p11) defined this boundary at the base of the lowermost cliff forming sandstone in Ebbadalen, and at the top of the lowermost red sandstone bench along Tricolorfjellet, and suggested that this boundary represents an unconformity. Our field observations shows no evidence for such a major break in deposition. Since the lower red beds, which previously have been included in the Svenbreen Formations (Hulteberget Member), show more in common with the Ebbadalen Fm., Johannessen (1980) consequently proposed that this part of the succession should be included in the Ebbadalen Formation. Aakvik (1981) formally proposed this idea and placed the lower boundary of the Ebbadalen Fm. at the first development of proper red beds.

A lithostratigraphic subdivision based on the first occurrence of red beds corresponds much better with the stratigraphic divisions made at other localities on Svalbard (eg. Bjørnøya, Hornsund, Bellsund and St. Jonsfjorden) where similar lithological transitions represent formation boundaries (Gjelberg and Steel, 1981). It should also be noted that Lyutkevick (1937) and Livshits (1966) included the red beds within their Lower "gypsum-bearing strata", which corresponds with the Ebbadalen formation. The previoius stratigraphy has been difficult to accept because the boundary between the Svenbreen and Ebbadalen Fms. is difficult to find at different localities.

THE NEW STRATIGRAPHIC SUBDIVISIONS

As a consequence of the above, the following lithostratigraphy is proposed:

The Hørbyebreen Fm., with its subdivision into the Triungen and Hoelbreen Members remains unchanged.

The Svenbreen Fm., is still subdivided into two members; the Sporehøgda Member and the Birger Jonsonfjellet Member. The Sporehøgda Member is restricted to the sandstone dominated part at the base of the formation. The prominent coal-bearing shales located above the Sporehøgda Member, and which previously made the lower part of the Hulteberget Member, are here defined as the uppermost member of the Svenbreen Fm., and given the name the Birger Johnson-fjellet Member after one of the few locations where it is completely exposed. The lower boundary of this new member is easy to observe at most localities by the relative sudden transition from prominent sandstones to coal-bearing shales Fig. 4.3. The upper boundary is not always so obvious as the transition zone between coal-bearing shales to red beds (here included in the Ebbadalen Formation) is often poorly exposed.

The Ebbadalen Formation is subdivided into four members. This subdivision, which is shown on Fig. 4.4 is mainly adopted from Johannessen (1980), although the lower red beds, here named the Anservika Member, are now included in the Ebbadalen Formation. This stratigraphy differs considerably from that proposed by Holliday and Cutbill (1972). A comparison between the old and the new stratigraphy is shown in Fig. 4.4. Definitions and description of the new stratigraphy were given by Johannessen (1980) and only a short review will be presented here:

The Anservika Member is here defined only to comprise the lowermost red shales and sandstones. The lower boundary of the member occurs where the coalbearing shales are replaced by non-carbonaceous red beds.

The Ebbaelva Member consists of grey/green shales

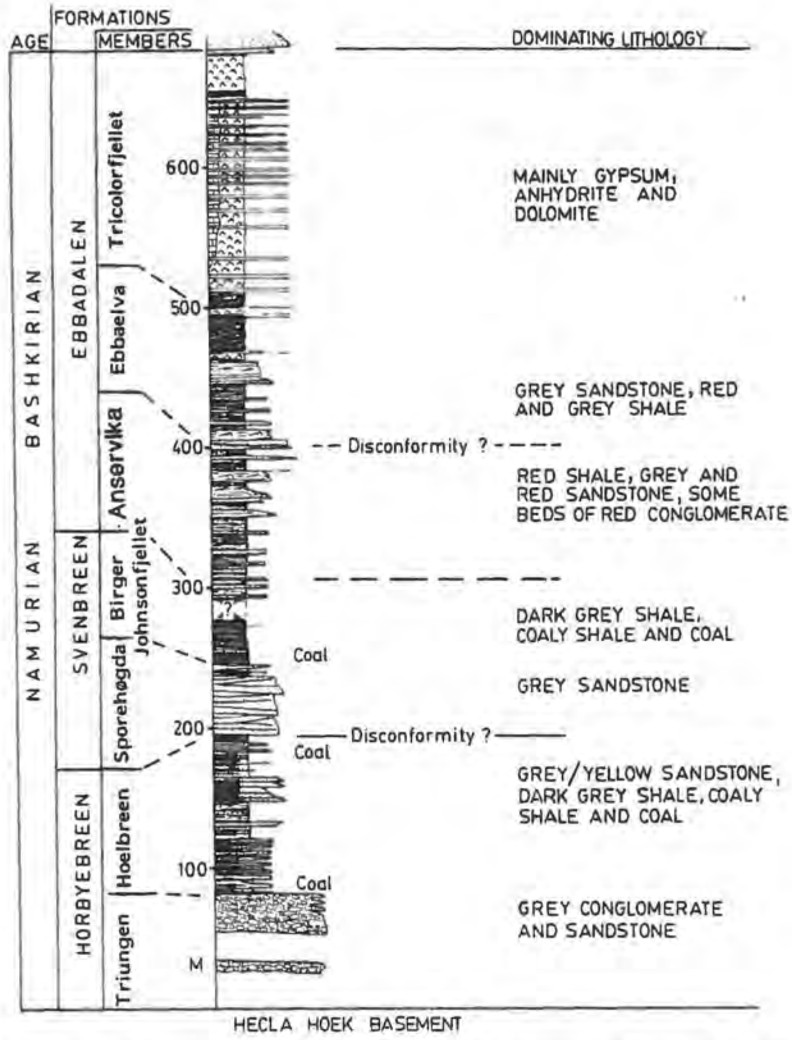

Fig. 4.3 Generalised stratigraphic column from Lower-Middle Carboniferous of Central Spitsbergen.

interbedded with grey and yellow sandstones. The lower boundary (in the Ebbadalen area) is defined by the first occurrence of cliff-forming sandstones, associated with grey shales, and corresponds to the old formation boundary of Holliday and Cutbill (1972). The Gerritelva Sandstone Member of Holliday and Cutbill (1972) is now not found worthy of member status, and was included in the Ebbaelva Member by Johannessen (1980).

The Odellfjellet Member was defined by Johannessen (1980) and corresponds to the lower and upper Red Bed Facies of Holliday and Cutbill (1972). It consists of red, grey and yellow conglomerates and sandstones, red shales (sometimes with gypsum nodules) and yellow dolomites. The deposits are organised into 15-30 m thick cycles. The type locality is on the east side of Odellfjellet with a total thickness of 284 m. The member interfingers with both the Ebbaelven and the Tricolorfjellet Member (Fig. 4.4). The disputed Pyramiden conglomerate (Lyutkevich 1937, Gee et al. 1953, Cutbill and Challinor 1965, Holliday and Cutbill 1972) is now included in the Odellfjellet Member (see Johannessen 1980).

The Tricolorfjellet Member was defined by Holliday and Cutbill (1972). It consists of gypsum/anhydrite in alternation with black and yellow limestone/dolomites and black shales. Red sandstones and mudstones, related to the interfingering Odellfjellet Member, are important in the western and central developments. The lower boundary of the Tricolorfjellet Member is defined by the first occurrence of anhydrite/gypsum beds. The Teltfjellet Member of Holliday and Cutbill (1972), was included in the Tricolorfjellet Member by Johannessen (1980).

The boundary between the Ebbadalen Fm. and the overlying Nordenskiöldbreen Fm. is easily recognised in the central parts of the basin where thick sabkha sequences are replaced upwards into yellow and green sandstones, and yellow dolomites (Holliday and Cutbill 1972).

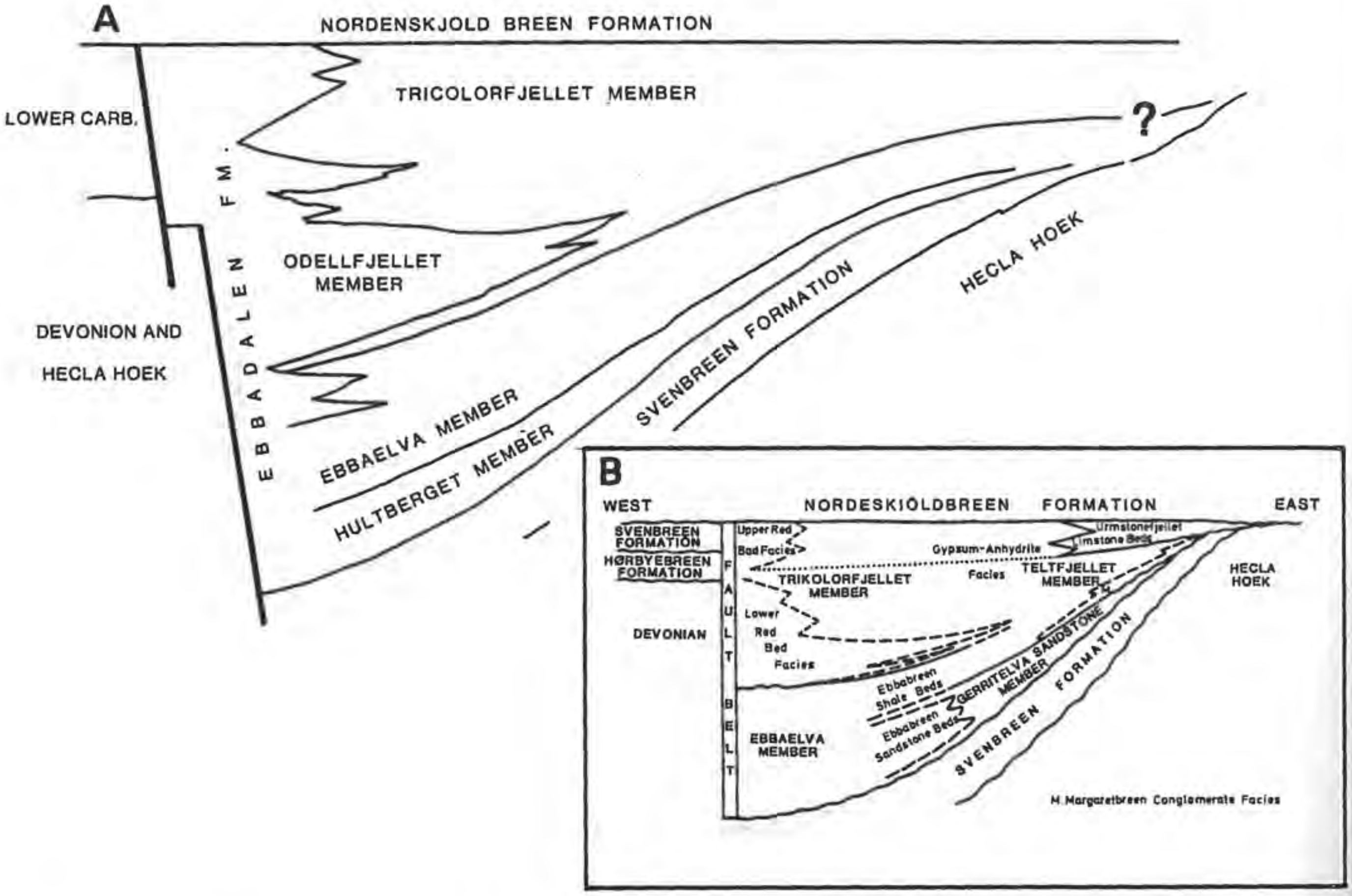

Fig. 4.4. Comparison between the new stratigraphy (A) and the old stratigraphy (B) of the Ebbadalen Formation.

AGE

The coalbearing succession of Central Spitsbergen (Billefjorden Group) has for a long time been known to be of early Carboniferous age (e.g. Nathorst 1910, Orvin 1940, Forbes et al. 1958). Playford (1962/1963) investigated the palynomorphs of the group and established a biostratigraphy in the succession. On the basis of this work, and by comparison with the palynomorphs investigated by Kaiser (1970, 1971) from Bjørnøya, Cutbill and Challinor (1965) regarded the Hørbyebreen Fm. to be of late Famennian - early Visean age, and the Svenbreen Formation of late Visean - Namurian age. The fusulinid fauna from the Ebbadalen Formation indicates a Bashkirian age (Holliday and

Cutbill 1972). Macrofossils are present both in the yellow and black carbonates of Ebbadalen Fm., and one of the brachiopod genera (stratifera), present in the Ebbaelva Member (Holliday and Cutbill 1972) has previously been regarded as restricted to the Lower Carboniferous (Sarycheva and Sokolskaya 1952, Muir, Wood and Cooper 1960) which raises the possibility that much of the lower part of the Ebbadalen Formation is of Lower Carboniferous (Namurian) age rather than Middle Carboniferous. On the other hand the carbonates occurring in the upper part of the Odellfjellet Member show a development which is typical for the Moscovian sediments on Svalbard. Moreover, as is typical for this stage elsewhere the carbonate of the shell and shell fragments is very often replaced by red silica (David Worsley pers. comm.).

TECTONIC SETTING

The tectonics of the area have been extensively described by Harland et al. (1974), and only some of the most important features will be repeated here. Figures 4.1 and 4.2 show the most important faults in the studied area, and that the faults control the present lithological distribution. One of the most important faults is the Devonian Balliobreen Fault (Harland et al. 1974) which separates the (Lower-Middle) Devonian Wood Bay and Mimer Valley Formations (Friend 1961, Friend and Moody-Stuart 1972) from the lower Hecla Hoek (Harker Group), so that the Carboniferous succession overlies Devonian rock to the west and Hecla Hoek to the east of the fault.

In general the Upper Palaeozoic strata exposed along Billefjorden have been little affected by the Tertiary Orogeny and the strata are often flat-lying with little tectonic deformation.

There are, however, some few indications of overthrusting in the Ebbadalen - Ragnardalen area (Fig. 4.1), although the displacements are relatively small, and the thrusts may be difficult to observe in the often poorly exposed valley-sides. It is probable that this compressional faulting took place during the Tertiary.

Locally in an area extending from Ragnardalen to Ebbadalen a limestone breccia, the Ragnarbreen Breccia (McWhae 1953, p.293), occurs between the Ebbadalen and Nordenskiöldbreen Fms. McWhae (1953) suggested a tectonic origin of the breccia, whereas Holliday and Cutbill (1972) argued that it was a solution breccia due to dissolved anhydrite-gypsum). This breccia occurs in the zone of overthrusting, and it is suggested here that it is a solution breccia developed along the fractured thrust zone.

HØRBYEBREEN FORMATION

The best outcrops of the Hørbyebreen Formation occur along the Billefjorden Fault Zone (Fig. 4.1), but it is also well exposed at scattered localities between Billefjorden and Dicksonfjorden. The total thickness of the formation ranges between 138 and 238 m, with the greatest thickness recorded from Triungen and Lemstrømfjellet (Fig. 4.5).

TRIUNGEN MEMBER

The Triungen Member consists mainly of grey sandstones and conglomerates. There are, however, some thick sequences of grey shale (interstratified with thin sandstone strata) present in the type section on Triungen (Fig. 4.5). It is also probable that fine grained sediments are relatively common at other localities, as such sediments usually are poorly exposed, and many of the gaps in the stratigraphic record may represent fine grained sediments. The thickness of the member varies between 5 and 125 m in the investigated area. It is thickest on the west side of Triungen and thinnest at Elsabreen (Fig. 4.5).

Facies description

Conglomeratic facies sequences - Two different categories of coarse-grained facies sequences have been recognised. Representative examples of this sequence are shown in Fig. 4.6, and termed Facies sequence T1 and T2.

Characteristic for Facies sequence T1 is that is consists largely of conglomerates, both clast-supported or matrix-supported, with a coarse sandy matrix. Sequences usually fine upwards into trough cross-stratified sandstones. Conglomerates are, however, the dominating lithology and may occur in a multistorey manner, resulting in relatively thick units. The thickness of individual sequences, however, rarely exceeds 3 m. The conglomerates are usually horizontally or low-angle, trough cross-stratified.

The sequences assigned to the T2 category differ from those of T1 in being sandstone-dominated (Fig. 4.6). Each sequence starts with a relatively thin, fine-grained conglomerate or pebbly sandstone, usually horizontally stratified, and is overlain by relatively thick units of trough cross-stratified medium/coarse sandstones, which finally fines upwards into ripple laminated and plane laminated fine/very fine sandstone and siltstone.

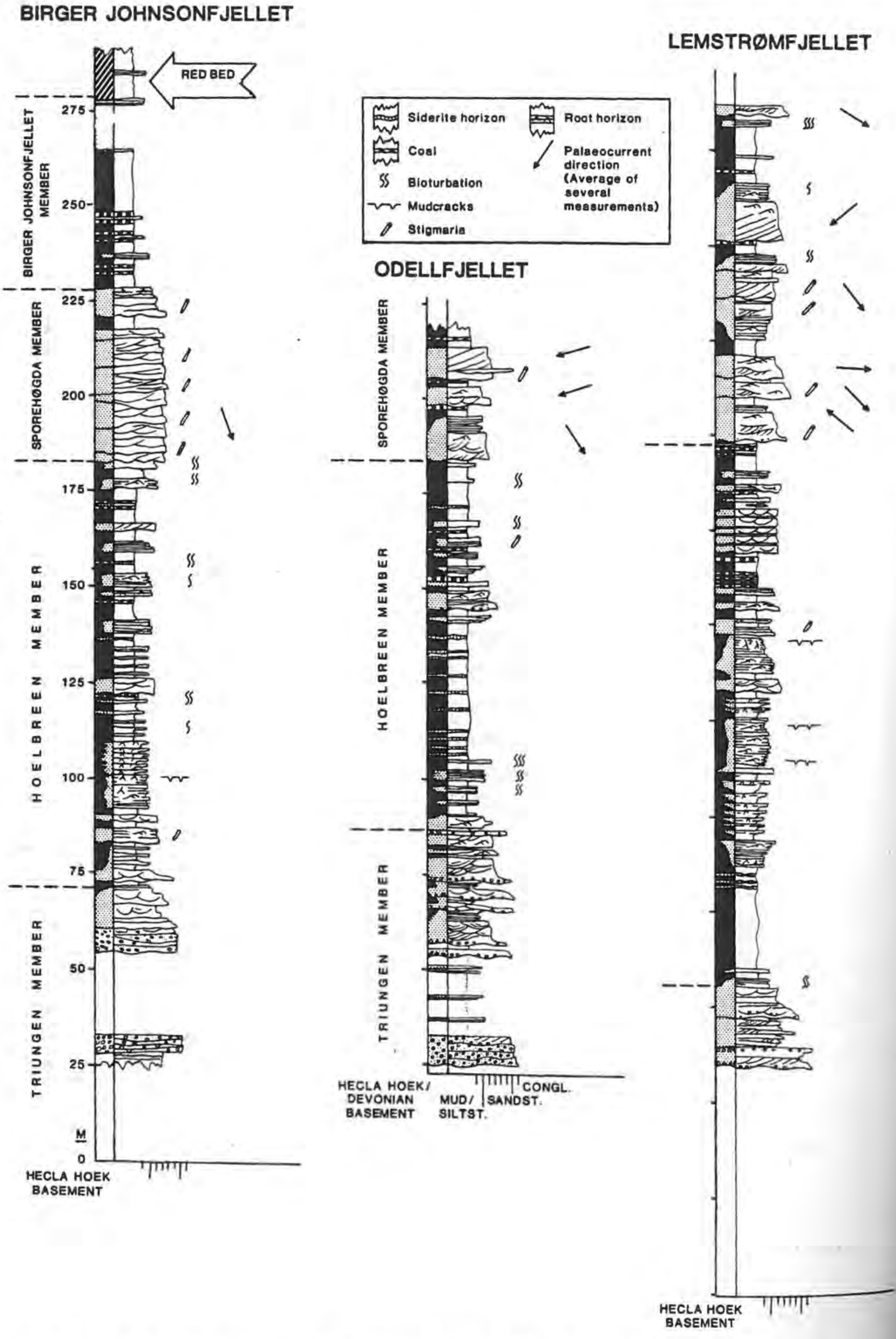

Fig. 4.5 Stratigraphic logs from the Billefjorden Group, Central Spitsbergen.

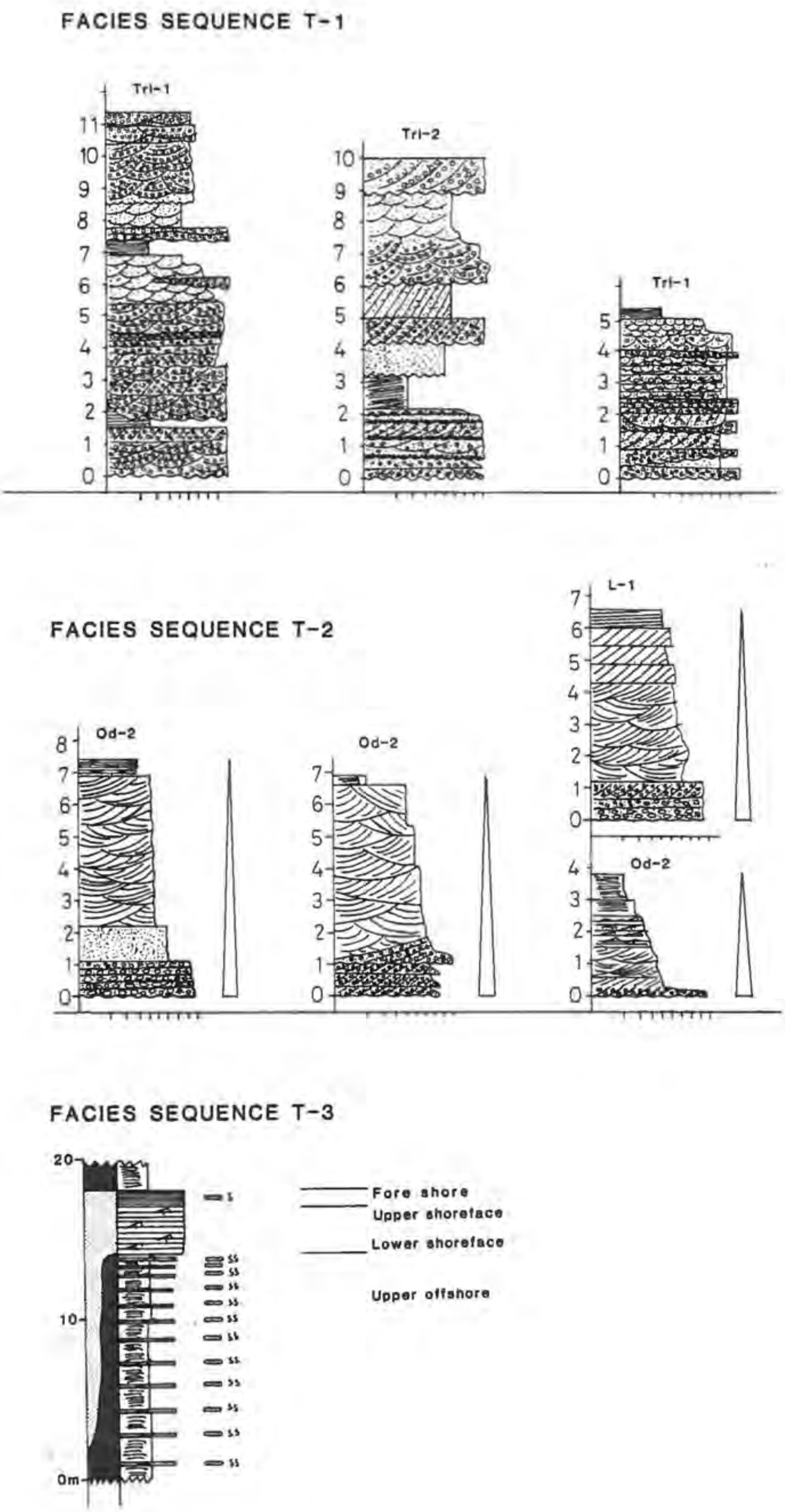

Fig. 4.6. Facies sequences from the Trinungen Member (Hørbyebreen Formation), Central Spitsbergen. From Aakvik (1981).

There are many similarities between these sediments and the braided stream conglomerates/sandstones from the Orustdalen Fm., both with respect to lithology and sequences, and a similar interpretation may be applied. Facies sequence T1 is thought to represent more proximal braided streams than the T2 sequences (Aakvik 1981).

Coarsening upward, progradational sequence (Facies sequence T-3) - This sequence consists of an 18 m thick coarsening upward sequence, recorded only from the type locality on Triungen. The lower 14 m consists of grey mudstone in alternation with thin (10-20 cm), fine - very fine, grey/green, ripple-laminated sandstone, which becomes more abundant upwards. Wave-ripple lamination is present in the sandstones. The uppermost 4 m of the sequence consist of horizontally stratified fine-medium sandstones with some intervals of wave ripples. Individual sandstone sets are often separated by thin (2-3 mm) mudstone drapes.

The uppermost part of the sequence is dominated by plane-parallel, evenly laminated sandstones.

Strongly orientated bedding-plane trace fossils are common, especially in the lower and middle parts of the sequence.

Information on this sequence is too sparse to give a thorough interpretation. It is, however, suggested that it represents some kind of progradational infill of a relative permanent water-body, where the uppermost part of the sequence most likely represents a prograding shoreline (fig. 4.6). Because no marine or marginal marine indicators were recorded either in the sequence or in associated sediments, a lacustrine environment is tentatively suggested (see also Aakvik 1981).

Overall interpretation and palaeogeography

Palaeocurrent analyses suggest that the coarse clastic sediments which dominate the Triungen Member were deposited by braided streams, developed from two different source areas (Fig. 4.7). One of the source areas was located to the east (see also Cutbill et al. 1976), probably related to the Ny Friesland High, whereas the other was located to the west and probably to the south. The composition of the conglomerates also indicates two source terranes as chert is a far more important constituent in the westernmost (Triungen) exposures (up to 70% of the clasts, which otherwise consist of vein quartz, quartzites and quartizitic sandstones). The coarsest sediments of the Triungen Member occur on Birger Johnsonfjellet (M.P.S. 15-25 cm), which represents one of the easternmost exposures of the member. Due to the increased thickness, and the significant increase of graiz size towards the south-western margin of Ny Friesland, it is suggested that this approximately represents the eastern margin of the basin. There is no clear evidence that this basin margin was tectonically active during deposition of the member. However, there are other indications of synsedimentary tectonic activity. This is most easily seen in the Triungen area where such faulting is identified both because of dramatic thickness variations (Fig. 4.12) and by facies changes across a narrow interval. It is possible that this fault was responsible for the development of the water-body into which facies sequence T-3 was deposited.

The Triungen Member shows on a large scale, a gradual fining upwards into the predominant shaly Hoelbreen Member.

HOELBREEN MEMBER

Hoelbreen Member conformably overlies the Triungen Member, and the boundary is placed where black and grey shales become the dominating lithologies. The thickness ranges between 80 and 140 m and shows a general tendency to increase towards east, up to the south western margin of Ny Friesland block. The member consists generally of black/grey shales and mudstones, interstratified with thin benches of ripple laminated sandstones, coal, coaly shales and horizons of clay ironstone (siderite). Thin sandstone strata (2-50 cm) interstratified with thin mudstones (up to 20 cm thick) are common lithological combinations within the formation, and form several meters thick sequences (Fig. 4.5). In situ plant rootlets are very common.

Only a few prominent sandstone sequences (3-5 m thick were recorded in the member.

Coal seams occurs at several levels (Fig. 4.5). However the thickest seams are located in the uppermost part of the member in the Pyramiden area.

Facies sequences

According to the studies of Aakvik (1981) the following facies sequences are present in the Hoelbreen Member:

1) Facies Sequence H-1 - Point bar deposits of high-sinuosity stream channels. These facies are relatively rare and only a few sequences 3-5 m were recorded.

2) Facies Sequence H-2 - Abandoned channel fill, mainly of the neck cut-off type (Fig. 4.9 A).

3) Facies Sequence H-3 - Prograding and aggrading levee deposits (Fig. 4.9 B).

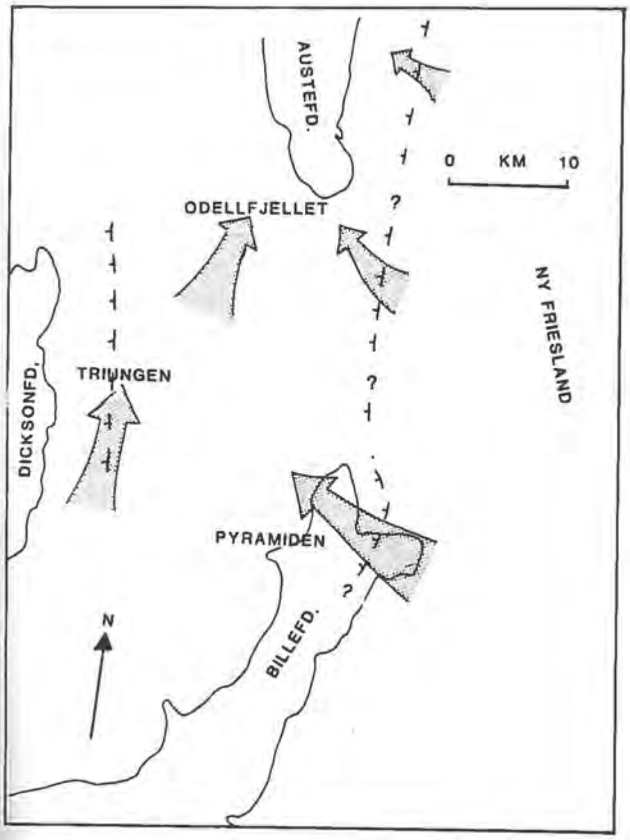

Fig. 4.7. Palaeocurrent distribution in the Trinungen Member (Hørbyebreen Fm.) Central Spitsbergen.

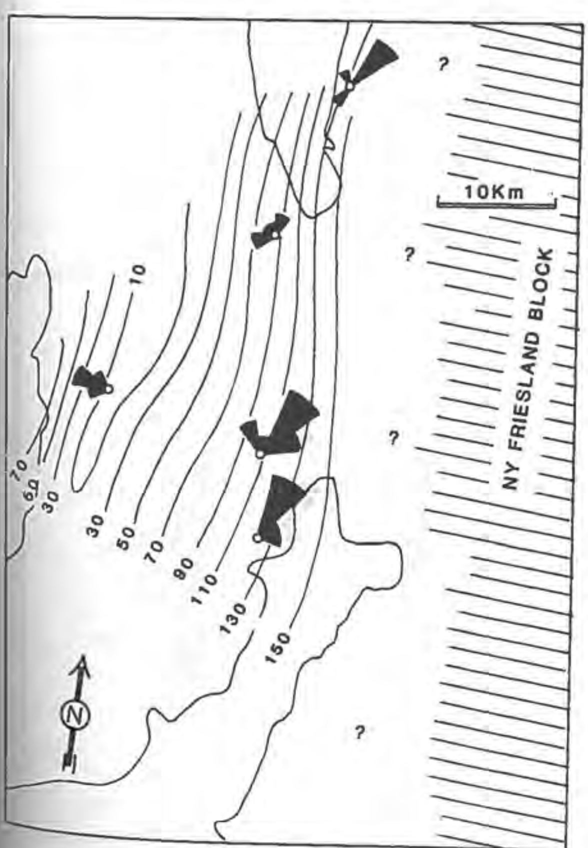

Fig. 4.8. Palaeocurrent distribution and thickness (20 m isopachs) of the Hoelbreen Member (Hørbyebreen Fm.) Central Spitsbergen.

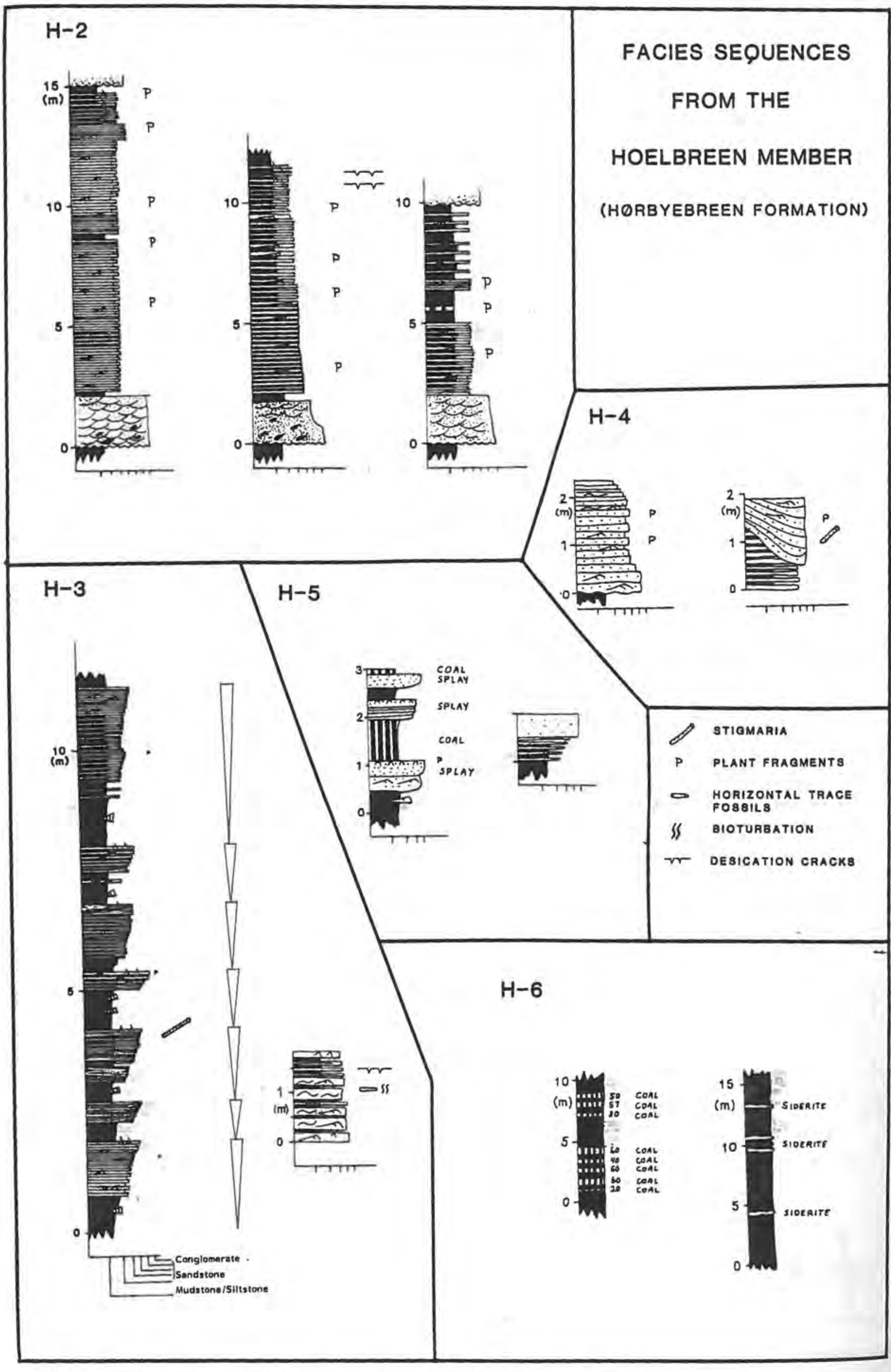

Fig. 4.9. Facies sequences from the Hoelbreen Member. From Aakvik (1981).

4) Facies sequence H-4 - Crevasse channel deposits (Fig. 4.9 C).

5) Facies sequence H-5 - Crevasse splay deposits (Fig. 4.9 D).

6) Facies sequence H-6 - Flood basin deposit (Fig. 4.9 E).

Since similar deposits have been described from other localities of the Billefjorden Group (Gjelberg 1978, Gjelberg 1981a, 1981b, Aakvik 1981) it will here only be referred to the Figures 4.9, 4.10 which shows representative sections from most of the Facies sequences.

Overall interpretation and palaeogeography

The Hoelbreen Member mainly reflects deposition in flood-plain or delta-plain environments, where a large range of subenvironments, such as levees, crevasse splays, flood basins and abandoned channels, dominated. Fully developed point bar deposits of high sinuosity channels are surprisingly scarce, and it is a problem to explain why so few distributary channel sandstone bodies are present within these thick floodplain accumulations. Aakvik (1981) discussed this problem, and suggested that the main river channels were mostly confined to fixed positions and that the rivers were able to keep these positions due to the fact that fine-grained cohesive sediments, which have accumulated in the adjacent flood-basins, were difficult to erode. The river therefore tends to reoccupy the older meander belts rather than erode a new position due to avulsion.

Simulation models of alluvial stratigraphy shows that meander belts in general would spread out over the entire flood plain if the subsidence is uniform (Allen 1978, Bridge and Leeder 1979). The situation is different,

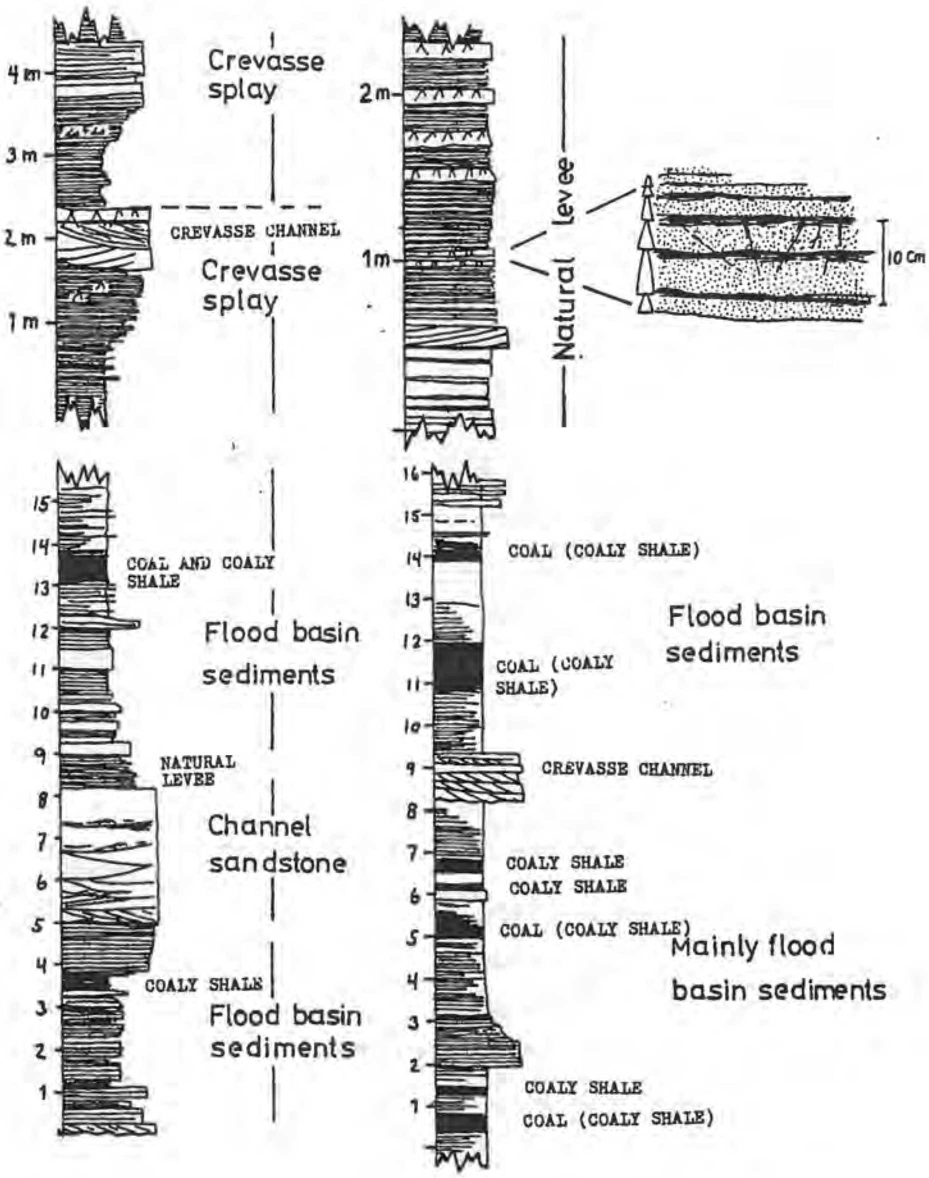

Fig 4-10. Typical association of facies and facies sequences in the Hoelbreen Member (Hørbyebreen Fm), Central Spitsbergen.

however, when the insinking across the basin floor is asymmetrical (eg. half graben). In this case most of the meander belts would tend to occupy that side of the basin where the subsidence rate was highest (Bridge and Leeder 1979), providing that the sediment influx from the sides is insignificant. This could be the situation for the Hoelbreen Member as the thickness of the member increases rapidly eastwards towards the Ny Friesland Block (Fig. 4.8), indicating an asymmetric insinking of the basin. It is therefore probable that most of the river channels occupied an area east of the present exposures, somewhere in the large synform between the Billefjorden Fault Zone and the Ny Friesland Block (Fig. 4.12).

Most palaeocurrent data suggest that the drainage direction of the river system was approximately towards north, and it is suggested that the Hoelbreen Member developed in a N-S extended basin limited by the Ny Friesland Block to the east. The supply of coarse clastic sediments from the eastern margin was very limited during deposition of the Hoelbreen Member.

SVENBREEN FORMATION

SPOREHØGDA MEMBER

The Sporehøgda Member is very well exposed in the Billefjorden area where the competent quartzitic sandstones of the member form prominent cliffs. This is especially the case on the west side of Petuniabukta where the member is interstratified within easily weathering shales, fig. 4.5. On the east side of Petuniabukta the sandstones of the Sporehøgda Member more or less directly overlie the Precambrain basement of the Ny Friesland High. However, the exposures are relatively poor in this area.

The member is 30-40 m thick along the Billefjorden Fault Zone west of Petuniabukta but increases to more than 90 m northward to lemstrømfjellet, where it splits into several sandstone sequences, each separated by horizons of shales figs. 4.5.

Description

The Sporehøgda Member is composed of several superimposed sandstone sequences. Individual sequences have a slight fining upward tendency from erosively based, coarse /very coarse sandstone in the lower part into mainly medium grained sandstones in the middle and upper parts. This sequence ranges in thickness from a few meters to more than 10 m (Fig. 4.5). Sequences are often truncated by the overlying sequence, resulting in thick units of complexly stratified sandstone. On Birger Johnsonfjellet a 35 m thick unit consists of 9 superimposed sequences (Fig. 4.5).

The erosion surfaces which separate individual sequences are strongly undulating with an amplitude of more than two meters. Giant (7-8 m) forests similar to those observed from the Tunheim Member on Bjørnøya (lateral accretion surfaces), were recorded from some of the sequences.

Relatively thick units of fine-grained material are preserved between sandstone sequences especially in the northern part of the investigated area.

Plant fossils, mainly preserved as carbonaceous films and as impression of trunks, occur frequently within the member.

Overall interpretation and palaeogeography

Both with respect to vertical and lateral development, the deposits of the Svenbreen Member show many similarities with the Tunheim Member on Bjørnøya (Gjelberg 1981a), and a similar interpretation is suggested. Consequently, the sandstones of the Sporehøgda Member most likely represent point bars of meandering streams. The interstratified fine grained sediments show most of the characteristics typical for flood-basin and levee deposits (see above).

The multistorey nature of the sandstones suggest that insinking was relatively slow as compared to the frequency of lateral shifting of the channels so that a low percentage of overbank material was preserved.

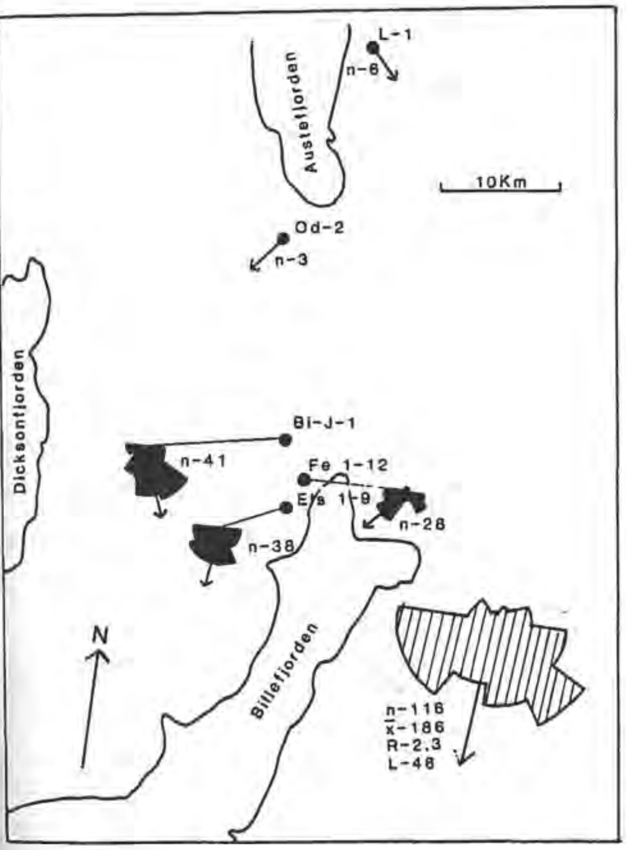

Fig. 4.11. Palaeocurrent distribution in the Sporehøgda Member (Svenbreen Fm.) Central Spitsbergen. From Aakvik (1981).

Palaeoccurent analysis suggests that the average direction of river drainage was towards south (Fig. 4.11). This is the opposite of the drainage direction for the Hoelbreen fluvial systems, which appear to have been towards north. This observation seems to favour the assertion of Cutbill et al. (1976) that there is an unconformity between the Hørbyebreen and Svenbreen Formations.

It is, however, suggested that the basin, which probably was related to major N-S orientated tectonic lineaments, had an N-S elongated form, with the main source areas located to the west and east. The north-south orientated drainage system described above, most likely represents the axial system of the basin (Fig. 4.13). This basin configuration make it easier to understand the dramatic change of palaeocurrent observations, as a change of the axial drainage direction could occur without major dislocations of the scource area. It is also a supporting fact that the marine transgressions which occurred during deposition of the overlying Ebbadalen Formation, probably entered both from the north and from the south, indicating lowland in both these directions (Johannessen, 1980). The observed change of palaeocurrents do therefore not necessarily indicate dramatic changes of the palaeogeographic setting.

BIRGER JOHNSONFJELLET MEMBER

This member is best exposed on Birger Johnsonfjellet and at Elsabreen (Figs. 4.2 and 4.5), where the thickness is 50 and 55 m respectively. The Elsabreen locality is most accessible. However, since the name already has been used (Elsabreen Beds of Cutbill and Challnar, 1965), Birger Johnsonfjellet is here preferred as type locality. Beside these two exposures, the member also partly outcrops at Anservika, Odelfjellet and Ebbadalen.

Description and interpretation

The Birger Johnsonfjellet Member consists mainly of black/grey shales, coaly shales and coals, interstratified with thin siltstone and sandstone benches (Fig. 4.5).

The facies sequences of the Birger Johnsonfjellet Member are all similar to sequences described from the Hoelbreen Member, and similar modes of interpretation have been used. Most dominating is the development of thick flood-basin sequences, which contain several, relatively thin coal seems (10-180 cm thick). Coal seams thick enough for mining occurs mainly within the lowermost 20 m of the member. The thickest coal seem recorded is 180 cm thick and occurs in the Elsabreen area.

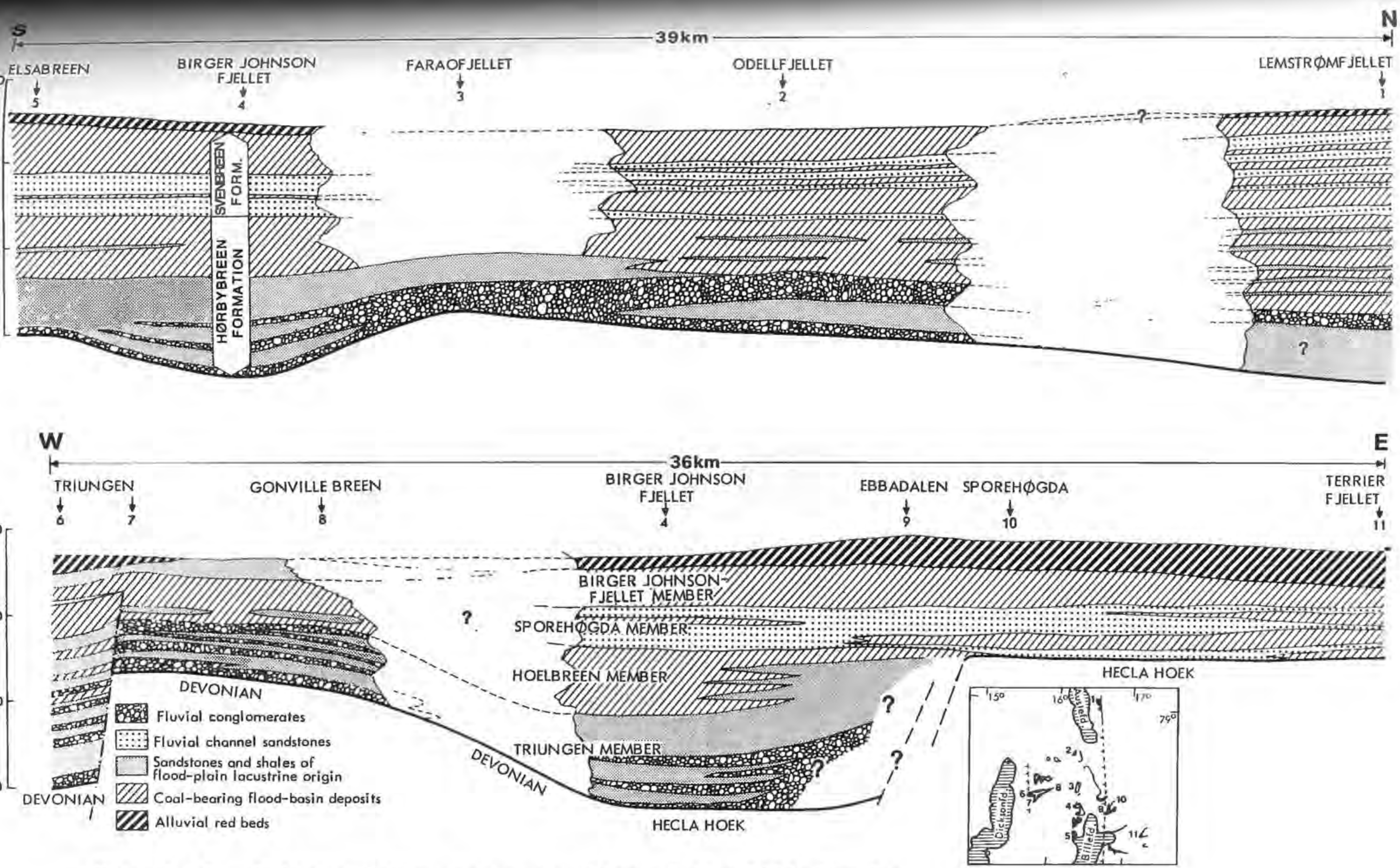

Fig. 4.12. Interpretative reconstruction of the Billefjorden Group Central Spitsbergen.

The palaeocurrent data recorded from the Birger Johnson-tjellet Member are not sufficient to give a reliable picture of the drainage system.

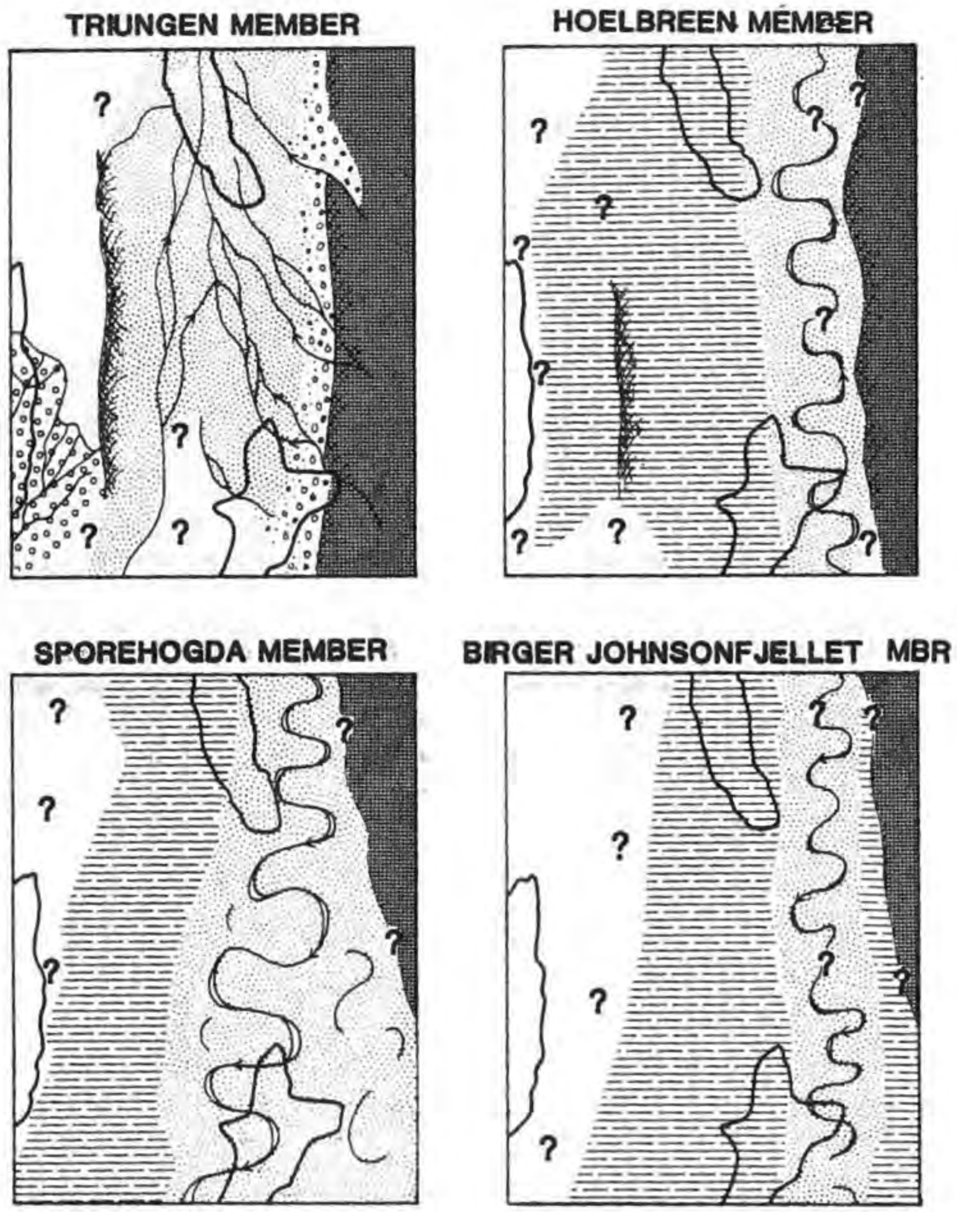

Fig. 4.13. Palaeogeographic reconstruction of the Lower Carboniferous basin in the Central Spitsbergen (Billefjorden/Dicksonfjorden area).

BILLEFJORDEN GROUP - LATERAL DEVELOPMENT AND PALAEOGEOGRAPHY

An interpretative reconstruction of the Billefjorden Group in Central Spitsbergen is shown in Figure 4.12. The reconstruction is presented with two cross-sections; one in a north-south direction, running subparallel with the supposed axis of the basin, the other crossing the axis in an east-west direction. The north-south section shows a rather even development with relatively low relief of the basin floor (relative to the base of the Sporehøgda Member). The east-west section, however, betrays a dramatic variation in thickness and facies development, which most likely reflects the effect of syn-sedimentary faulting. It is suggested that an active fault (or fault zone) restricted the basin to the east. This fault was probably most active during deposition of the Triungen Member (?Tournaisian). Another synsedimentary fault was located in the Triungen area (Fig. 4.12) and is probably related to rotational block faulting.

An outline of the palaeogeographical development of the Billefjorden Group is given in Figure 4.13. Since the palaeogeographical conditions have been described above, only Figure 4.13 is referred to here.

* * *

EBBADALEN FORMATION (GIPSDALEN GROUP)

The general sedimentological history of the Ebbadalen Formation is well known from published work by Holliday and Cutbill (1972). Detailed facies analysis has later been carried out by Johannessen (1980), who revised the stratigraphic subdivision and proposed a new model of development with respect to palaeogeography, palaeotectonic and depositional environments.

As emphasised above, the red beds of the Hulteberget Member of Cutbill and Challinor (1965), which previously were included in the Svenbreen Formation, are here taken as the lowermost member of the Ebbadalen Fm. and named the Anservika Member. (See also Aakvik 1981).

Only a short resumé of the work carried out by Johannessen and Aakvik will be given below.

PALAEOTECTONIC SETTING

The Ebbadalen Fm. was deposited in a N-S trending basin (The Billefjorden Trough), with a maximal thickness of 700 m in the west, thinning eastwards to 130 m at Terrierfjellet. The basin therefore has the form of a half-graben (e.g. Holliday and Cutbill 1972, Johannessen 1981) with its deepest side against the Billefjorden Fault Zone (Fig. 4.18). The best exposures occur along a line of NNW-SSE extension between Odellfjellet and north Bunsow Land. In addition there are a few good outcrops at Faraofjellet, Pyramiden and Anservika.

ANSERVIKA MEMBER

The Anservika Member generally consists of red and subordinate grey shales, red and grey sandstones and red conglomerates. Three stratigraphic logs from the member are shown in Fig. 4.14. According to the description and interpretation given by Aakvik (1981), the following types of deposit have been recognised:

1) Mass flow deposits - Red disorganised polymict conglomerates; set thickness 20-30 cm, maximum particle size (M.P.S.) - 5-6 cm.

2) Flood channel (conglomeratic) deposits - Through cross-stratified sequences 1-2 m thick (fining upwards) M.P.S. 2-3.

3) Sandy channel deposits - Trough cross-stratified sequences, 2-3 m thick (max. 5 m).

4) Alluvial /plain/coastal plain and lagoon deposits - Mudstone (mainly red) interstratified with thin sandstones (red and grey). Individual units may be more than 15 m thick. Planolites rugulosus are common trace fossils.

5) Prograding shoreline deposits - Grey sandstone, coarsening upwards from fine to medium sandstone; 5-7 m thick sequences.

Since similar facies have been described from the Landnørdingsvika Fm and Hyrnefjellet Fm, no further description is needed here.

Most of the coarse grained deposits (conglomeratic) are probably derived from the west, and represent the earliest indications of tectonic activity along the Billefjorden Fault Zone (Cutbill et al. 1976). A reliable palaeogeographic model is difficult to reconstruct due to insufficient data, but it is suggested that continental conditions prevailed most of the time of deposition. However, during short periods of maximal rise of relative sea level, parts of the basin were under marine conditions, and prograding shoreline sequences developed. The marine transgressions probably came from the north.

EBBAELVA MEMBER

The southernmost exposures consist of large scale, cross-stratified sandstones, deposited from braided streams flowing towards northwest. These streams entered standing water northward, and in the Ebbadalen area mouth bars, 2-7 m thick developed. Ripple lamination is the

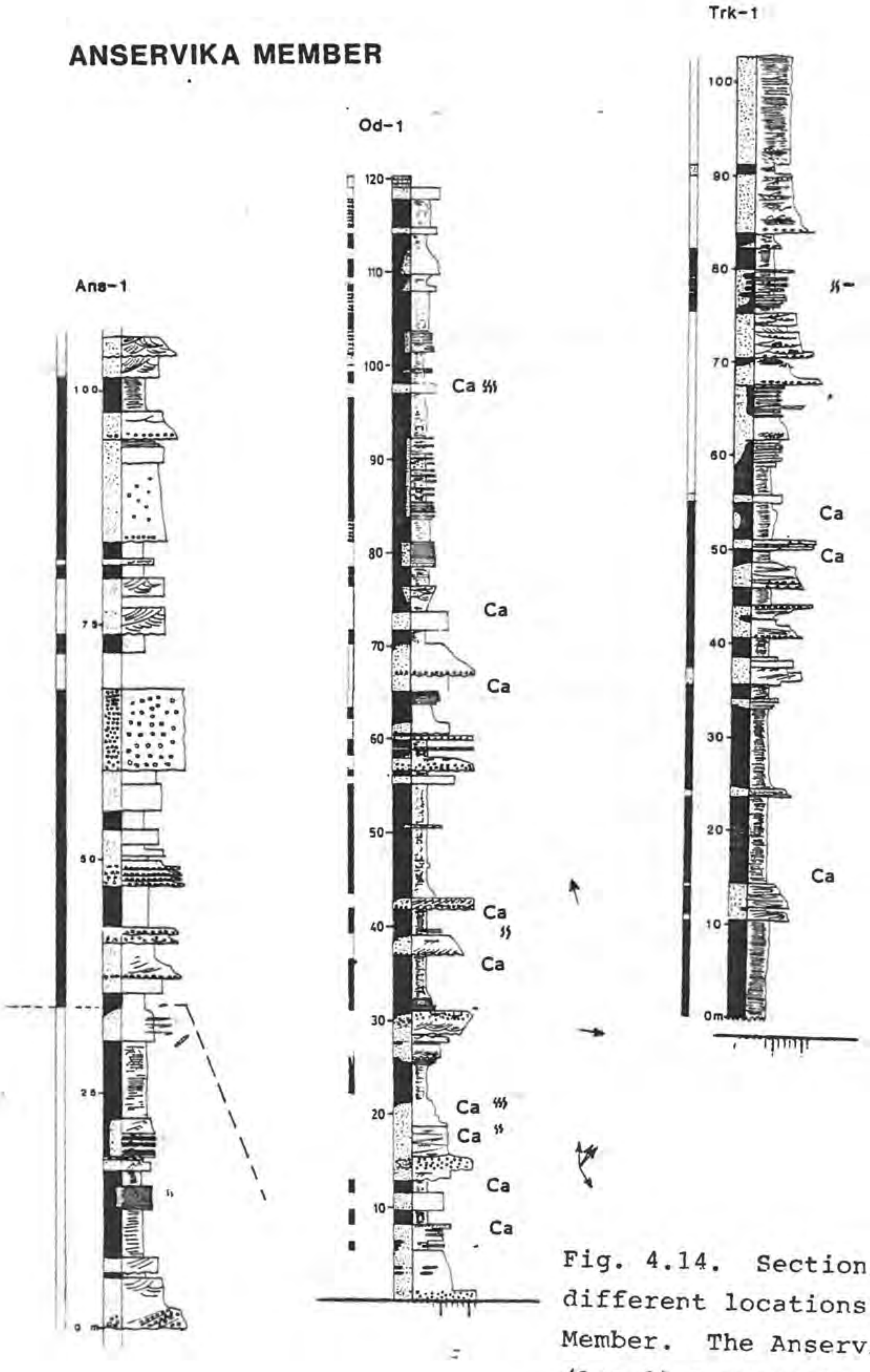

Fig. 4.14. Sections from three different locations of the Anservi[ka] Member. The Anservika profile (Ans-1) represents a more proxima[l] development than the other profil[es.] The Anservika profile was measure[d by] Aakvik 1981. The other profiles [are] from Odellfjellet (Od-1) and Tricolorfjellet (Trk-1).

dominating structure in these deposits. The laterally associated black/green shales, with some thinly stratified, bioturbated sandstones and dark carbonates, suggest deposition in shallow seas or lagoons (Johannessen 1980). A few indications of subaerial exposure have been recorded within these fine-grained sediments, where the structures also indicate low to moderate tidal influence. Closely associated are yellow sandstones with dolomitic cement and fossil fragments. These sandstones are mainly plane-parallel laminated and low angle cross-stratified with bioturbated intervals. The sequences show a slight coarsening upwards, and have been interpretated as prograding barrier islands, which restricted the clastic coastal plains to the south-east from the more open marine conditions to the north-west.

ODELLFJELLET MEMBER

The Odellfjellet Member is located close to the Billefjorden fault Zone, and consists of red and grey conglomerates and sandstones, red shales, yellow dolomitic sandstones and fossil-bearing dolomites, often arranged in well defined cycles (20-40 m). Individual sequences are usually coarsening upwards from a sandy lower part to conglomerates in the upper part, which commonly are capped by yellow dolomittic lithologies (Fig. 4.15).

The coarse clastic units often have a wedge-like geometry which relate them closely to the Billefjorden Fault Zone (Fig. 4.18).

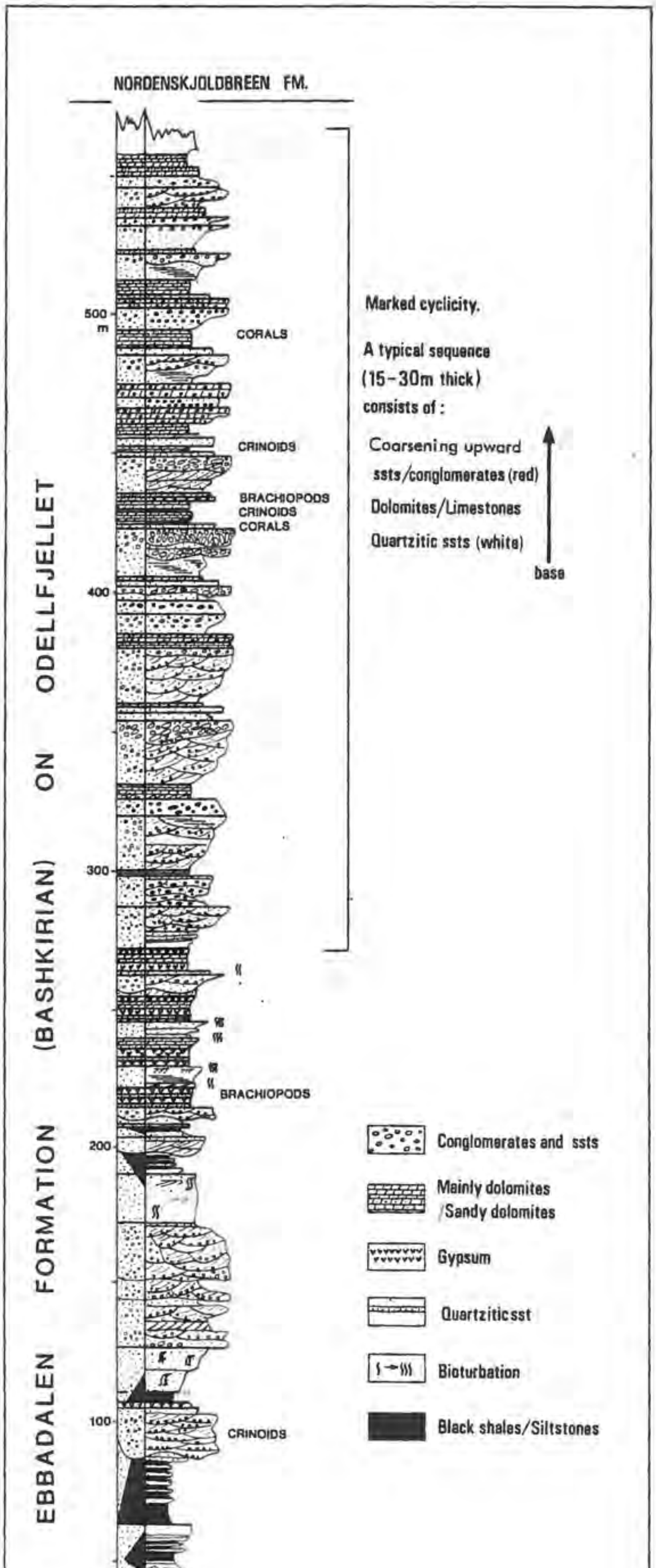

Fig. 4.15. Stratigraphic column from the Ebbadalen Formation (Bashkirian) on Odellfjellet. These sediments were deposited close to the active weste margin of the Billefjorde Trough. The lower part of the formation (the Anser Member) is not shown. Fr Johannessen and Steel (19

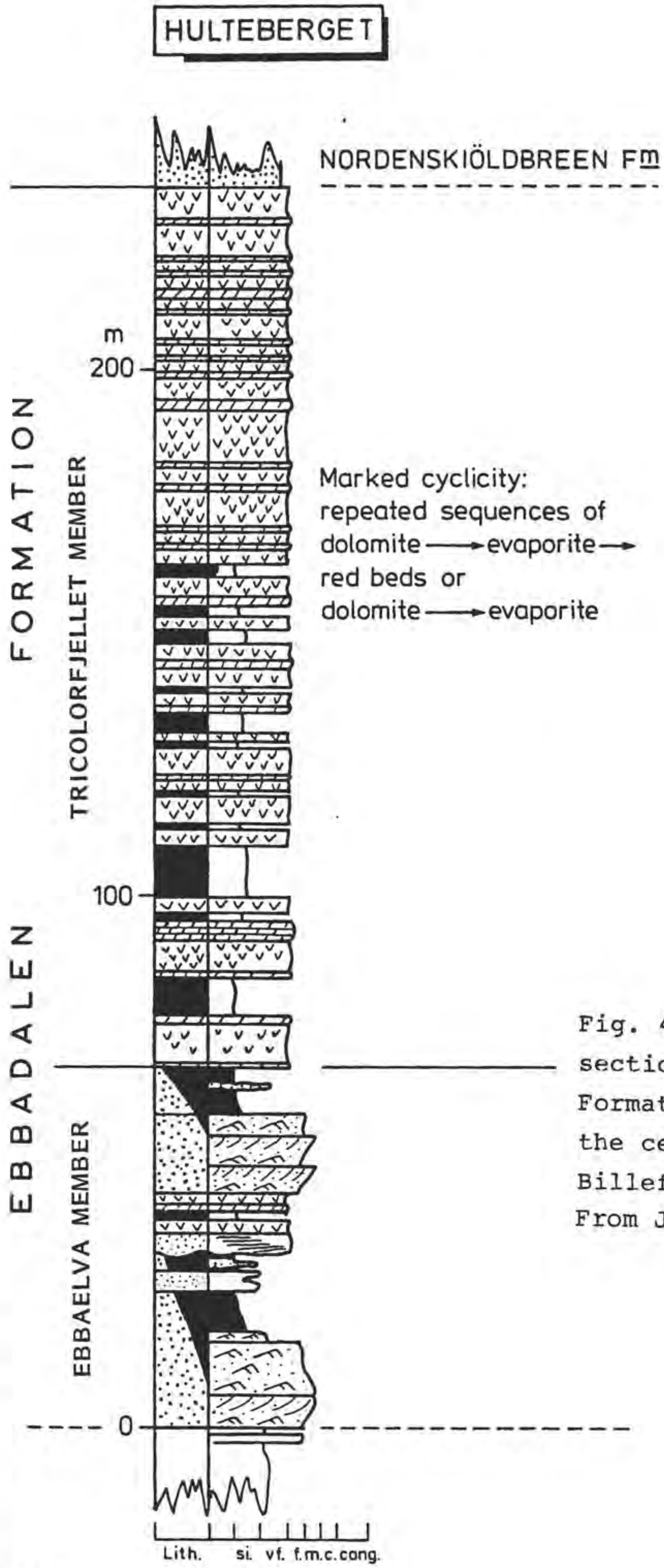

Fig. 4.16. Stratigraphic section from the Ebbadalen Formation on Hulteberget, in the central area of the Billefjorden Trough. From Johannessen (1980)

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Subaerial conglomerates and sandstones of stream channel and debris flow types are common in most proximal deposits and are often associated with red, blocky mudstones, but also well sorted sandstones (probably eolian). These sediments, which was deposited on typical arid alluvial fans, are distally associated with red, plane parallel, well laminated sandstones (often bioturbated) and red mudstones which may contain gypsum nodules. These laterally associated facies have been interpretated as playa lake deposits (Johannessen 1980). Some other types of distally associated sediments are thick sequences of anhydrite and dark dolomites, interpretated as sabkha sequences, and green sandstones and thin green mudstones with occasional rounded gipsum fragments. Brachiopods and wave ripple lamination indicate that marine conditions were closely associated with the alluvial fans.

A special type of grey and yellow conglomerate and pebbly sandstone, common at Pyramiden and Odellfjellet, show many characteristic features typical for subaqueous debris flows (Johannessen 1980). Marine fossil fragments are often present and it is suggested that the deposits represent subaqueous debris flows on alluvial fans which built out directly into the sea (fan deltas). Such fan-delta sequences are 15-30 m thick, and consist mainly of subaqueous debris flow deposits in the lower part and alluvial fan deposits in the middle and upper part. Typical beach, and eolian deposits may be present on the top.

As already stressed, most of the conglomerates of the Odellfjellet Member are organised into well-defined coarsening upward cycles (Fig. 4.15), which very often are capped by thick (fossil-bearing) dolomite benches (Fig. 4.17). The cycles are superimposed on each other, and on Odellfjellet they form a total thickness of 300 m. These clastic cycles seems to be closely related to sabkha sequences in the central parts of the basin.

Johannessen (1980) argued that the cyclicity developed in close relationship to tectonic movements along the Billefjorden Fault Zone, probably in the manner already suggested for both the Landnørdingsvika and the Hyrnefjellet Formations.

TRICOLORFJELLET MEMBER

The Tricolorfjellet Member consists mainly of gypsum and anhydrite in alternation with dark dolomites. The evaporites are probably developed on coastal sabhkas, whereas the dark dolomites are thought to represent shallow water conditions such as lagoons (Johannessen 1980).

This member is developed mainly in the central areas of the Billefjorden Trough, the thickness is approximately 250 m in the Tricolorfjellet area, but thins southeastwards to less than 100 m (Fig. 4.18).

The sequences in the lower part show a significant change across the Ebbadalen Fault (Fig. 4.2) especially with respect to thickness, but also according to facies development, indicating that the fault was active during the early development of the Tricolorfjellet Member.

The alternations of carbonates and evaporites are organised in cycles 4-6 m thick, which may be traced across the central part of the basin until they terminate against alluvial fan lobes of the Odellfjellet Member (Fig. 4.18). Individual cycles usually start with a dark dolomite which is overlain by laminated anhydrite and dolomite, followed by a thick zone of anhydrite (with chicken-wire structures). The cycles are usually capped by red mudstone, with or without gypsum nodules. An idealised sequence is shown in Fig. 4.19. The evaporitic facies have been interpretated as sabkha deposits both by Holliday and Cutbill (1972) and Johannessen (1980).

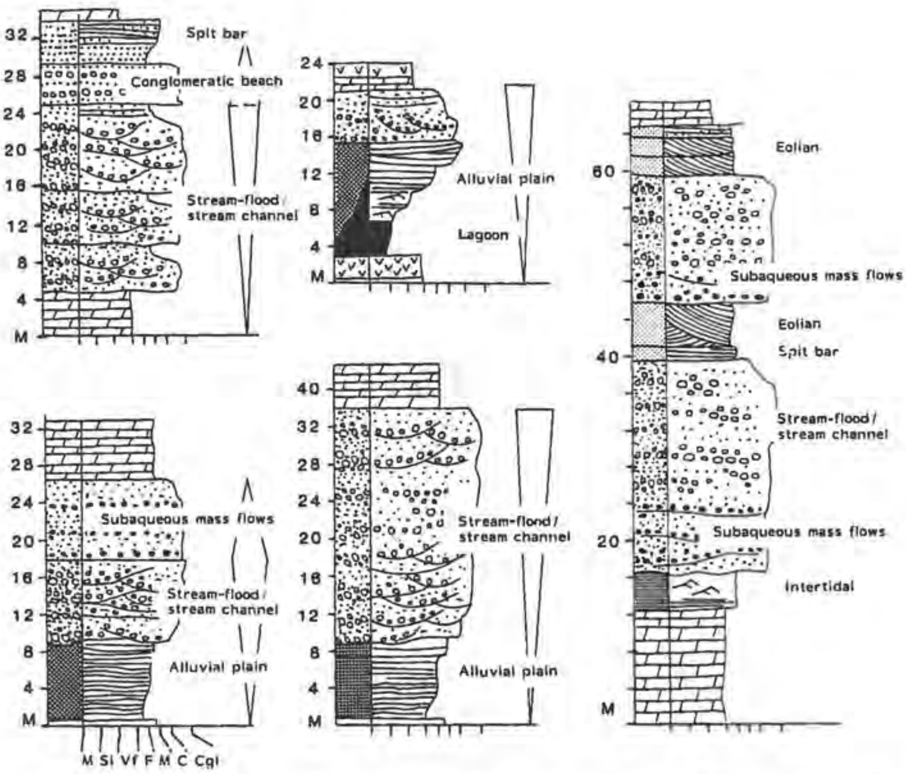


Fig. 4.17. Typical (coarsening upward) sequences from the Ebbadalen Fm. Central Spitsbergen. From Johannessen (1980). Note the capping of carbonates at the top of individual sequences.

The carbonate beds of these sequences seem to be closely related to the clastic coarsening upward cycles of the Odellfjellet Member both in space and time, as many of the beds may be correlated across the basin, and finally found to overlap the coarsening upward alluvial fan lobes to the west.

It is suggested that the carbonates represent situations of sudden marine transgression, probably due to tectonic downwarping at the basin floor. The overlying evaporites reflect the following development of prograding coastal sabhkas.

Anhydrite is the dominating evaporite mineral on Spitsbergen. However, due to permafrost effect, gypsum occurs mainly on the surface of the exposures as thin crusts, or as vein infiling cement (Lauritzen 1977, 1981).

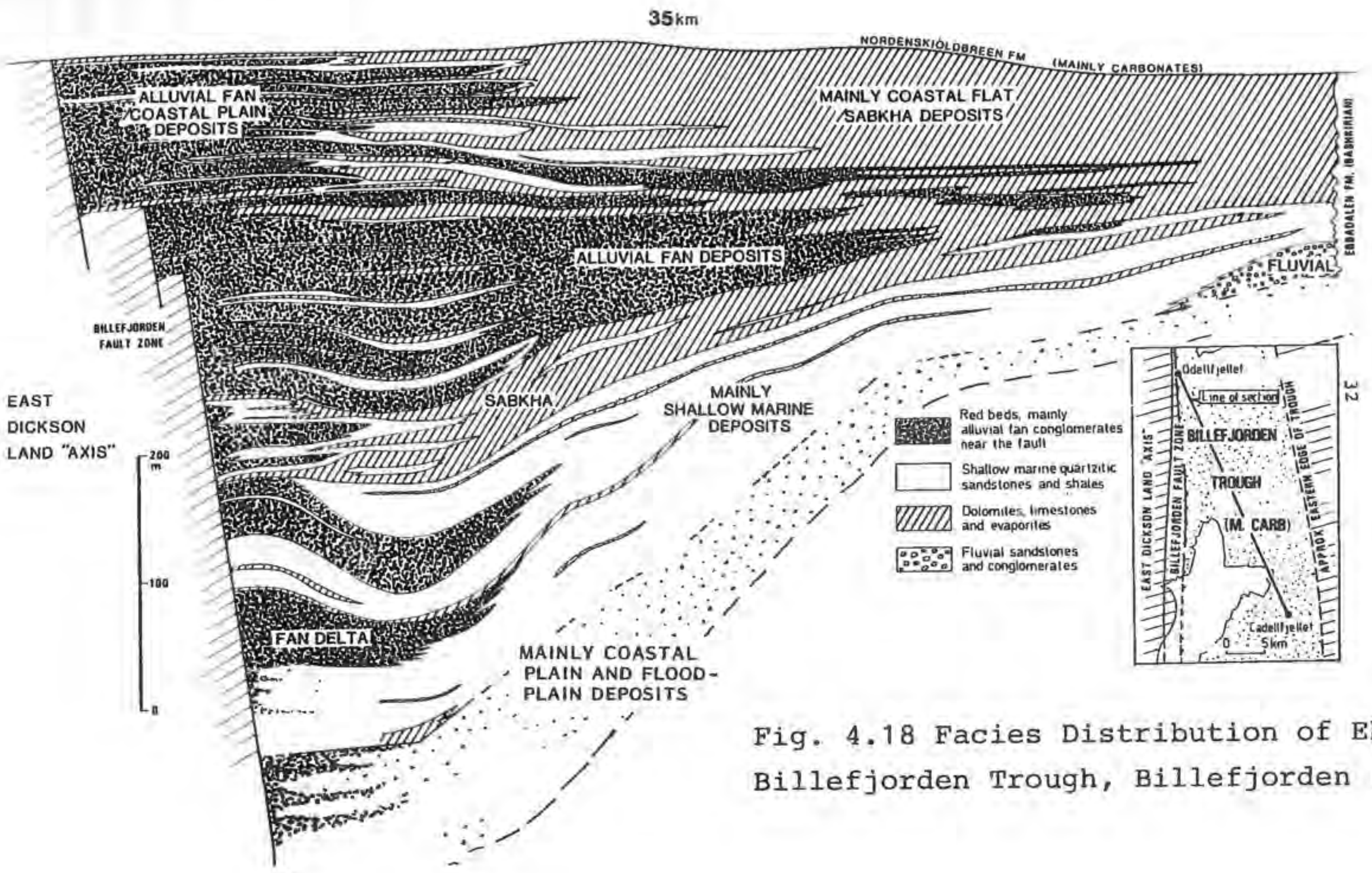


Fig. 4.18 Facies Distribution of Ebbadalen Formation. Billefjorden Trough, Billefjorden (from Johannessen 1980).

THICKNESS	LITHOLOGY	ENVIRONMENT
0,5-2m	Red mudstone, with or without gypsum nodules	Alluvial/coastal plain, playa
3-5m maks 20m	Anhydrite with chicken-wire fabric	Supratidal
	Laminated anhydrite and dolomite	Intertidal/supratidal
0,5-4m maks 4m	Black limestone and dolomite (Green sandstone and mudstone may be present)	Lagoon/intertidal, open marine

Fig. 4.19. Idealised sequence of the dolomites/evaporites in the Trikolorjellet Member (Ebbadalen Fm.). From Johannessen (1980).

EBBADALEN FORMATION-LATERAL/VERTICAL DEVELOPMENT AND PALAEOGEOGRAPHY

An outline of the vertical and lateral development of the Ebbadalen Formation is shown in Figure 4.18. This section starts close to the Billefjorden Fault Zone at Odellfjellet, and runs obliquely across the basin.

The lowermost part of the Ebbadalen Formation (Anservika Member) is dominated by red continental mudstones/sandstones and shallow marine sandstones, deposited along the axial tract of the basin. Laterally equivalent coarse clastic sediments developed along the active Billefjorden Fault Zone (B.F.Z.). Shallow marine and fluvial conditions dominate the next 100-200 m (Ebbaelva Member), but conglomerates become gradually more significant along the B.F.Z. The upper part of the formation consists mainly of fanglomerates interfingering with coastal flats and sabhka deposits (Odellfjellet and Tricolorfjellet Members). Fanglomerates and marginal marine deposits dominate the western areas, near the B.F.Z. whereas coastal sabhkas mainly developed in the central parts of the graben. Shallow water carbonates developed along the eastern margin (Urmstonefjellet Limestone Beds of Holliday & Cutbill, 1972).

The palaeogeographic reconstruciton shown in Figure 4.20 represents four main phases of development of the Ebbadalen Formation. A) Hulteberget Member, B) Ebbabreen Member, C) Lower Odellfjellet and Tricolorfjellet Member, D) Upper Odellfjellet and Tricolorfjellet Member.

Throughout the Ebbadalen Formation there is a gradual overlap of nonmarine by marine facies, so that by Late Carboniferous time the basin was largely marine dominated.

* * *

Again we can see that the same large-scale trends that were recognised from Bjørnøya and the Hornsund area are also present in the Billefjorden Trough. The Lower Carboniferous succession is characterised by deposition in rather humid climates, whereas the uppermost part of the Svenbreen and Ebbadalen Formations reflect arid or semiarid climatic conditions. Coarse clastic debris flooded into the basin from a tectonically active margin in the west. Periodic lowering or tilting of the graben floor caused rapid marine transgressions which produced the characteristic non-marine/marine cyclicity observed. Marine carbonates increased in abundance upward and by Upper Carboniferous time typical marine conditions predominated.

An outline of the tectonic and sedimentary history of development of the Billefjorden Trough during Lower and Middle Carboniferous is briefly summarised in Figure 4.21.

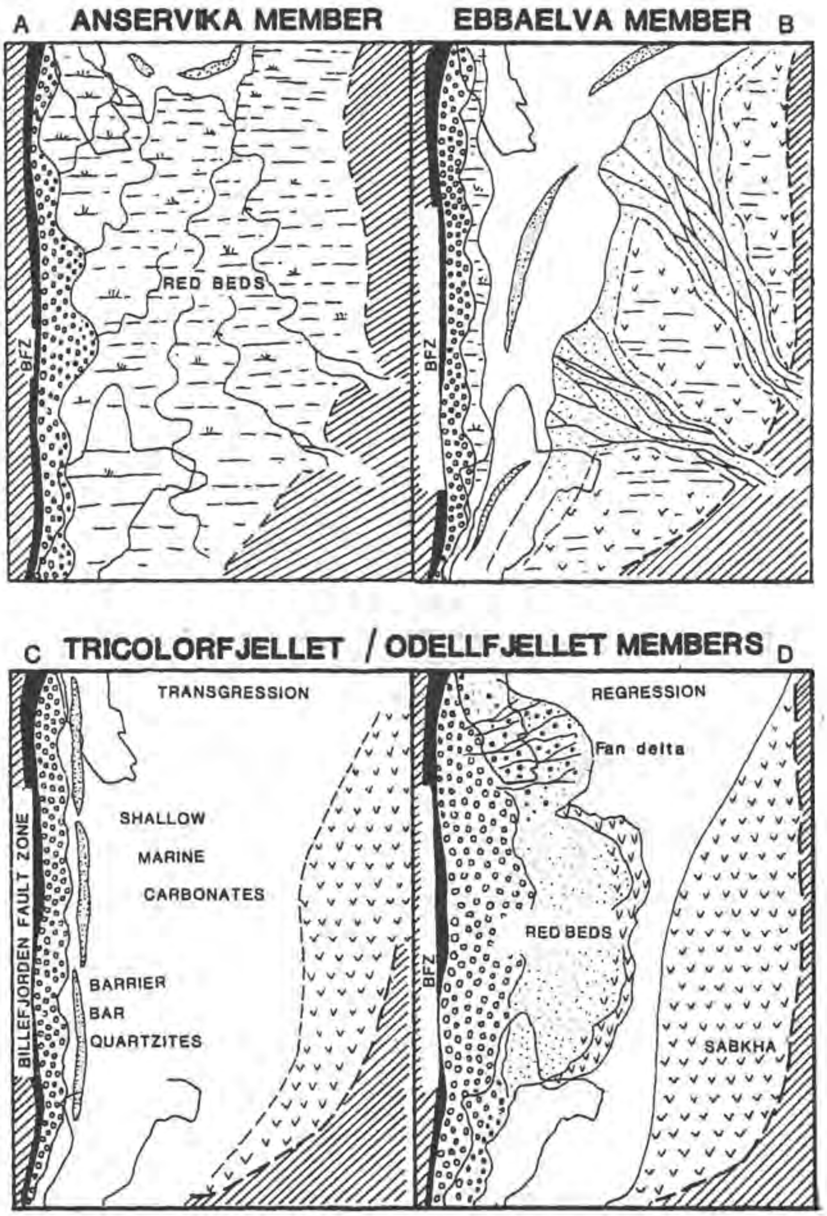


Fig. 4.20. Paleogeographic reconstruction of the Billefjorden Trough through Bashkirian time.

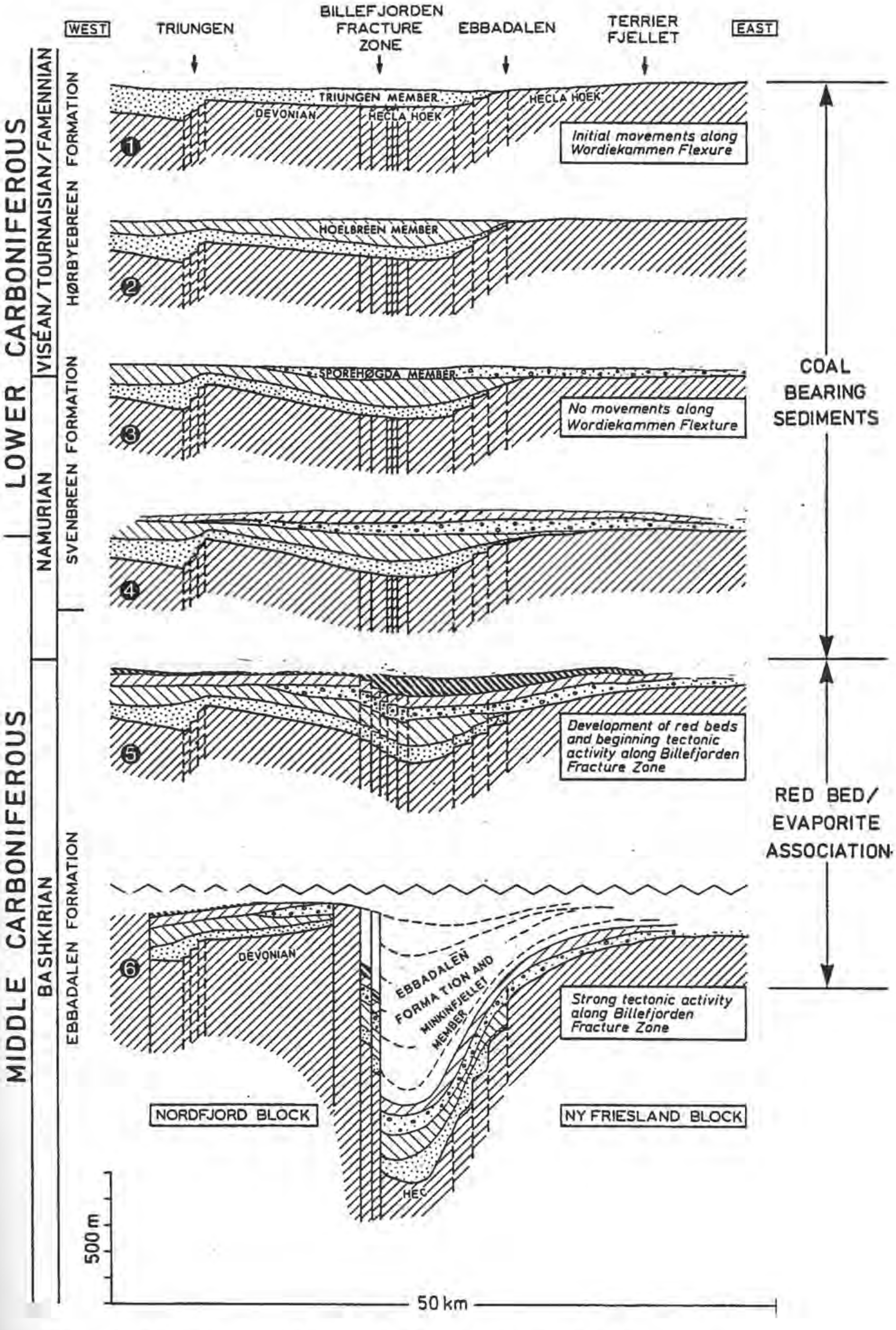


Fig. 4.21. An outline of the tectonic/sedimentary development of the Billefjorden Trough in Lower-Middle Carboniferous time.

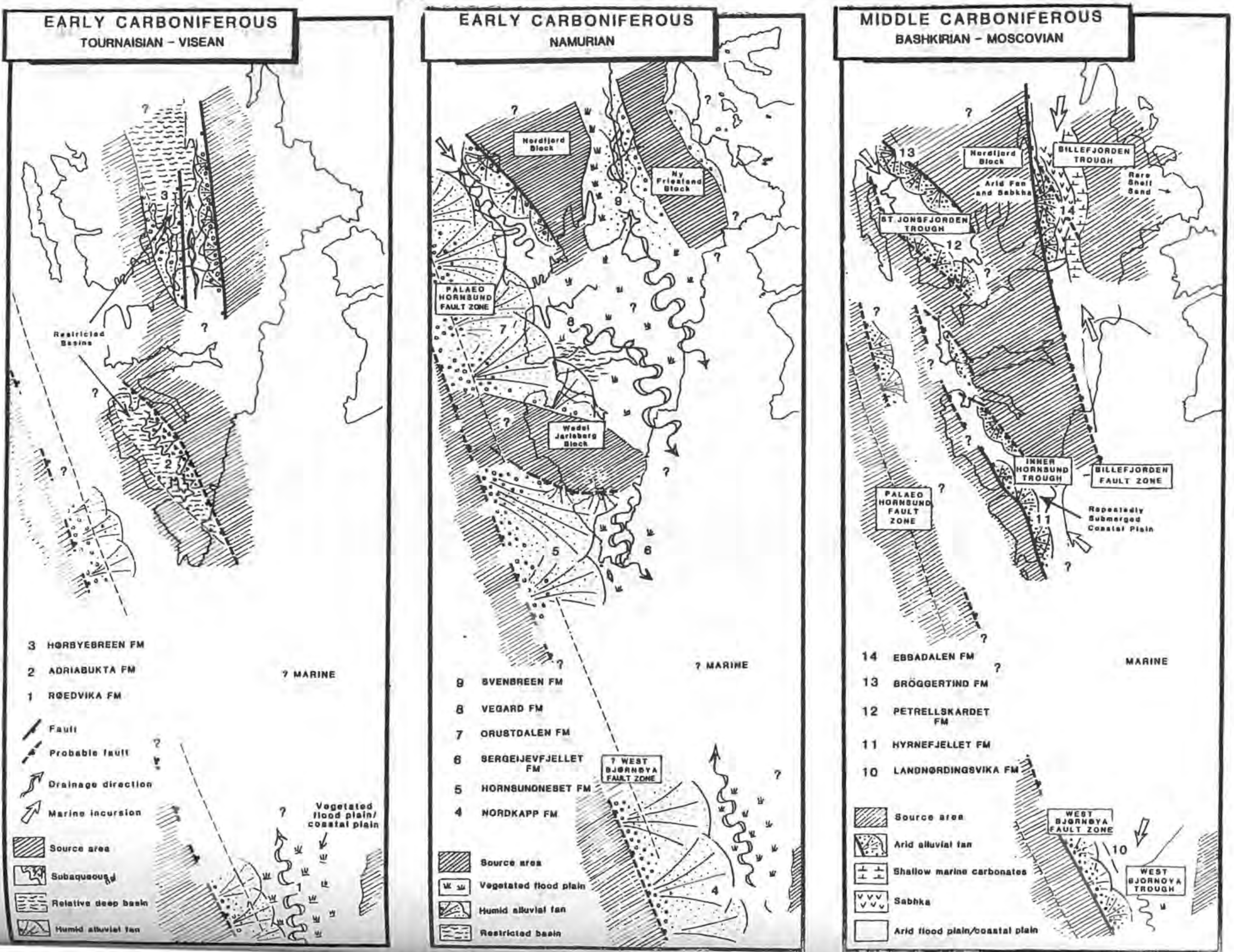
PART IV

SUMMARY AND DISCUSSION

EARLY - MID (BASHKIRIAN)CARBONIFEROUS PALAEOGEOGRAPHY ON SVALBARD

Tournaisian-Visean - A reconstruction of the Tournaisian-Visean palaeogeography of Svalbard is shown in Fig. 5.1 A. The most obvious feature is the development of grabens or half grabens, orientated in a northwesterly direction in central and southern Spitsbergen. These basins were probably bounded by faults on their eastern and western sides. On Bjørnøya, this development is reflected in the Røedvika and Nordkapp Formations, which represent mainly continental depositional environments. The Adriabukta Formation (Hornsund) indicates deposition in relatively deep water (turbidites). Interfingering coarse clastic material entered the basin from the east, mainly by subaqueous gravity flows. The lateral extension of this basin is unknown. In central Spitsbergen (Billefjorden) area the Hørbybreen Formation indicates deposition on flood plains and lakes, whereas coarse-grained, braided stream deposits developed along the eastern margin (Fig. 5.1 A).

Namurian - In Namurian times, extensive braided stream systems occurred along the western side of Spitsbergen (Fig. 5.1 B) and probably developed as coalescing humid alluvial fans (the Orustdalen and Hornsundneset Formations). These fans probably interfinger with flood plain deposits in the more distal parts (eg. the Vegard, Sergeijevfjellet and Svenbreen Formations). The distal flood plain environment became more important towards the late Numurian time, and finally covered most of the early Carboniferous basins on Spitsbergen.


EARLY CARBONIFEROUS
TOURNAISIAN - VISEAN
Restricted Basins
3 HØRBYEBREEN FM
2 ADRIABUKTA FM
1 RØEDVIKA FM
? MARINE
Fault
Probable fault
Drainage direction
Marine incursion
Vegetated flood plain/ coastal plain
Source area
Subaqueous
Relative deep basin
Humid alluvial fan
EARLY CARBONIFEROUS
NAMURIAN
Nordfjord Block
Ny Friesland Block
PALAEO HORNSUND FAULT ZONE
Wedel Jarlsberg Block
9 SVENBREEN FM
8 VEGARD FM
7 ORUSTDALEN FM
6 SERGEIJEVFJELLET FM
5 HORNSUNDNESET FM
4 NORDKAPP FM
? MARINE
? WEST BJØRNØYA FAULT ZONE
Source area
Vegetated flood plain
Humid alluvial fan
Restricted basin
MIDDLE CARBONIFEROUS
BASHKIRIAN - MOSCOVIAN
Nordfjord Block
BILLEFJORDEN TROUGH
Arid Fan and Sabkha
Rare Shelf Sand
ST JONSFJORDEN TROUGH
INNER HORNSUND TROUGH
BILLEFJORDEN FAULT ZONE
PALAEO HORNSUND FAULT ZONE
Repeatedly Submerged Coastal Plain
14 EBBADALEN FM
13 BRÖGGERTIND FM
12 PETRELLSKARDET FM
11 HYRNEFJELLET FM
10 LANDNØRDINGSVIKA FM
MARINE
WEST BJØRNØYA FAULT ZONE
WEST BJORNOYA TROUGH
Source area
Arid alluvial fan
Shallow marine carbonates
Sabhka
Arid flood plain/coastal plain

A correlation of the Billefjorden group along western Spitsbergen is shown in Fig. 5.2. The most significant feature is the Wedel Jarlsberg Land High, and the thick accumulation of Namurian sediments close up to this block, on both the northern and southern sides. Relatively rapid subsidence near the northern margin of the high, probably caused the development of relatively persistent standing water which strongly influenced the development of the Vegard Formation in the Bellsund area (turbidites). The rate of deposition was locally relatively high during Namurian time, and in the Hornsund area it averaged 100 m/my. It is suggested that the early Carboniferous basins on Spitsbergen represent grabens or half grabens developed in a tensional (or transtensional) tectonic regime.

Bashkirian - The development of the Bashkirian contrasts strongly with the Lower Carboniferous, as coarse clastic red beds, representing arid or semiarid alluvial fans now dominate the deposition along the active faults, which bounded relatively narrow grabens or half grabens (Fig. 5.3). Flood-plain, coastal-plain and shallow marine deposits dominate the axial tracts of the grabens. The influence of marine environments became more important with time, and dominated by Moscovian time.

The location and extension of the main Bashkirian grabens are shown in Fig. 5.3, and are represented with the Landnørdingsvika, Hyrnefjellet, Ebbadalen and the Petrellskardet Formations. Characteristic for the Bashkrian palaeogeography of Spitsbergen is that fault lines which mainly were inactive during Lower Carboniferous, now became active and developed extensive narrow orientated, en echelon basin margins probably in a transtensional tectonic setting. (See also Figs. 2.24, 4.21 and 5.1).

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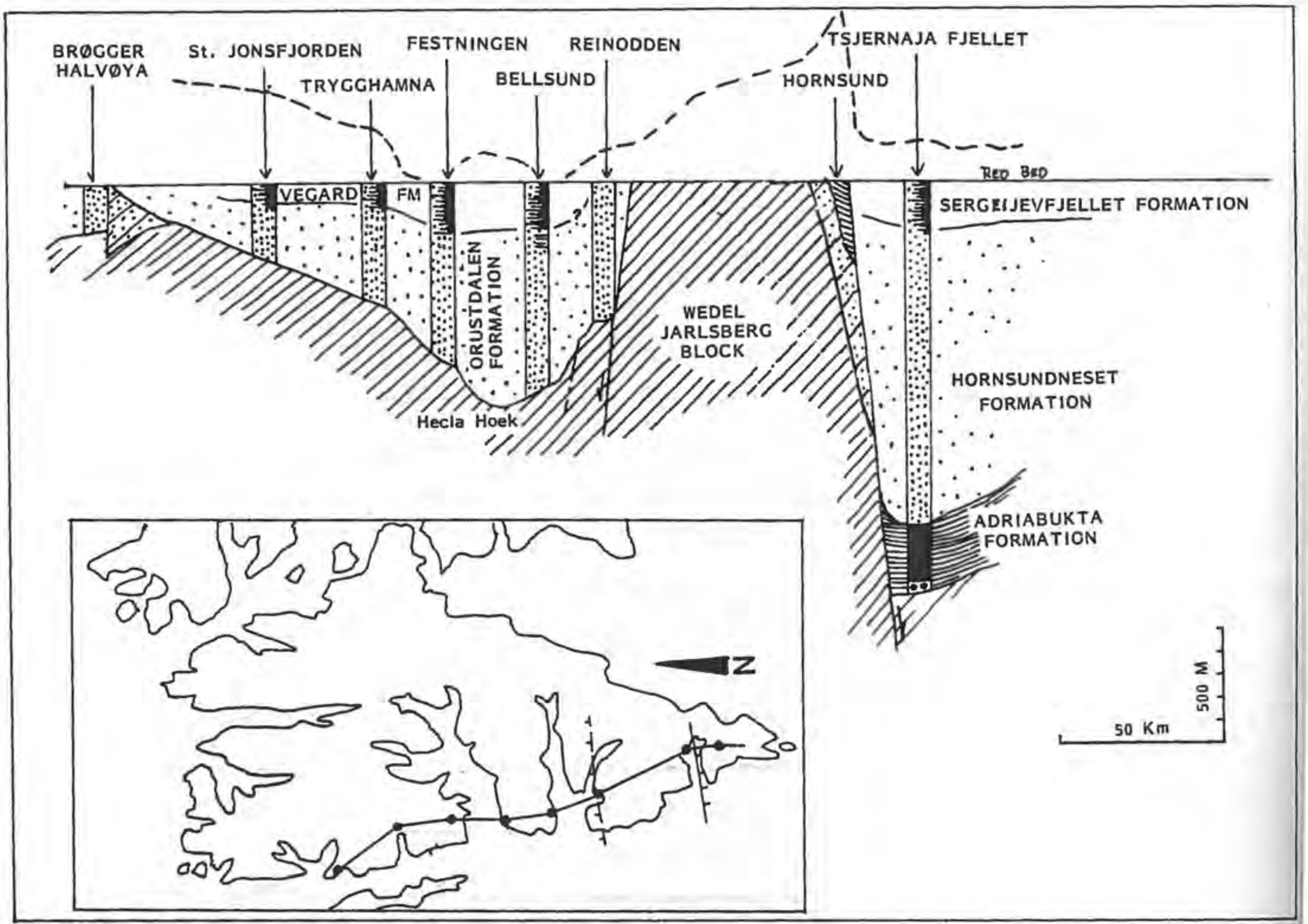

Fig. 5.2. Correlation of Lower Carboniferous sections along the west coast of Spitsbergen. The base of the red beds have been used as datum. The stippled line indicates the thickness of the overlying red beds. Note that the thickness of the Lower Carboniferous succession shows an approximately inverse relationship with the thickness of the red beds (Middle Carboniferous) in the area between St. Jonsfjorden and Sørkapp Land.

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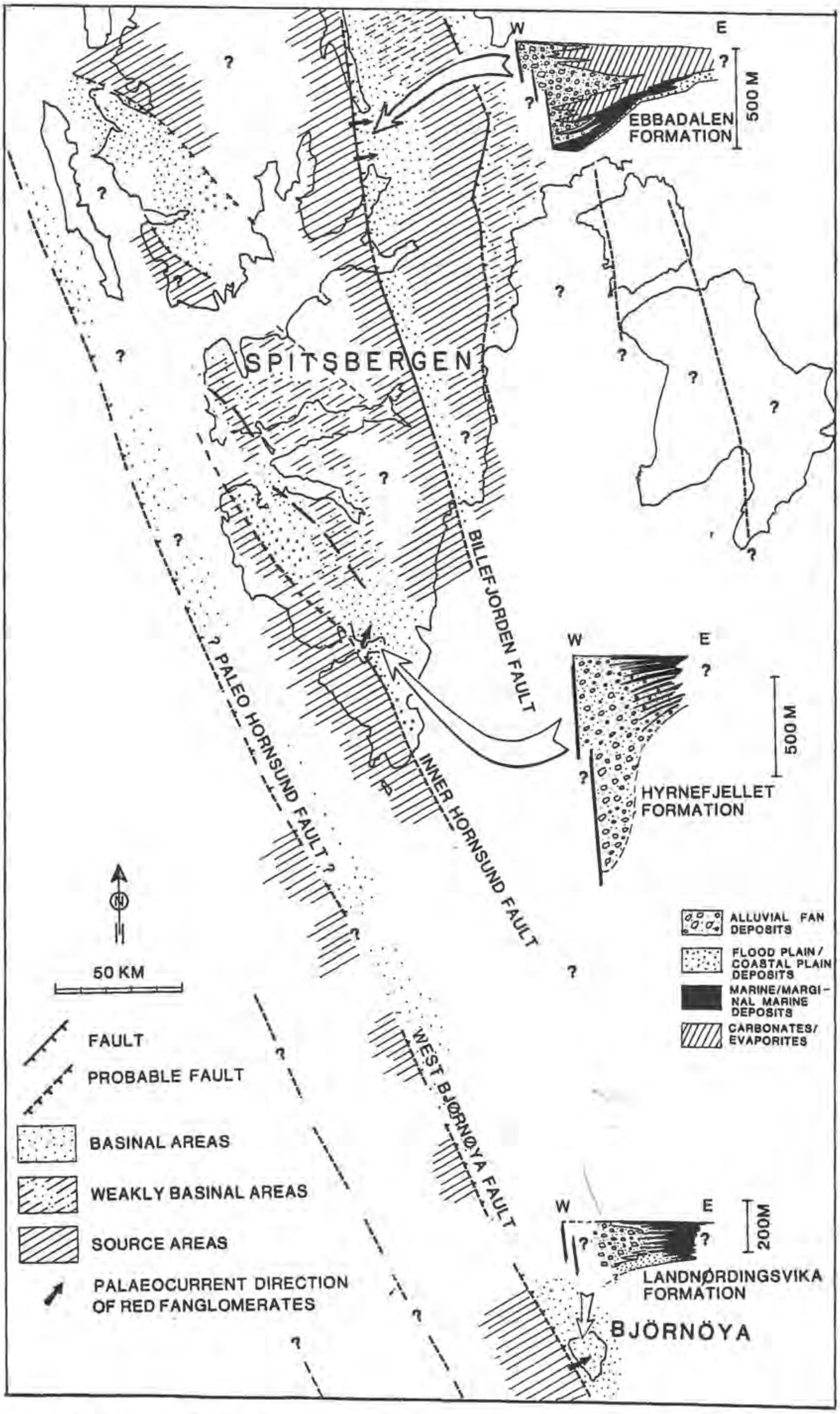

Fig. 5.3. Main Bashkirian tectonic elements and basins on Spitzbergen. From Gjelberg and Steel 1983.

This tectonic activation is most obvious in the Inner Hornsund Trough (Gjelberg and Steel, 1982) in West Bjørnøya Trough and in the Billefjorden Trough, where it caused the development of narrow basins compared to that of the Lower Carboniferous. It is likely that the Bashkirian basins developed in a completely different regional-tectonic regime than that which produced the Lower Carboniferous tensional rift systems. This is also indicated by the fact that the basins developed in different locations and orientation, by the much more intense tectonically active margins and by an approximately inverse thickness relationship between the Billefjorden Group and overlying Bashkirian red beds (Fig. 5.2).

It is suggested, on the basis of the tectonic development and <u>en echelon</u> configuration of the Middle Carboniferous basins on Spitsbergen that the regional tectonic regime during Middle Carboniferous time was one of strike-slip or oblique-slip. The en echelon pattern of the basins (Fig. 5.1) suggests a sinistral strike slip regime.

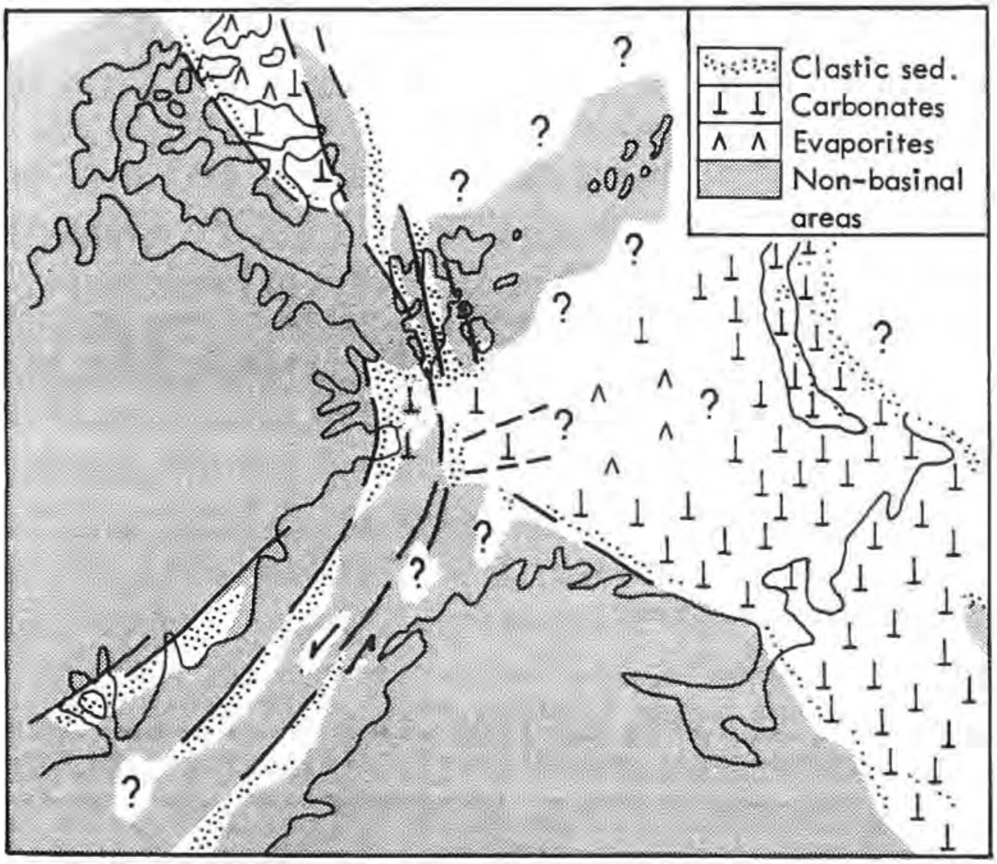

Fig. 5.4. Early - Middle Carboniferous palinspastic reconstruction of the north Atlantic and Barents Shelf region.

In order to understand the development of the Carboniferous basins on Svalbard, a summary of regional tectonics desireable.

Three theories have been proposed for the development of the northeast Atlantic Carboniferous basins particularly those in Britain: megashear; tension from Rheic Ocean subduction; tension from rifting of the North Atlantic. The first and last of these theories are considered most likely and only those are considered further. The megashear theory, outlined by Arthaud and Matte (1977) and utilised by Ziegler (1981) states that a wide zone of sinistral transcurrent faulting affected Europe during early and late Carboniferous. Supporting data for this theory has been published by Kent and Opdyke (1979) who found, on the basis of palaeomagnetic studies, that there was a left lateral displacement of approximately 1500 km between the Northern Appalachian and cratonic North America during early Carboniferous time. They argued that this displacement is similar in magnitude and sense to the difference in Devonian palaeopoles, and concluded that the Devonian displacement continued into early Carboniferous time. This is also in agreement with the investigations of Van der Voo and Scotese (1981) who found palaeomagnetic evidence for a large (>2000 km) sinistral offset along the Great Glen fault during Carboniferous time.

In a recent paper Harland et al. (in press) suggested that large-scale sinistral strike-slip movements took place between Svalbard and Greenland in mid-Carboniferous times. Based on stratigraphic evidence they stated that the three provinces of Svalbard (western, central and eastern) were united in Bashkirian time in a position to the north-east of Greenland. It was from that position that Cenozoic ocean spreading separated Svalbard from Greenland by extensive dextral strike-slip movements. According to Harland et al. (in press) there is now palaeomagnetic data from eastern Spitsbergen which suggests that by lower Namurian times this area was located well to the south of its Permian position with respect to Greenland and North America.

The other important theory of Carboniferous palaeogeography is that of an early late Palaeozoic rifting and drifting in the north Atlantic between "Greenland" and "Europe". The effect of this theory on the Svalbard/Greenland boundary is also important to consider. The theory of incipient Late Palaeozoic plate separation in the North Atlantic has previously been published by Russell and Smythe (1978), Smythe *et al.*

(1983) and Russell and Smythe (1983). Russell and Smythe (1983) related the development of the Oslo graben to this important tectonic event which took place in late Middle Carboniferous (Moscovian) time (Olaussen 1981). Due to the left bend in the northeasternmost Atlantic area in this model, incipient spreading would lead to dextral strike-slip along the margin west of Svalbard, such as also happened later in early Tertiary times when the West Spitsbergen Orogeny developed.

According to the above model, late Middle Carboniferous Svalbard should have been influenced by dextral strike-slip movements. The late Carboniferous basins on Svalbard have a somewhat different configuration than the Bashkirian ones as the former are broader and there was less tectonic activity along the margins. There was some reactivation along older Bashkirian fault margins, especially in the Billefjorden and Inner Hornsund Troughs but on western Spitsbergen and Bjørnøya this reactivation resulted in a reversed drainage and part inversion of the basins (Netland 1981, Agdestein 1980). It is possible that these local tectonic changes may well reflect the important regional changes which resulted from an eventual Late Carboniferous rifting in the North Atlantic.

A tentative conclusion from the above discussion, with respect to the regional tectonic setting is therefore that, during early Carboniferous times there was a tensional tectonic setting on Svalbard (with little or no strike-slip components). Rift basins with continental clastic (sand - shale) sedimentation developed. During Middle Carboniferous strike-slip movements took place along important NW-SE fault lines. Narrow basins with rapid, conglomeratic sedimentation dominated along fault margins.

The regional tectonic interpretation of the observed Middle Carboniferous strike-slip movements is not fully understood yet. However, a variant of the megashear hypothesis is that it may have been a response to oblique collision of the north Europe and north American plates with a south Europe plate, or one of several rotated plates in the manner depicted by Lorenz (1976).

The Late Carboniferous basins on Spitsbergen do not directly suggest a dramatic change of regional tectonic regime, from sinistral to dextral strike-slip movements, which should be excepted if an early phase of rifting took place in the North Atlantic. On the other hand, a rifting and drifting as illustrated by Russell and Smythe (1983, Fig. 2) would most likely lead to transtensional tectonics and may explain the relatively moderate basinal changes observed on Svalbard from Middle through Late Carboniferous times.

CONCLUSIONS AND DISCUSSION

It is clear that important climatic, tectonic and environmental changes occurred in late Namurian to early Bashkirian time throughout the Svalbard region. The most obvious was the rather dramatic climatic change from humid to arid conditions, and the change from continental to marine conditions, resulting from a regional rise in sea level. This appears always to occur in association with, and soon after the first red beds. The widespread gradual change from continental to marine conditions in all major basins or troughs are documented and it is emphasised that this heralds the incoming of carbonate-evaporite sedimentation in the region which was to persist into the Lower Permian.

The onset of rifting in the region and the appearance of red beds was not quite so closely related in time. In all areas there is evidence of fault-controlled, coarse, clastic sedimentation prior to the climatic change. In this connection we can look more closely at the effect of climate, the change from relatively humid to more arid conditions, on basin margin sedimentation and the resultant facies.

Under the early, relatively humid conditions the marginal facies in the fan-swamp/floodbasin association shows the following features in contrast to the more arid fan-playa/sabkha association:

1. Mineralogy is more mature, with a dominance of quarts and quartzite framework grains.

2. Texture is more mature, especially as regards to the amount of clay matrix and the sorting, although degree of grain rounding may be similar in both cases.

3. Average grain size in the fanglomerates of the humid system is smaller.

4. Braided stream facies dominate the humid system whereas mass flow and stream-flood facies are much more important in the arid association. Where the fans were subaqueous, there is little difference between the two situations.

5. Analysis of facies sequences shows little obvious vertical organization in the former association while vertical coarsening (produced by progradational tendencies) is usually clear in the latter association.

As regards the overall contrast, it is worth noting that where the most proximal facies are not exposed, it may not be at all obvious that the more humid association is a fault-controlled, basin margin facies. However, the palaeocurrent patterns and the interfingering lateral relationships to basin-axis coal-bearing sequences suggest that the Hornsundneset and the Nordkapp Formations represent distal parts of fluvial dominated alluvial fans.

Within the red bed succession of all three areas there is a certain facies sequence that is repeated. This is especially clear where coarse-grained sediments are developed in Inner Hornsund (Figs. 2.14 and 2.20) and in Billefjorden (Fig. 4.15). In the most proximal sequences the dominating motif is an upward-coarsening red bed sequence capped by a shallow marine quartizitic sandstone. In more distal reaches the marine sandstone

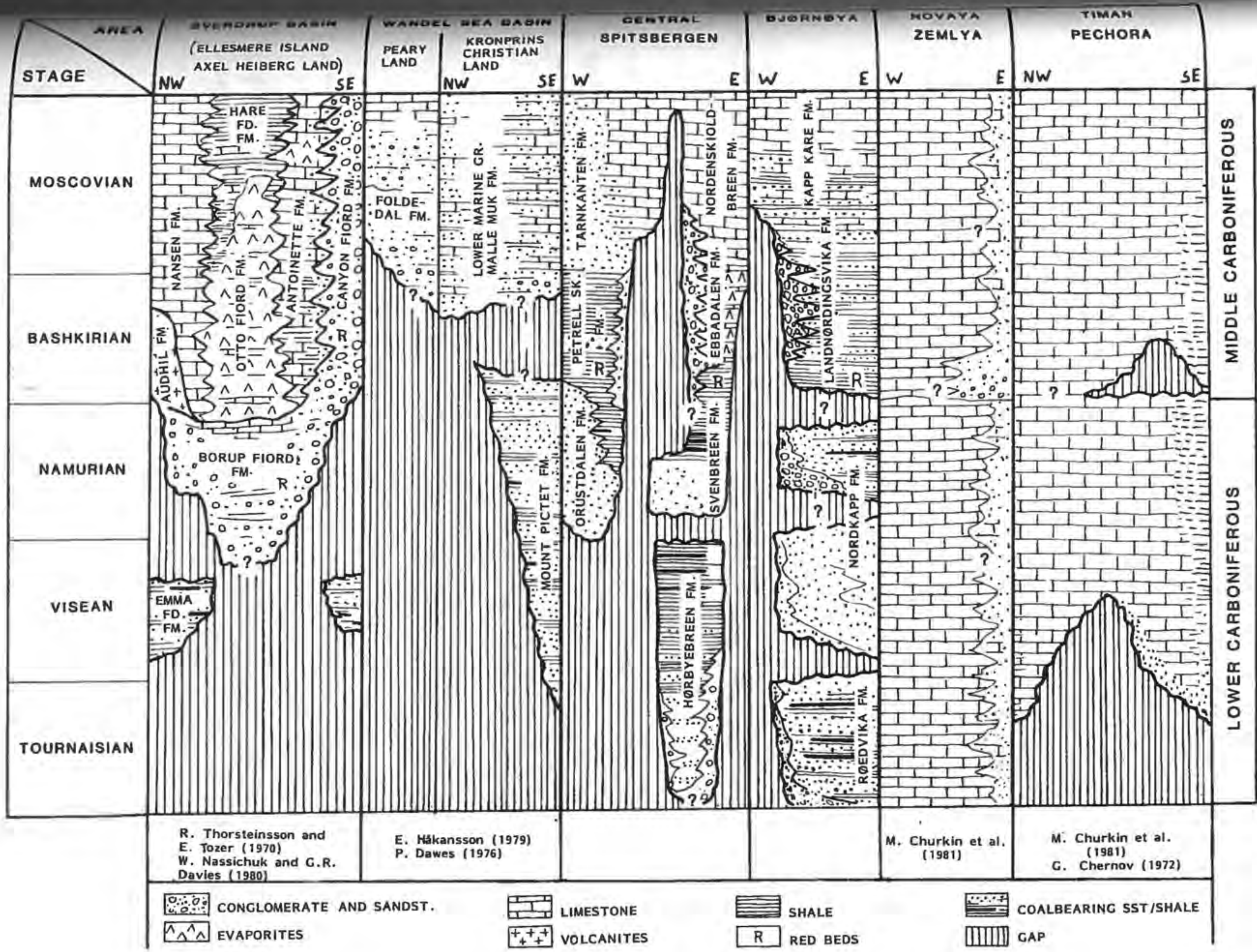

Fig. 5.5. Stratigraphic correlation chart for the Lower-Middle Carboniferous in Arctic Areas.

member is overlain by dolomite. This most likely represents a sudden lowering of base level, and a marine transgression (demonstrably basin-wide in the case of the Billefjorden Trough at least), producing first a marine reworking of the alluvial surface and then carbonate sedimentation, followed more gradually by the marginal response in the form of progradation of the alluvial fans.

Because of their widespread and coarse-grained nature as well as the deep basin context these motifs are taken to represent discrete episodes of movement, along the bounding faults. The scale of such sequences (<30 m) is consistent with the scale of fault scarps produced by rapidly repeated movement of short intervals along fault lines in the Basin and Range Province in historic times (Wallace 1977).

A Lower - Middle Carboniferous climatic change simular to that discussed above has also been tentatively identified in the literature from other Arctic areas (Fig. 5.5), but in the Sverdrup Basin this occured earlier in Namurian times, (Thorsteinsson and Tozer 1972, p 569, Nassichuk and Davies, 1980) and the change seems to be less dramatic.

In the Wandel Sea Basin a similar change may have taken place near the mid-Carboniferous boundary, but in this area middle Carboniferous sediments are missing, due to uplift and erosion (Dawes 1976, Håkansson 1979), so that the exact time interval for the climatic change is not known.

From Andøya, Northern Norway, Dalland (1979, 1981) reported a change from humid to arid soil profiles (from deeply weathered granites to (?caliche), which probably represents a mid - Carboniferous age.

There are three main hypotheses that may explain the distinct climatic change which has been identified throughout Svalbard:

(1) There may have been a world-wide climatic change, but this is considered unlikely, since arid conditions appeared later in Central Europe.

(2) The period of time under discussion falls within that period when there was closure of the Hercynian Ocean and the convergence of Laurasia and Gondwanaland into a large continent (Irving 1977). It is possible that this joining of continents and creation of topography along the Hercynian suture zone may have had far-reaching climatic effects, particularly in producing a more arid climate for the northerly regions.

(3) The northward motion of Laurasia during mid Carboniferous time (?2000 km), which caused the extensive strike-slip movement (Harland et al. in press) may have carried the present day Svalbard area rapidly through fixed climatic zones. This hypothesis is reasonable in view of the palaeolatitude of Svalbard in Carboniferous time (just south of 30°N). It also explains why the change from humid to arid conditions always occurs just after the onset of extensive tectonic activity in Bashkirian times and which reflect the development of Strikslip basins. It also explains why the climatic change occurs earlier in the Sverdrup Basin which was located to the left of the strike slip zone. (Fig. 5.4), and consequently not subjected to such rapid northward movements. It also explains why the climatic change seems to have been less distinct here.

The last hypothesis is the one which best explains the observed changes, and is consequently the prefered interpretation here.

The long-term relative sea level rise which is evident from an overall change from fluvial to marine deposits may either have been eustatic or dependent on widespread Middle Carboniferous subsidence over much of the northwestern corner of the Barents Shelf, again possibly related to contemporaneous uplift of Hercynian Europe. Data given by Vail et al. (1977) on global cycles of relative change of sea level during Phanerozoic time suggest that a cycle of relative sea level rise was initiated at about that time.

The regional tectonic setting on Svalbard during Carboniferous time is still problematic, but it seems likely that tension (or transtension ?) dominated the early Carboniderous. Sinistral movements took place in Middle Carboniferous. In late Caroniferous transtensional, possible dextral movements may have taken place due to an early phase of rifting and drifting in the north Atlantic, (Russell and Smythe 1983).

ACKNOWLEDGEMENTS

The research presented herein forms part of the University of Bergen's Svalbard Project (1975-1979). Special thanks are due to the Norwegian Applied Science Research Council (NTNF), the Norwegian Oil Directorate and Norwegian Polar Research for supporting the Carboniferous field work. I want to thank Ron Steel for supervising the work and for valuable help both with the manuscript and with the interpretation of field data.

The data from Hornsund and from Billefjorden were collected largely during the Statoil Svalbard Expeditions of 1977 and 1979. I gratefully acknowledge the co-operation of Jacob Bleie and Ånon Spinnanger who allowed us to participate in the expeditions and to publish the results.

I also want to thank Norsk Hydro for encouragement with this work and for typing of the manuscript.

Thanks are also due to Johan Petter Nystuen for critically reading the Bjørnøya part of the manuscript, to David Worsley for discussion , to Erik Johannessen and Roar Aakvik for discussion, access to their data from the Billefjorden area, and field assistance. I also want to thank Arvid Nøttvedt for discussion and for critically reading parts of the manuscript. Thanks also to Vidar Larsen and Geir Haarr for discussion and for field assistance.

Finally I will thank my wife Marit Kollsete for support and patience during the work.

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Attachments

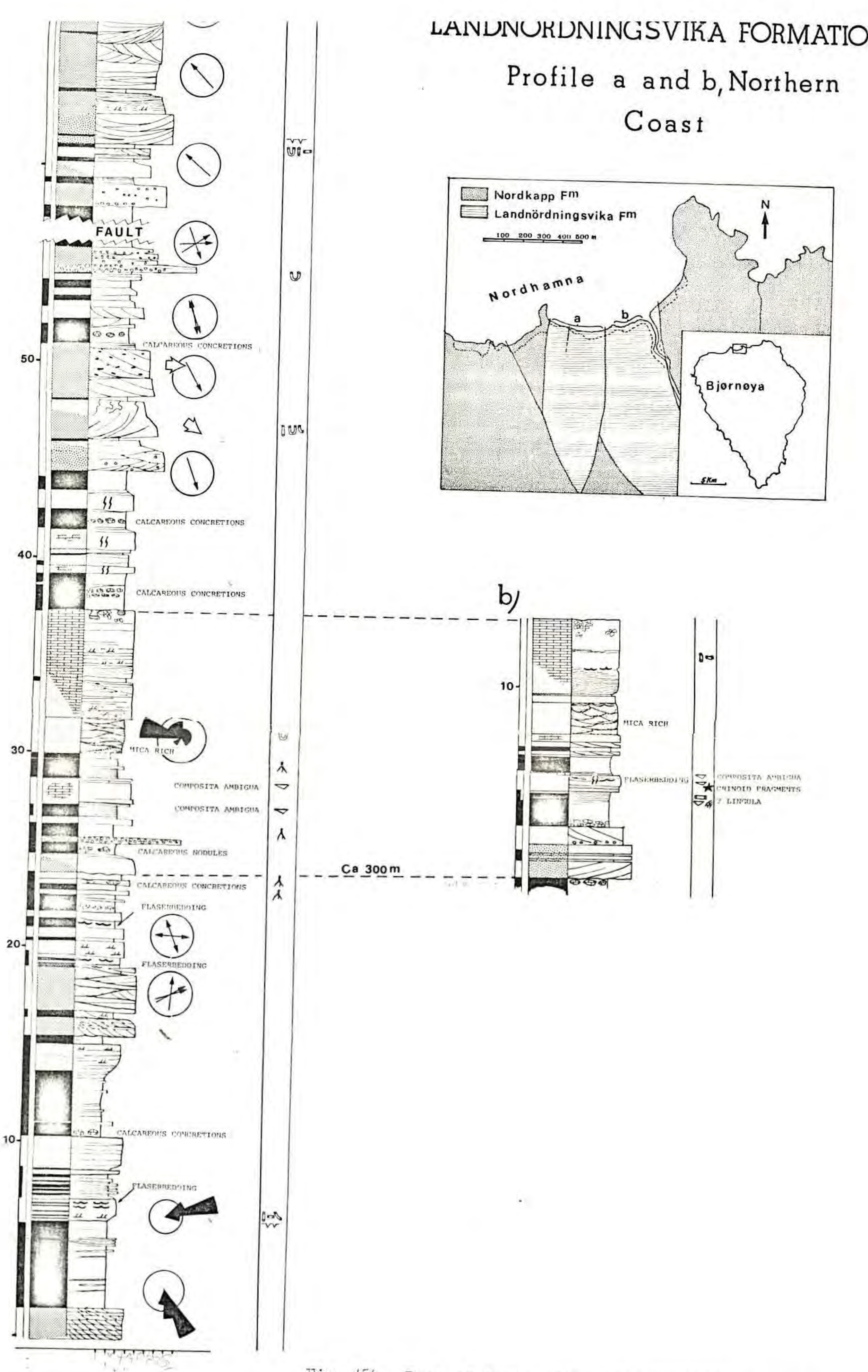
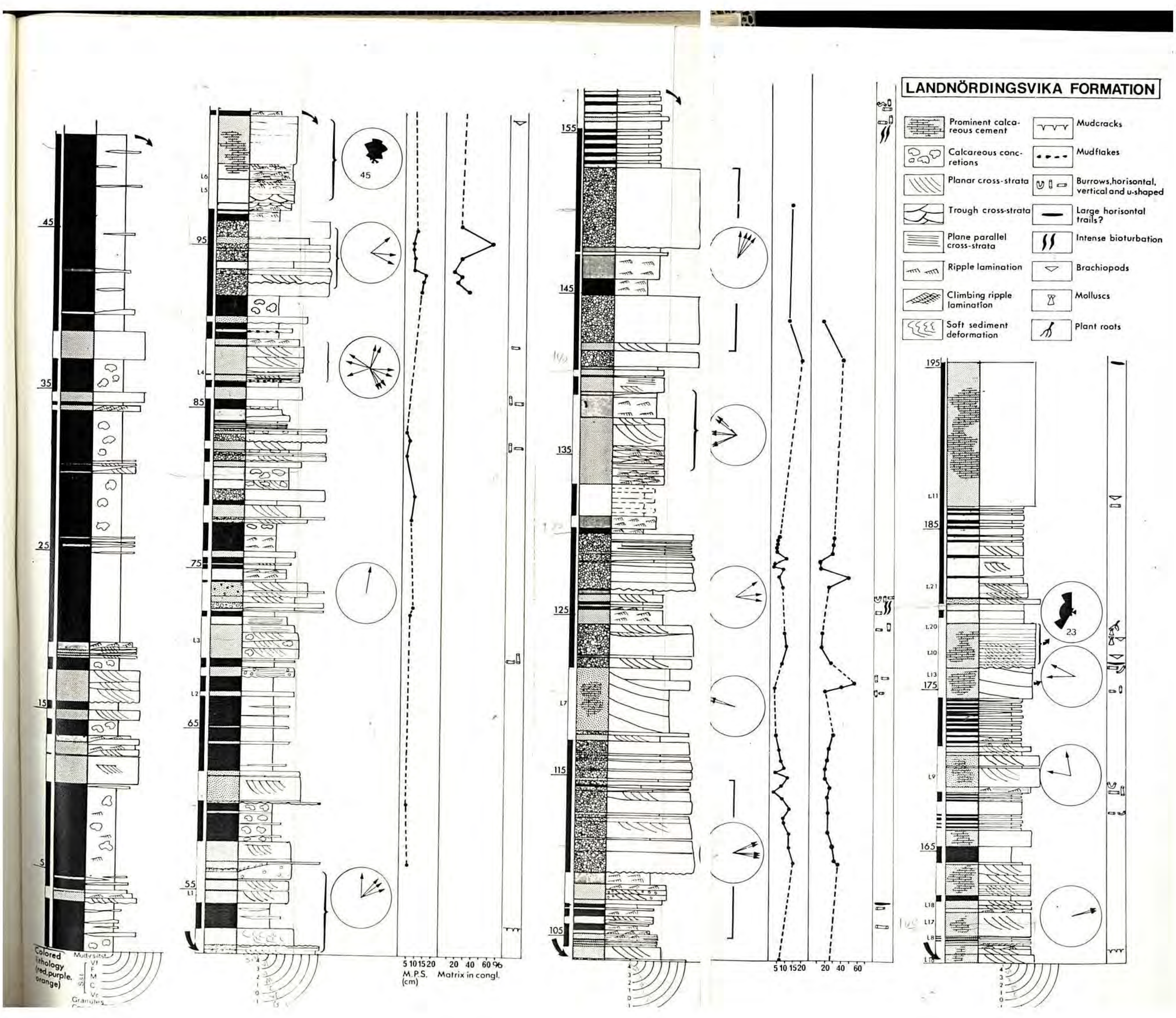


Fig. 156. Part of Landnørdingsvika Formation, exposed in Nordhamna on the north coast.



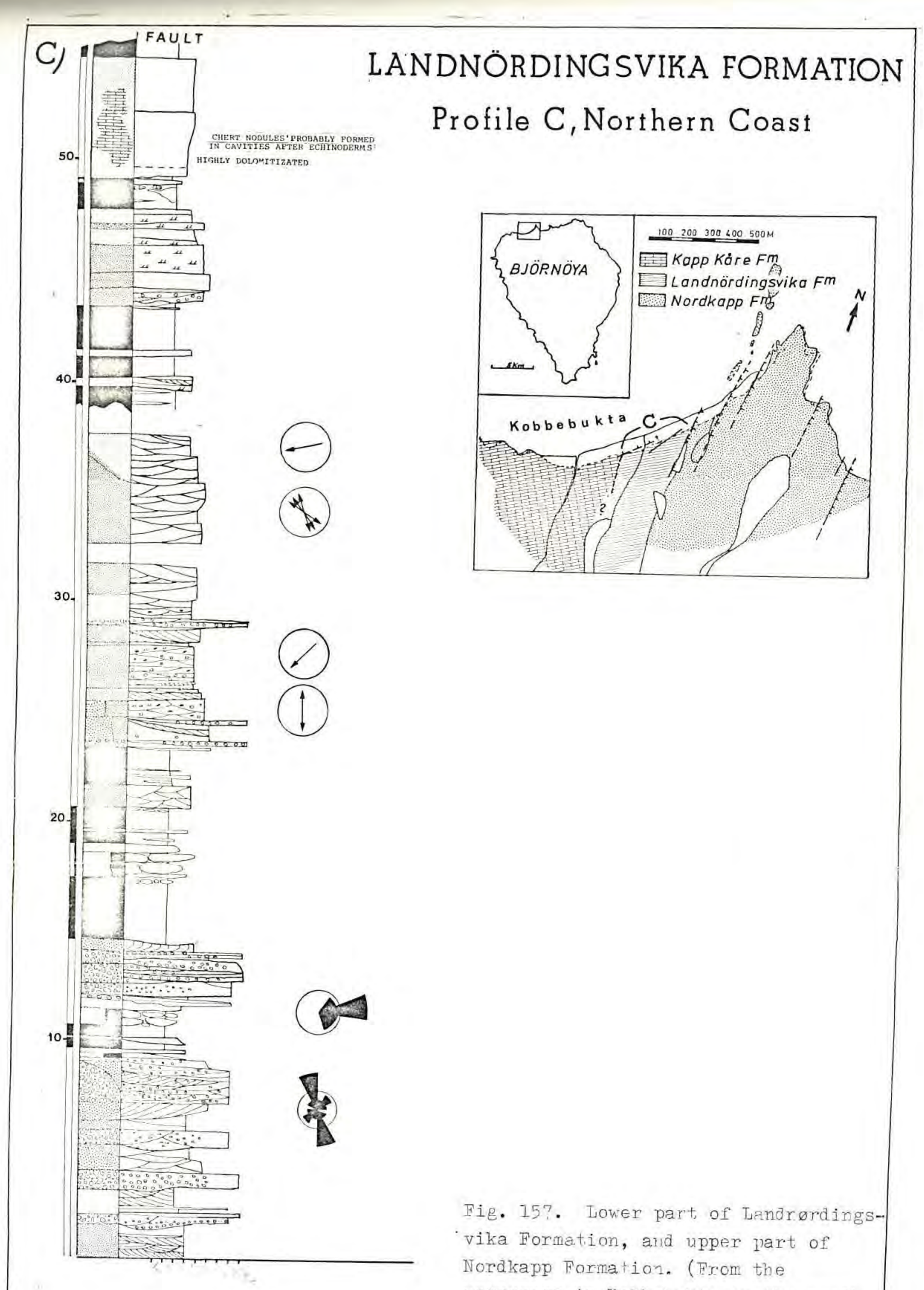


Fig. 157. Lower part of Landrørdingsvika Formation, and upper part of Nordkapp Formation. (From the exposures in Kobbebukta on the north coast.)

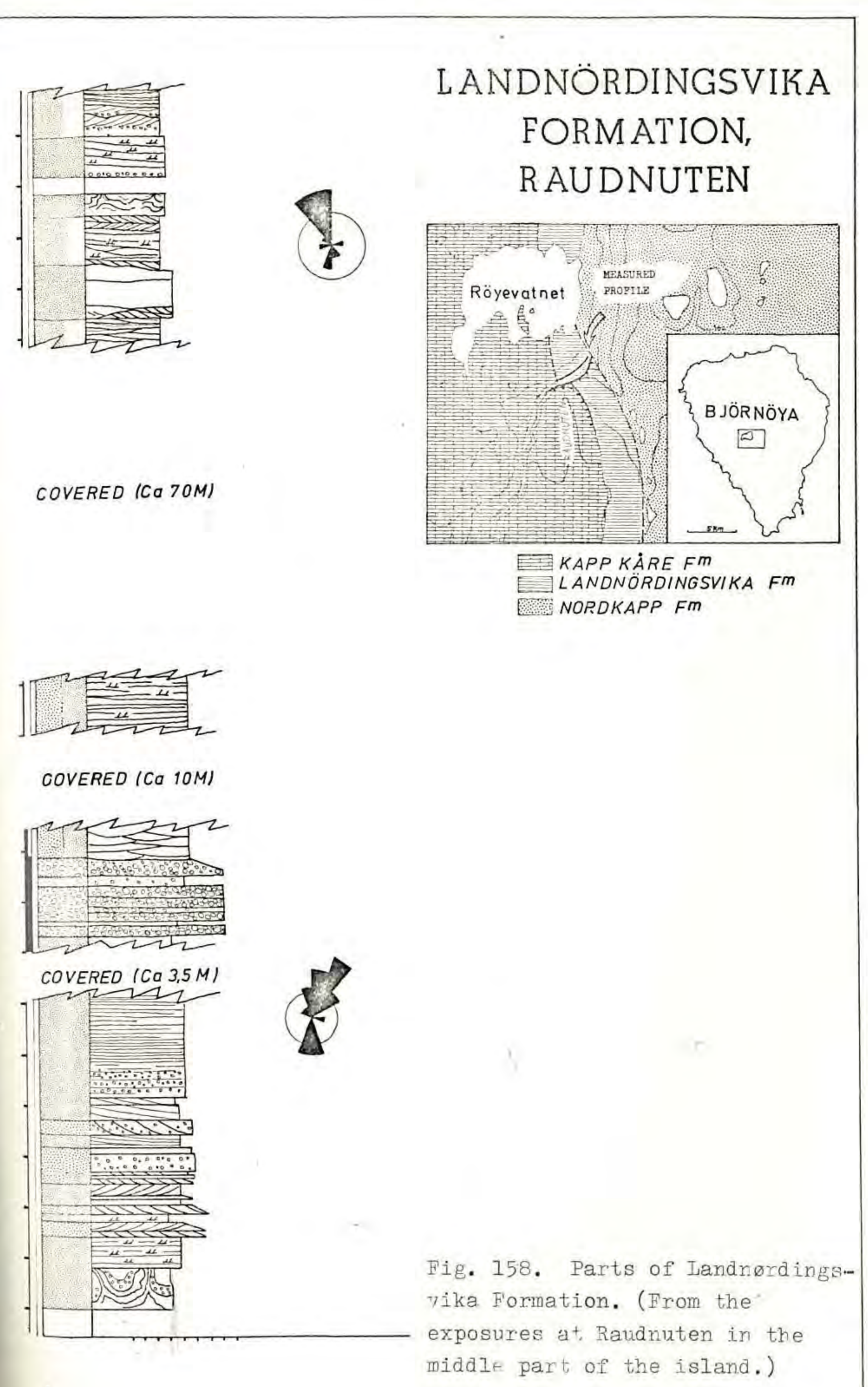
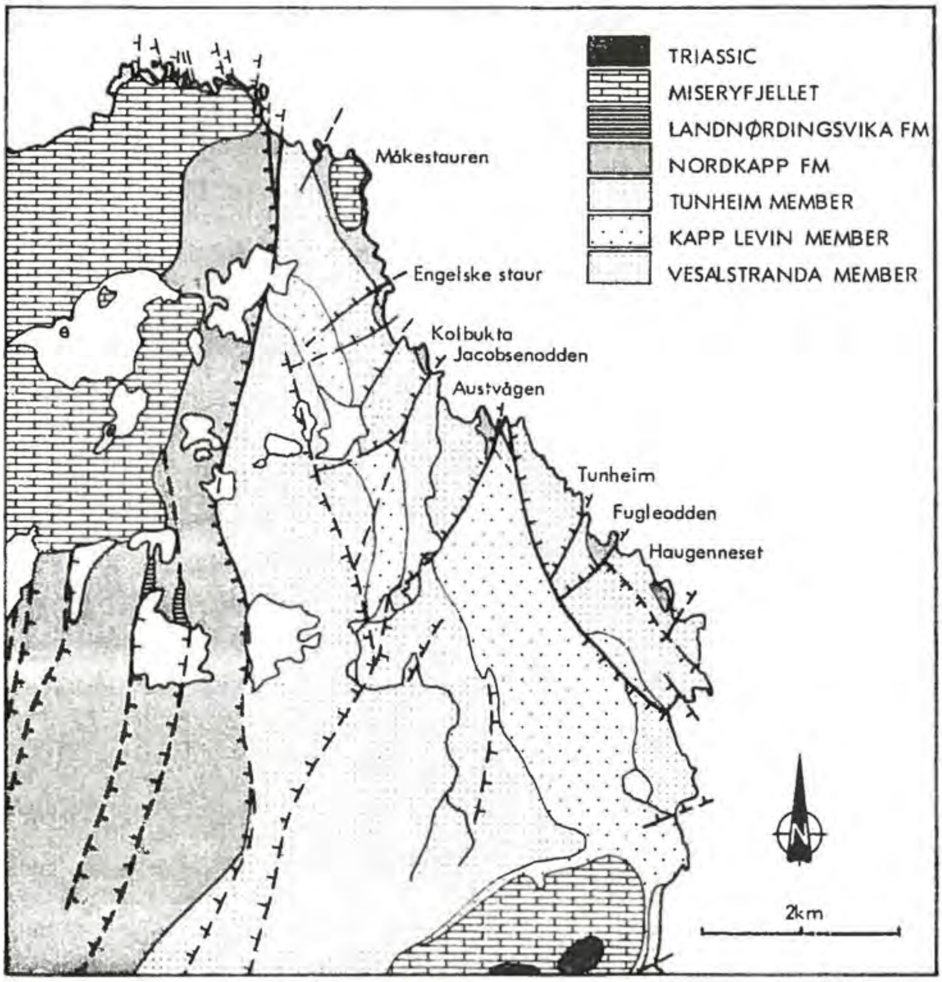


Fig. 158. Parts of Landnørdingsvika Formation. (From the exposures at Raudnuten in the middle part of the island.)

THE TUNHEIM MEMBER (LOWER CARBONIFEROUS) BJØRNØYA - A FIELD GUIDE

GEOLOGICAL MAP OF NORTHEASTERN BJØRNØYA



Based on Horn and Orvin (1928)

JOHN GJELBERG
University of Bergen

SOME ASPECTS OF FLUVIAL SEDIMENTOLOGY IN THE TUNHEIM MEMBER RØEDVIKA FORMATION (LOWER CARBONIFEROUS) BJØRNØYA, SVALBARD

By
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ABSTRACT

The Tunheim Member (Tournaisian, Røedvika Formation), Bjørnøya, was deposited in the axial part of a graben or half-graben (Gjelberg, 1981). The member is entirely of fluvial origin and may roughly be divided into two lithological units (Fig. 1). The lower unit (> 30 m thick) consist of a complex stratified sandstone succession with occasional lenses of mudstone preserved beneath curved erosional surfaces. The unit is composed of 3-4 sandstone sequences, each sequence usually eroding into the underlying one. Individual sequences show typical characteristics of high sinuosity channel deposits, with lateral accretion surfaces well preserved. The multistorey nature of this unit reflects a high degree of sandbody connectedness.

The upper unit (> 30 m thick) consist mainly of mudstone and siltstone interbedded with sandstone and coal (Fig. 1). Two of the sandstone sequences are rather prominent (up to 10 m thick) and show all the characteristics common for high sinuosity stream channel deposits. Lateral accretion surfaces (epsilon cross stratification) are well developed and stream parameters such as bankfull width, meander wavelength and mean annual discharge have been calculated. Similar calculations applied to the individual sequences within the lower unit show that the streams depositing the sand in the lower unit were slightly larger than those for the upper unit.

The interconnectedness and aerial density of the channel belt deposits decrase dramatically from lower to upper unit, probably a result of one ore more of the following factors (see also Allen, 1978 and Bridge & Leeder, 1979): Increased rate of subsidence during deposition of the upper unit, increased floodplain with/channel belt size, increased mean avulsion period, increased vertical accretion and suspended load/bed-load ratio or more frequent overbank flooding (climatic change). The visible splitting of the upper unit northwards suggests an increased rate of subsidence in this direction, thus indicating the importance of the first of the above factors.

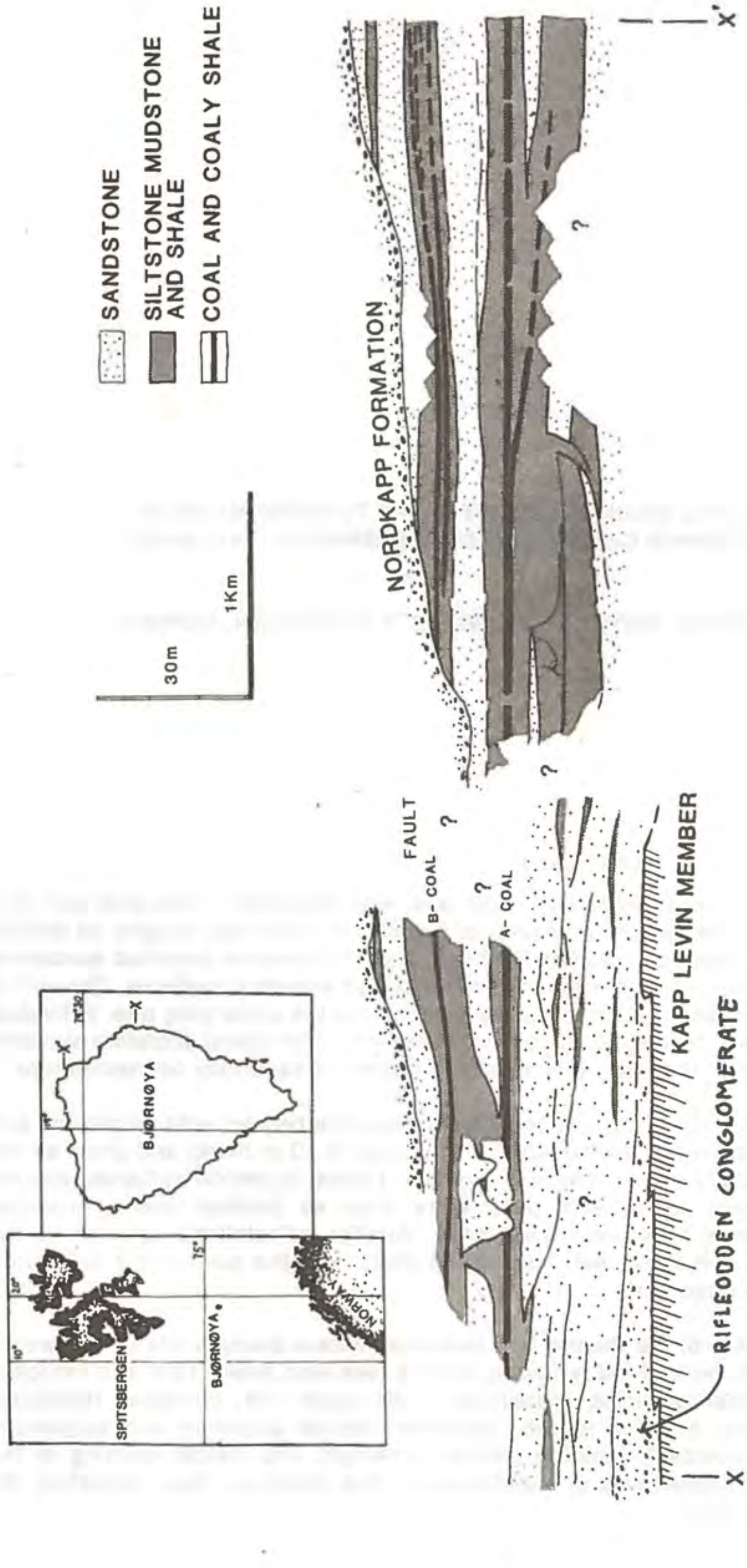

Fig. 1. Development of the Tunheim Member (Tournaisian), Bjørnøya. (See Fig. 12 for more details)

INTRODUCTION

The Tunheim Member (Tournaisian) which is the uppermost member of the Røedvika Formation, Bjørnøya, has for a long time been known to be of fluvial origin (Worsley and Edwards, 1976; Gjelberg, 1981; Gjelberg and Steel, 1981). The sediments have largely been interpretated as meandering stream depostits (Gjelberg, 1981) where the complex sandstone sequence below the A-coal represents a multistorey cluster of channel sandstone bodies deposited mainly as point-bars in meandering streams of relative low sinnosity. The sandstone sequence between the A and B coal (Fig. 1) has been interpreted as a high-sinnosity meandering stream deposits, where the fine-grained, coal-bearing sediments reflect the floodbasin sedimentation (Gjelberg, 1981). The drainage direction of the rivers were towards north-northwest, more or less parallel to the present coastline.

Recently new data from the Tunheim Member have been collected, giving some new information about the development of this member. The new investigations have been carried out mainly in the area between Austvågen and Kapp Olsen (Fig. 4), but some new data have also been obtained from the area between Austvågen and Haugenneset (Fig. 4). A simple sketch from the coastal exposures in the area between Framneset and Kapp Olsen has been made (with the exception of some inaccessible exposures), in order to get information about the geometry of lithological units and lateral facies changes.

During most of early Carboniferous time, a graben or half graben with an active fault margin just west of Bjørnøya existed. From this western margin fluvial-dominated alluvial fans migrated into the basin towards the east, while extensive floodplains occupied the axial tract of the basin. Tectonic activity and climate determined which of the two environments dominated the now exposed parts of the basin during any period of time. The underlying Kapp Levin Member and the overlying Nordkapp Formation represent the alluvial fan systems, while Tunheim Member generally represents the axial system. Traditionally all the exposures on the north-east coast have been assigned to the Tunheim Member (Horn and Orvin, 1928; Worsley and Edwards, 1976; Gjelberg, 1981). However, data from the most recent investigations suggest that the thick, coarse sandstone unit overlying the B- and C-coal should represent the Nordkapp Formation. This is indicated both by paleocurrent data and by depositional environment. Paleocurrent data indicate an easterly transport direction, as for the Nordkapp Formation, and the sediments reflect deposition by sandy braided stream systems (often poorly channelized). The base of this unit, which here is regarded as the lowermost part of Nordkapp Formation is sharp (Fig. 1), and a basal conglomerate is locally developed. It is suggested here that this boundary represents a small unconformity as it seems likely that it truncates Lower Carboniferous faults in the area. The probability that the boundary between the Røedvika and the Nordkapp Formation could be an unconformity has already been raised by Horn and Orvin in 1928.

A recently revised geological map from the north-eastern part of Bjørnøya is shown in Fig. 6. The vertical and lateral development of Tunheim Member is shown in Fig. 1. The lower half of the member consists of a complexly stratified sandstone unit (>m thick). The upper half consists mainly of mudstone and shale interbedded with sandstone and coal. Two of the sandstone sequences in this upper part are rather prominent (up to 10m thick). Two prominent coal seams occupy this upper unit: The A-coal and the B-coal (Horn and Orvin, 1928). The most recent investigations also unveil that the traditional correlation of the coal seams from the Tunheim area to Kolbukta (see Horn and Orvin, 1928; Gjelberg, 1981) is wrong. The uppermost coal seam in Kolbukta which traditionally has been regarded as the A-coal is in fact the B-coal (Fig. 1).

The Rifleodden conglomerate is not included in the discussion because it most likely represents the alluvial fan system rather than the axial system (Gjelberg 1981).

LOWER UNIT - (Multistorey channel sandstone).

The more than 30 metres thich sandstone succession located just below the A-coal in the area around Tunheim is composed of 3-5 sandstone sequences, each sequence eroding into the other, separated by an undulating erosion surface. In areas where mudstone lenses are preserved beneath the undulating erosion surfaces, the underlying sandstone sequence usually grades upwards into the mudstone. This together with the fact that each sequence has a sharp erosional base suggests a fining upwards character for individual sequences. However, the grain size in the sandstones varies generally little, and well-defined fining upwards sequences are scare (Fig. 2). The sandstone which is usually of medium grain size, is highly silicified, and primary sedimentary structures are not easily seen in vertical exposures. However, trough cross-stratification of varying scale dominate, and on bedding plane surfaces reliable paleocurrent data were recorded.

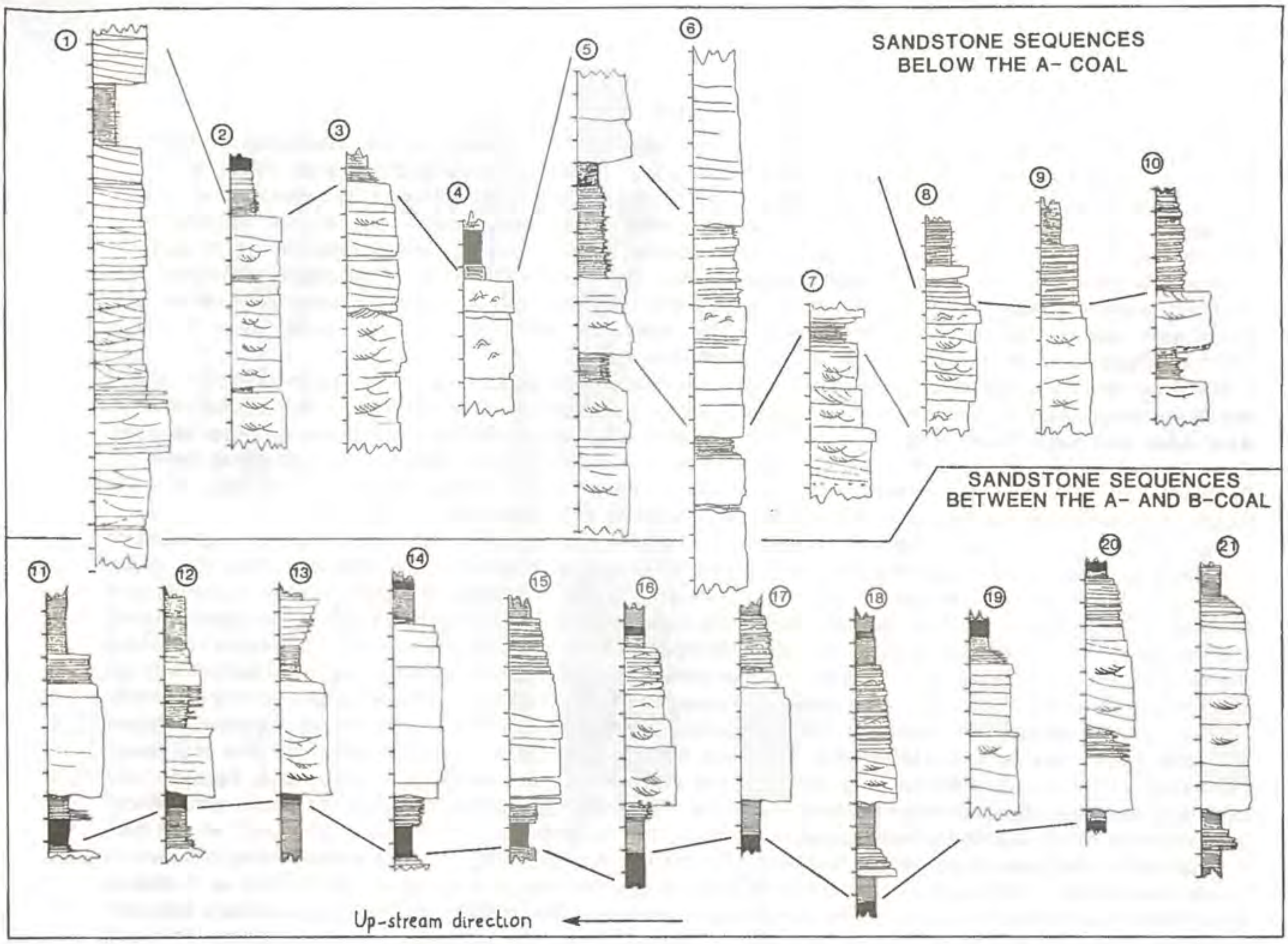

Fig. 2. Sandstone sequences from the Tunheim Member. The upper half of the figure represents sequences below the A-coal, while the lower part shows sequences occuring between the coal seams.

Gigantic cross stratification, often dissecting individual sequences from bottom to top (Fig. 3), are common. The dip of such cross-stratification varies from 5 to 10°. Superimposed smaller scale structures (troughs) indicate a paleocurrent direction approximately at right angles to the prograding direction of the gigantic foresets. The lateral extension of such cross-strata may exceed some hundreds of metres. The characteristics of each individual gigantic cross-stratified sandstone body strongly suggest that they represent point bar deposits of high-sinuosity streams, where the large, low angle foresets reflect the lateral accretion surfaces (Fig. 4) of point-bars. Well defined fining upwards sequences are rare, however, each individual sequence starts with an distinct undulating erosion surface, the relief of which often resembles that predicted theoretically by Bridge (1975). The character of basal scour surfaces indicates that scouring and filling continued with bar migration. Gigantic cross-stratification or epsilon cross-stratification is common in the sandstones of Tunheim Member, but as a result of low-angle and irregular development they may be difficult to recognize. The irregularity which often appears like «reactivation surfaces» may occur as a result of erosion parts of the point-bar during long periods of extreme discharge. Abrupt change in the lateral accretion direction for the point-bar may have somehwat similar effect, as this may result in parts of the point-bar for a long time being non-accretionary and even eroded, later on, this same part again may start to grow.

The primary geometry of individual sequences within this lower unit is not easily deduced, partly because they often are strongly eroded by the overlying sequence, and partly because lateral exposure is not sufficient. The thickness of the units varies considerably, and variation from 2.5 to 10 m over a distance of 150 m has bees recorded. Sequences also wedge-out rapidly into shale and mudstone. This explains the great thickness variation of the mudstone sequence located below the A-coal seam. Aspects of such wedging sandstone sequences are discussed in more detail below.

Usually individual sequences are easy to distinguish where the lateral exposures are good, as the extensive erosion surfaces separating each sequence are easy to distinguish from other beddingplanes. However, where the lateral control is poor, such erosion surfaces may be difficult to observe, and the multistorey character of the sandstone unit may be overloocked.

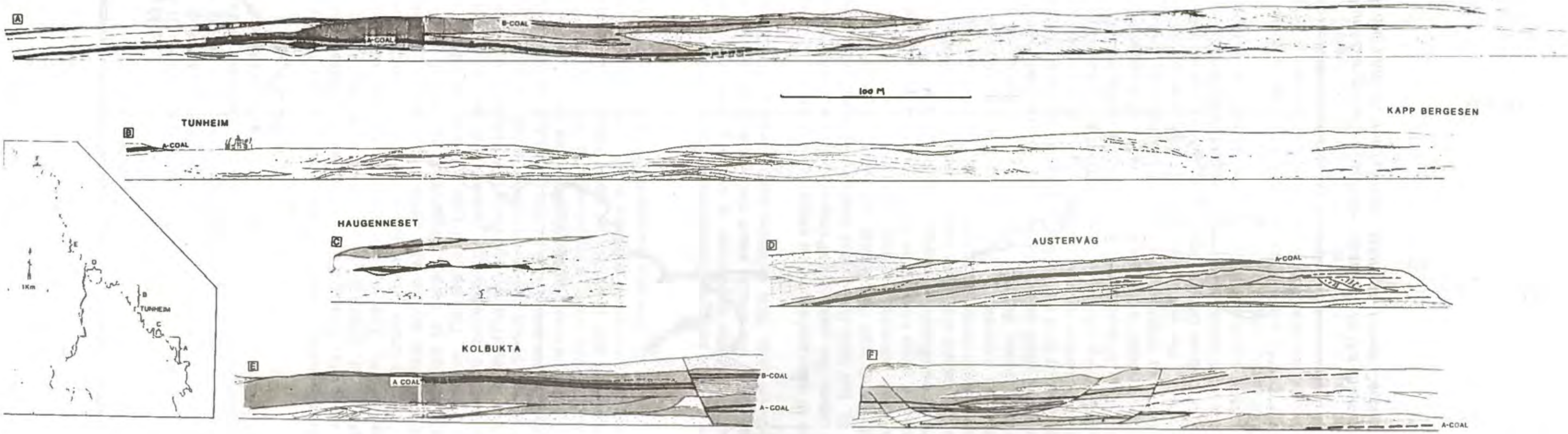

Fig. 3. Some coastal exposures of the Tunheim Member along the northeastern coast of Bjørnøya.

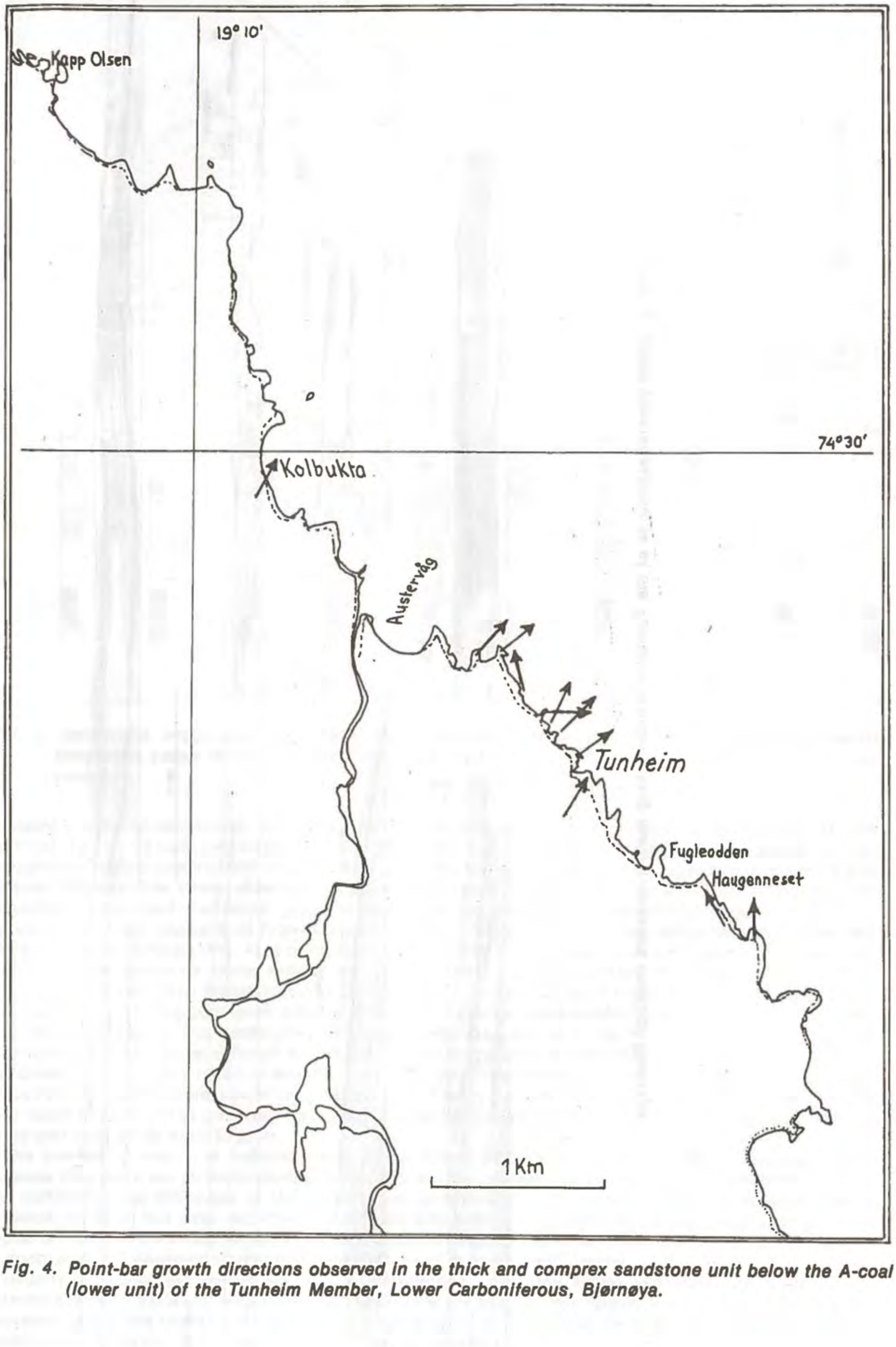

Fig. 4. Point-bar growth directions observed in the thick and comprex sandstone unit below the A-coal (lower unit) of the Tunheim Member, Lower Carboniferous, Bjørnøya.

UPPER UNIT - (Mudstone - shale - sandstone and coal association).

Above the complex stratified sandstone unit in the lower part of Tunheim Member (Lower Unit) occurs a succession of mudstone and shale, interbedded with sandstone, coal and coaly shale (Fig. 1). The thickness and lateral distribution of the different lithological components of this unit is highly variable. Two relatively thick and laterally extensive sandstone sequences occur. The most prominent of this occurs between the A- and the B-coal (Fig. 2). The other one is locally preserved beneath the erosion surface of the overlying Nordkapp Formation (Fig. 1).

Prominent sandstone sequences. Both of the prominent sandstone sequences within this upper unit reflect deposition in stream channels of high sinuosity. Figure 2 (lower half) shows some sections from the sandstone sequence between the A- and B-coal. Sharp erosive base and slightly fining upwards (especially in the uppermost part) is characteristic. The thickness of these prominent sandstone sequences is usually between 5 and 10 m. Trough cross stratification is the dominant sedimentary structure observed, and has been recorded in the lower and middle parts of the sandstone sequences. Primary sedimentary structures are, however, difficult to detect. Gigantic cross-stratification with an angle of dip ranging between 5° and 12° are common. This epsilon type of cross stratification (Allen, 1963), which also here represents lateral accretion surfaces (or palaeopoint bar surfaces) usually intersects the sandstone sequences from bottom to top (Fig. 6), but there is a tendency to flattening out towards the top of sequences. The dip direction (and hence the growth direction of the point-bars) for all the epsilon cross-strata observed within the sandstone sequences of the upper unit varies from east to west, through north. Each of these two prominent sandstone bodies appears to be laterally persistent and uniform, and usually occur at the same stratiggraphic level, with respect to the coal seams, over a distance of at least 6 km. Lateral accretion surfaces and paleocurrent data, however, show that these sandstones represent a meander belt elongated approximately towards north or northwest, and that is composed of a complex system of point-bars (Fig. 5), laterally connected, but locally intersected by abandoned channel fills.

The fine grained association — Figure 6 shows some selected fine-grained sequences associated both with the A- and B-coal. The variable thickness of these sequences is striking. The thickness of the fine-grained succession occuring immediately below the A-coal seam decreases from 23 metres in the Austvågen area to less than a metre in the Tunheim area. This variation occurs over a distance less than 2.5 km (probably not more than 1 km).

The fine-grained association consists mainly of grey and rusty red shale, mudstone and siltstone interbedded with thin sandstone strata. In some cases the associated fine-grained lithologies occur in an apparently random vertical arrangement (Fig. 6), but both fining and coarsening upwards sequences are present. Horizons of clay ironstone (siderite) and well developed underclay were recorded. Pyrite concretions are common just below the A-coal seam, commonly developed in sandstones. Root horizons occur locally below coal seams and may contain a large number of small root imprints, only a few mm thick, or large silicified imprints (30-40 cm thick) penetrating the sediments vertically.

The sandstone beds are, in most cases, sharply based and often have a sheetlike geometry. They may occur isolated or stacked. Thickness varies from centimetres to decimetres, but rarely more than a metre. The fine-grained association represents sediments deposited in: flood basin areas (included shallow lakes), abandoned channels, crevasse splays and levees. Sharply based sandstone beds interbedded in mud and siltstone probably represent the product of more severe flooding with active bed-form migration (Leeder, 1974). In a few locations it is possible to study how some thin sandstone beds are attached to the underlying meandering channel deposits (Fig. 7). Coarsening upwards sequences within the fine grained association may represent: crevasse splays, prograding infilling of lakes (abandoned channel infilling) or progradation of levees. Coarsening upwards infilling of abandoned channels is not common in Tunheim Member, and only two such observations in Austvågen were made. This type of coarsening upward sequence probably occurs where secondary flows are directed into abandoned channels, causing a progradational infilling. In most situations, however, the abandoned channel sediments become finer upwards especially in its lower parts, reflecting a gradual decrease in the supply of coarse material. The sediments in the uppermost part of such abandoned channels often differ very little from the surrounding fine-grained floodbasin sediments, and where lateral exposures are insufficient to see the geometry of the channel, such sediments can be very difficult to recognise.

In the thick sequences of fine-grained sediment in Austvågen and Kolbokta, abandoned channel sequences are common. Some of these abandoned channels seem to be laterally equivalent to some of the sandstone sequences in the lower unit, occuring just below the A-coal seam, implying that the areas were located beside an active meander belt. This explains the great lateral thickness variation of the fine-grained sequence below the A-coal.

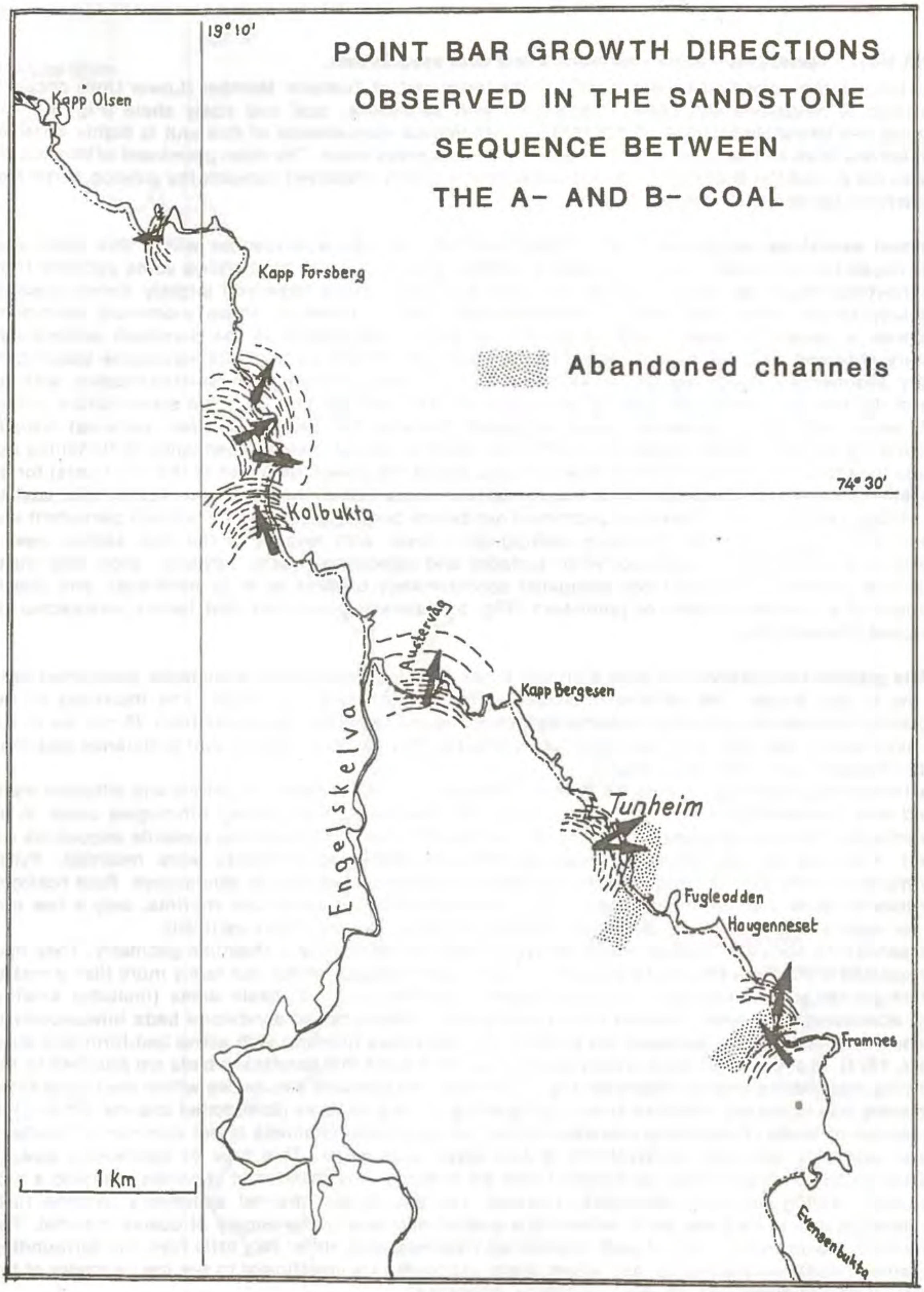

Fig. 5. Point-bars growth directions observed in the sandstone succession between the A- and B-coal.

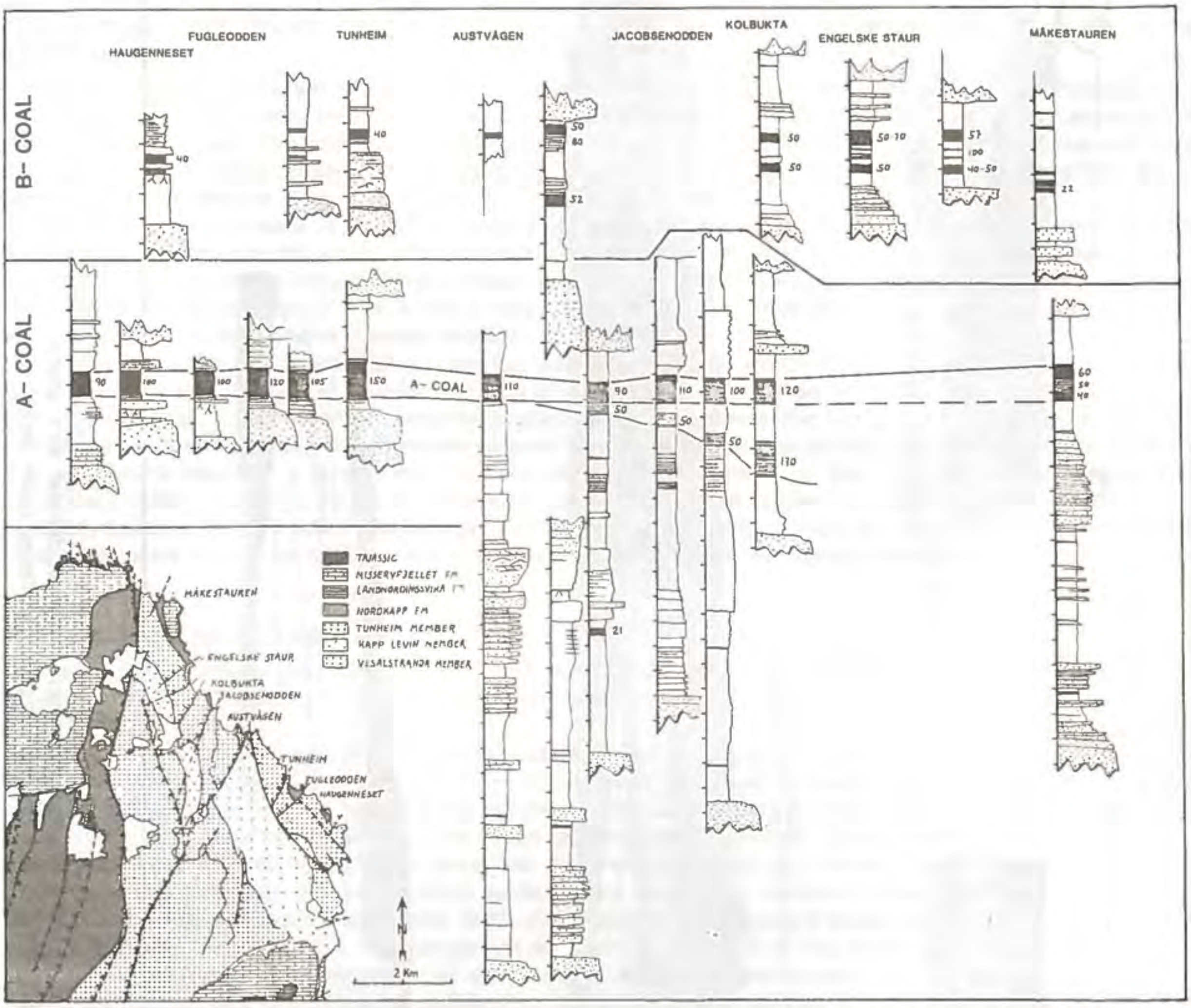

Fig. 6. Some fine grained sequences associated both with the A- and B-coals. A revised geological map from the northeastern part of Bjørnøya is included.

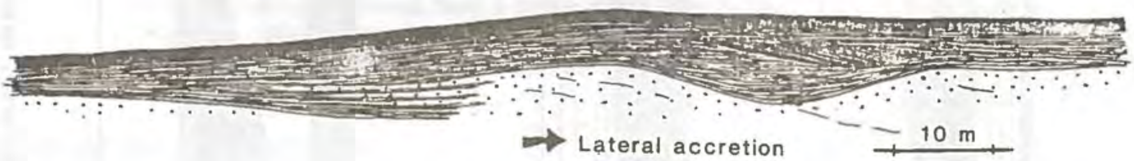

Fig. 7. Field sketch showing the A-coal (black line) and the immediately underlying sediments. The sandstone represents the uppermost part of a meandering channel sandstone body. The undulating paleosurface probably reflects scroll-bar topography. Note how the sandstone strata interfinger with the flood basin mudstone from one of the sand ridges, indicating several episodes of overbank flooding.

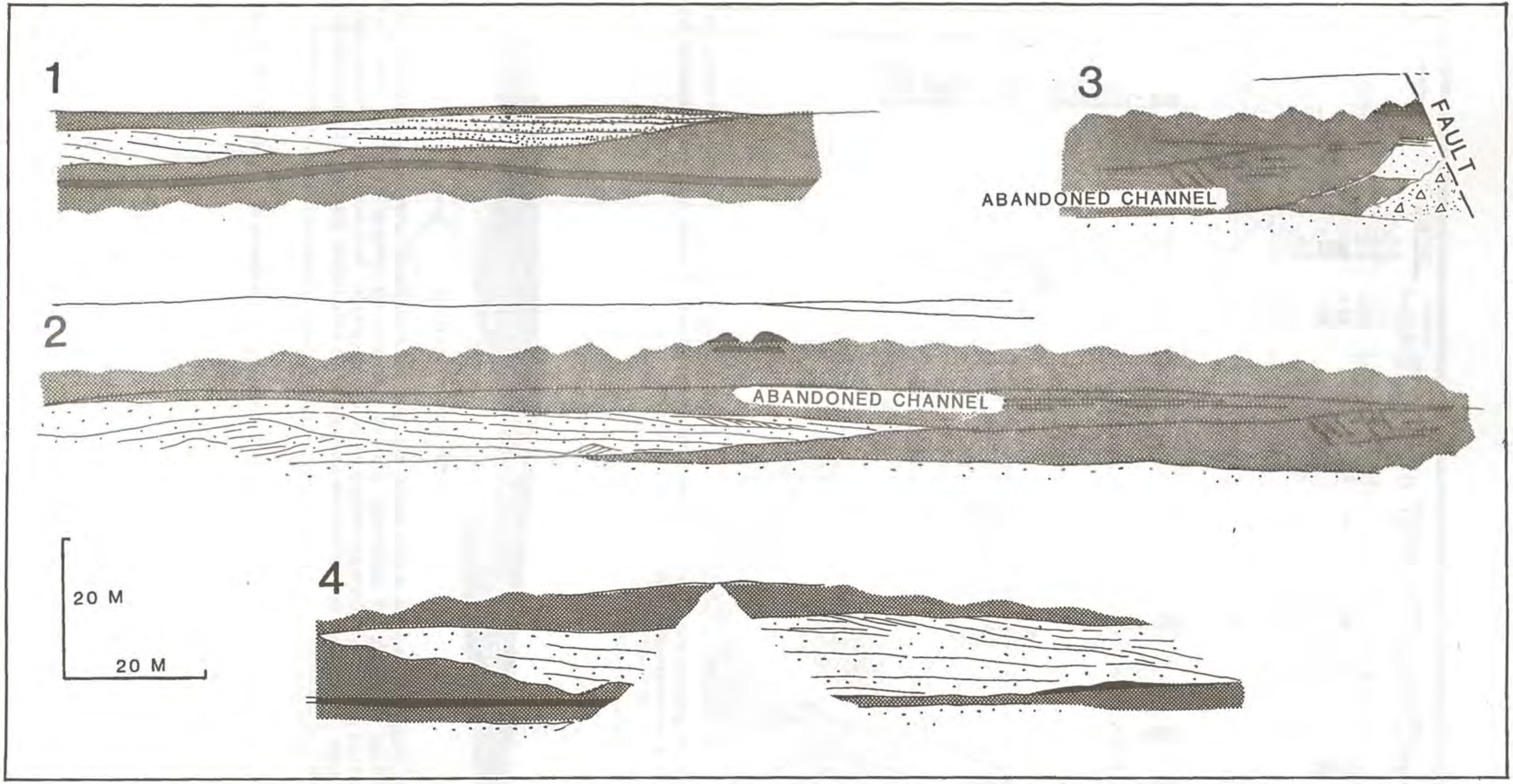

Fig. 8. Four different cases where channel sandstone bodies terminate into mudstone and shale sequences. See text for explanation. Note how marked point-bar paleo-surfaces often terminate into deep channel sours.

TERMINATION GEOMETRI OF THICK SANDSTONE SEQUENCES INTO THE FINE-GRAINED ASSOCIATION.

Figure 8 shows four different situations where thick sandstone sequences terminate into the fine-grained association of the Tunheim Member. Situations 1 and 2 represent abandonment and hence a cessation of lateral accretion, and the subsequent infilling of the abandoned channel. In situation 1 the infilling material is much more sandy than in situation 2, resulting in a more gradual lateral transition from sandstone to mudstone than in situation 2.

The situation illustrated in the third example represents an older channel sandstone body eroded against a concave channel bank. Abandonment of the channel resulted in the observed lateral facies change. The cut surface is surprisingly steep, suggesting that the eroded bank consisted of unconsolidated sand. An explanation of this is that a «cap» of vegetated mudstone and very fine sandstone probably the edge of the concave bank against erosion.

The fourth example represents a channel sandstone body which thins out and disappears into floodbasin sediments without termination into an abandoned channel as in cases 1 and 2. The sandstone starts with a shallow scour, which became gradually deeper at the same time as it migrated laterally. The maximum depth (12 metres) was achieved already after a lateral migration of 60 metres. The deposition of this sandstone began in a minor, shallow channel which pre-existed in the floodbasin area, probably a secondary reach. During a relatively short period of time, it increased its discharge dramatically and probably became the main river channel (abandonment). The «wedging out» of the sandstone in example 4 thus represents the initiation of a new river channel, rather than the lateral termination.

POINT BAR GROWTH DIRECTIONS.

864 paleocurrent measurements, mainly based on trough axes, show an average paleocurrent direction towards northwest, which means that the elogation of the meander belt was approximately parallell to the present coastline (Fig. 9).

A total of 20 measurements from epsilon cross-stratification or (in this case) lateral accretion directions have been obtained along the coastline from Framnes in the south to Kapp Olsen in the north. A great majority of those are directed towards the northeast. This is somewhat surprising as one should expect a more symetrical distribution around the mean paleocurrent resultant vector (noth-west). More of the lateral accretion should therefore be expected to have a westerly component. As indicated on fig. 9 a majority of the point-bar lateral accretion surfaces are orientated normal to the coastline, in seawards. Many of the small peninsulas along the north-east coast of Bjørnøya are made up of such gigantic cross-stratified sandstones (Fig. 10). The persistent direction (seawards) of the cross-strata is probably due to preferential preservation (dissipation of storm wave, erosive power would tend to be maximum where waves break upslope), tather than an original unidirectional arrangement of point-bar accretion surfaces. Point-bar lateral accretion surfaces orientated toward a westerly direction would, in most situations, not be preserved as peninsulas, and gigantic low angle cross-strata of this type are very difficult to detect in vertical exposures, where dip direction is orientated normal or approximately normal to the exposure.

Since a majority of the paleocurrent data shown in Figure 9 have been measured on the small peninsulas, the mean paleocurrent resultant vector will not be representative for the mean flow direction of the rivers which deposited the elongated sandstone bodies of the Tunheim Member, and it is suggested here that the average flow direction probably was more northerly than that indicated of Figure 9B.

Most of the lateral accretion surfaces have a downstream component. This corresponds well with the observations of Nanson (1980) on the Beatton River, suggesting that an oblique downstream growth of point-bars is the most common pattern in meandering rivers.

THE SIZE OF THE RIVER SYSTEM.

Numerical values for the size of the rivers depositing the sandstone bodies of the Tunheim Member are easy to obtain, due to the good exposures. An estimate of bankfull depth of the paleochannels may be made using the thickness of the coarse member (Leeder, 1973).

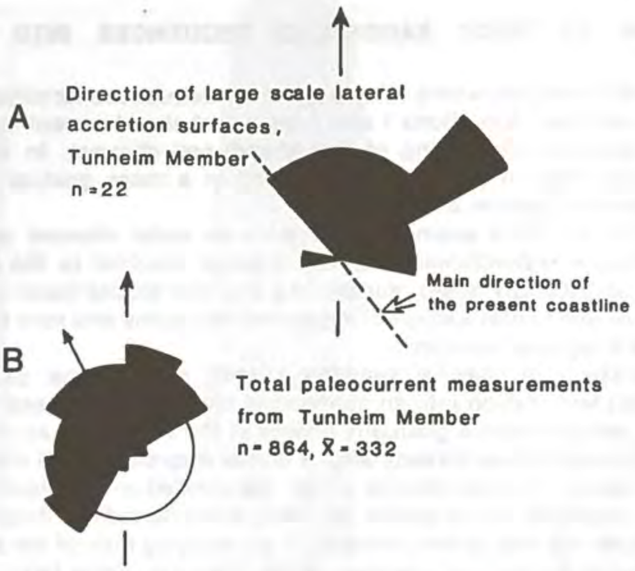

Fig. 9. A: Dip directions of all large scale lateral accretion surfaces observed in the Tunheim Member. B: Total paleocurrent distribution in the Tunheim Member. All paleocurrent directions measured in the member are plotted in the diagram (plotted at 30° intervals). n = total number of measurements $\bar{x}$ = the azimuth of the resultant vector.

TABLE I Sandstone between the A- and B-coal

h	β	w	Average
9	6°	128	$\bar{h}$ > 7.2 m
8	8	85	$\bar{w}$ = 86 "
4	10	34	$\bar{\lambda}$ = 3253'
10	6	142	$\bar{r}$ = 790'
5	12	35	$\bar{q}$ = 1682 cfs
5	5	85	$\bar{Q}$mm = 3104 cfs
6	5	102	
6	8	64	
6	5	1o2	

h = Bankfull depth, $\bar{h}$ = average bankfull depth, w = bankfull width ($w \approx \frac{3h}{2 \tan \beta}$), $\bar{w}$ = average bankfull witdth

β = Angle of accretion surfaces

$\bar{\lambda}$ = Average meander wavelength. The calculations is based on the formula

$$\lambda \approx 10.9\ w^{1.01}$$ (Leopold and Wolman, 1960)

$\bar{r}$ = Average radius of curvature of the meander. $r = (\lambda/4.7)^{1.02}$ after Leopold and Wolman (1960).

$\bar{q}$ = Mean annual discharge. Based on the equation $\lambda = 106.1\ \bar{Q}^{0.46}$ (Carlston, 1965).

$\bar{Q}$mm = Mean of month of maximum discharge. Based on the equation

$$\lambda = 80.0\ \bar{Q}.mm^{0.46},$$ (Carlston, 1965)

TABLE II Sandstone below the A-coal

h	B	W(w)	Average
10	10°	85	
5	9°	47	$\bar{h}$ = 8 m
6	10°	51	w = 105 m
9	5°	154	
6	10°	51	$\bar{\lambda}$ = 3980'
7.5	5°	128	$\bar{r}$ = 970'
7	5°	120	
12.5	5°	214	$\bar{q}$ = 2611 cfs
6	8°	64	
11	7°	134	$\bar{Q}$ = 4809 cfs

An approximate value for the paleochannel-width can be calculated from the formula (Leeder, 1937):

$$w \approx \frac{3\ h}{2\ \tan\ \beta}$$

where h represents the thickness of the coarse member, and β = the angle of lateral accretion surfaces. Values for the bankfull depth and width, together with calculations of average meander wavelength, average radius of curvature of the meander, mean annual discharge and mean of month of maximum discharge are given in Tables I and II. Table I represents the sandstone sequence occuring between the A- and B-coal, while Table II represents the sandstone sequences in the lower unit, below the A-coal. The data show that the paleochannels below the A-coal were slightly larger than those between the A- and B-coals. A modern river which corresponds fairly well in scale with the paleorivers of the Tunheim Members is the Murrumbidgee River in Australia (Schumm, 1968).

CONCLUSION

The lower unit of the Tunheim Member differs much from the upper coal-bearing unit even though both units were deposited by meandering streams. The interconnectedness and aerial density of the channel-belt deposits decreases dramatically from lower til upper unit. A clear explanation for this has not yet been found, but it most likely occurred as a result of one or more of the following factors (see also Allen, 1978 and Bridge & Leeder, 1979):

1. Increased rate of subsidence during deposition of the upper unit.
2. Increased floodplain width/channel belt size ratio.
3. Increased mean avulsion period.
4. Increased suspended load/bedload ratio (climatic change of drainage area).
5. Increased frequentcy of overbank flooding (climatic change).

The visible splitting and thickening of the upper unit northwards suggests an increased rate of subsidence in this direction. This tends to indicate that at least the first of the above factors was considerable importance.

Fig. 10.

Some examples of lateral accretion surfaces along the northeastern coast of Bjørnøya. a): From the northern part of Kolbukta. A 5 to 8 metres thick sandstone sequences (starting at about sea level on the right, and disappearing at the middle part of the picture on the left side) shows well developed lateral accretion surfaces (the cliff is ca. 30 m high). b) and c): Parts of point-bars with their lateral accretion surfaces orientated seawards. This seawards orientation of the gigantic cross-strata increases the preservation potential of the sandstones (see text).

Fig. 11.

Some typical coastal exposures of the Tunheim Member on the notheast coast. a) and b): multistorey channel sandstone of the lower unit. c): Section from the Tunheim area. The dark line in the middle part of the picture represents the B-coal. The C-coal is preserved only as lenses below the thick, epsilon cross-stratified sandstone sequence below the Nordkapp Formation. Arrow indicates the position of the A-coal. d): From Haugenneset. Arrows indicate position of the A-coal (see also Fig. 3). Note the highly scoured base of the sandstone overlying the A-coal. e): Deformation structure exposed on horizontal surface parallel to the bedding. Soft sediment deformation structures are very common in the sandstones of the Tunheim Member especially in the sandstone underlying the A-coal.

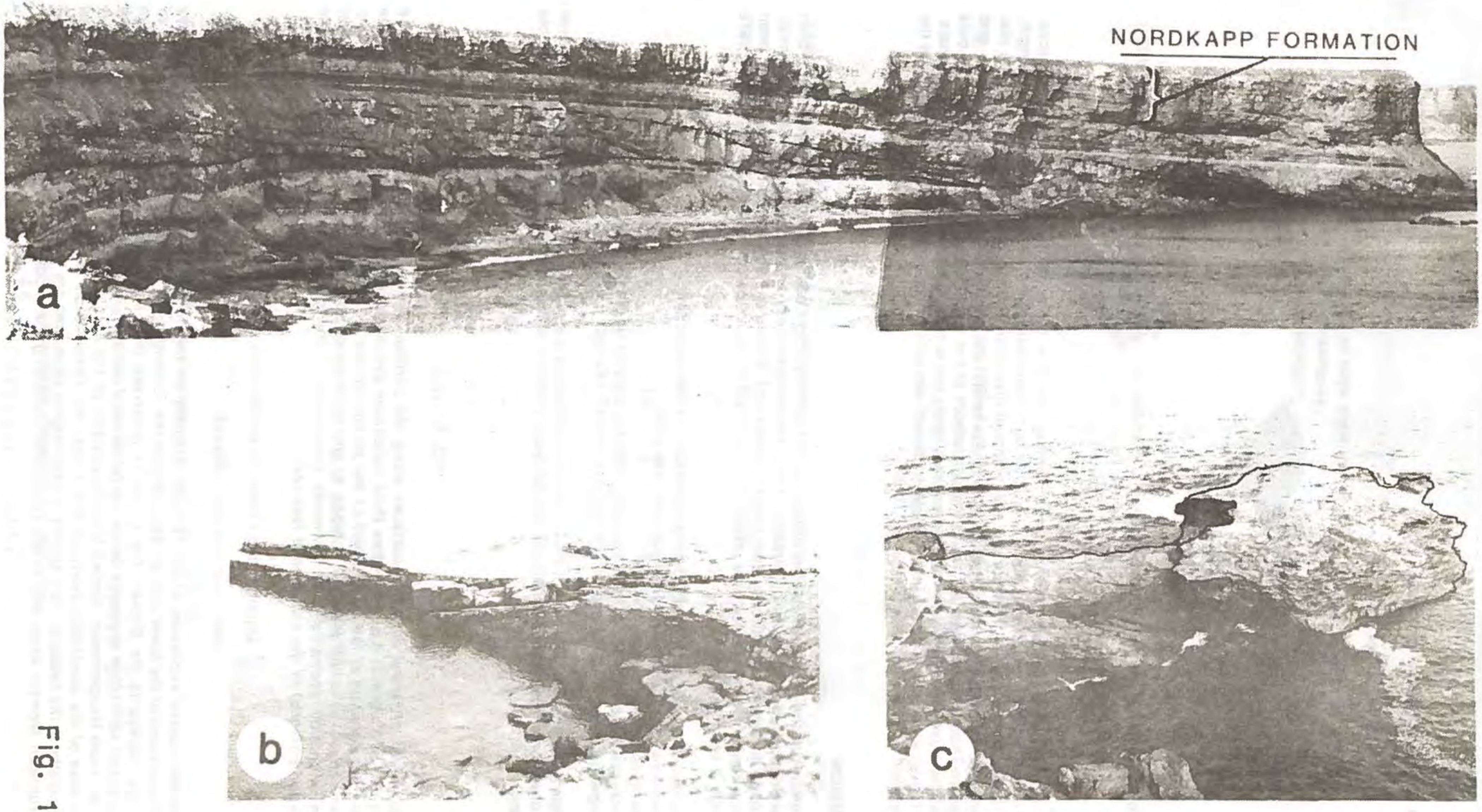

Fig. 10.

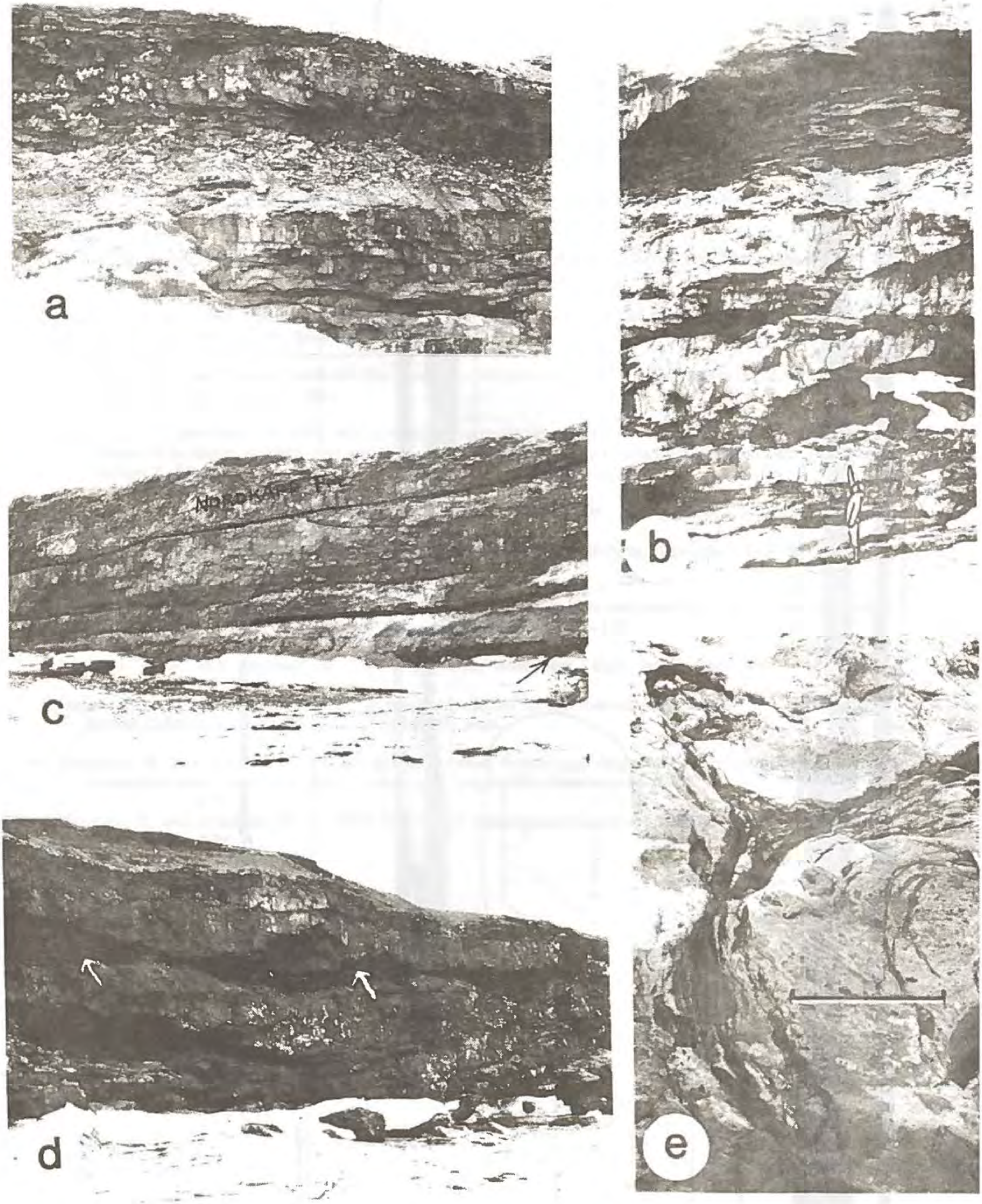

Fig. 11.

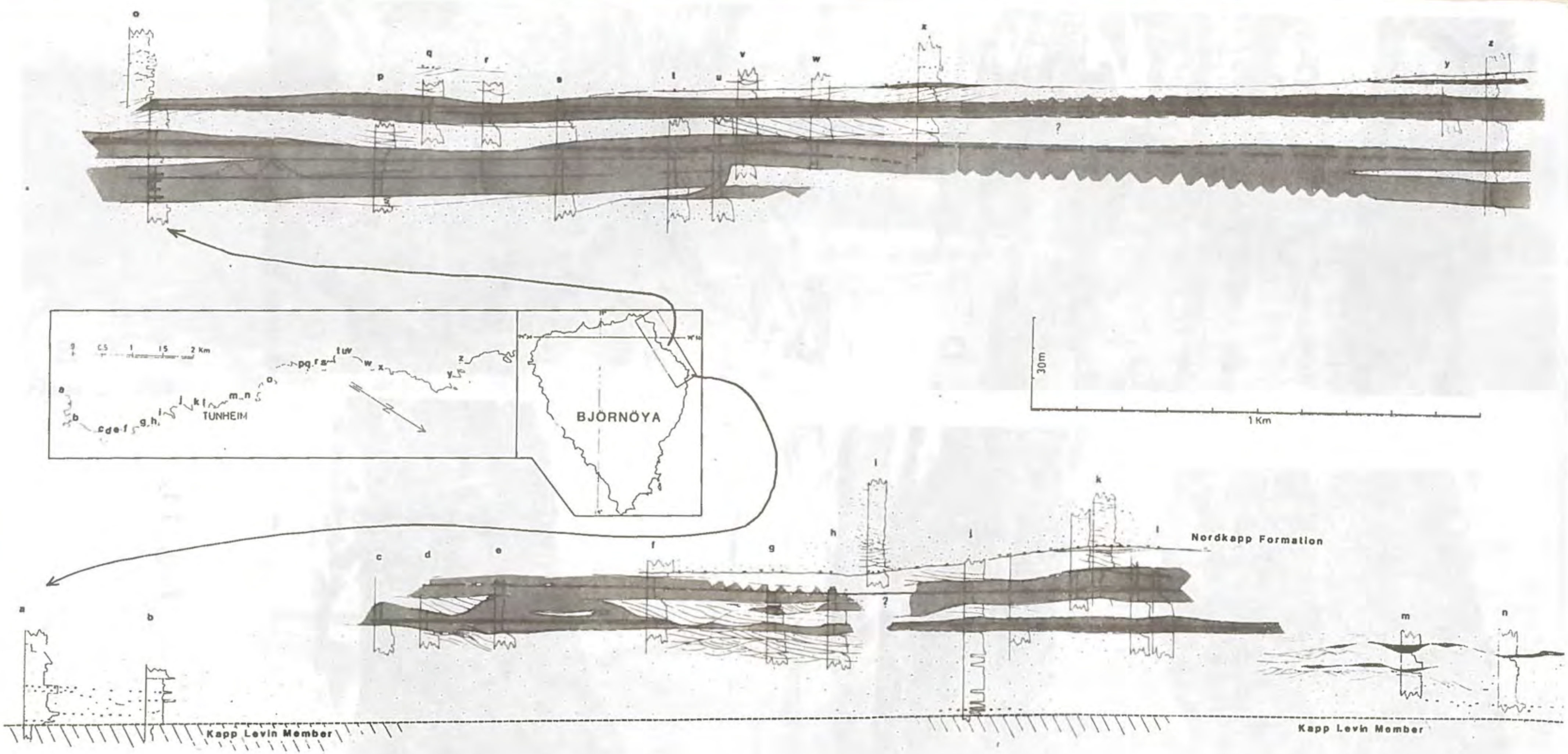

Fig. 12. Development of the Tunheim Member (Tournaisian), Bjørnøya.

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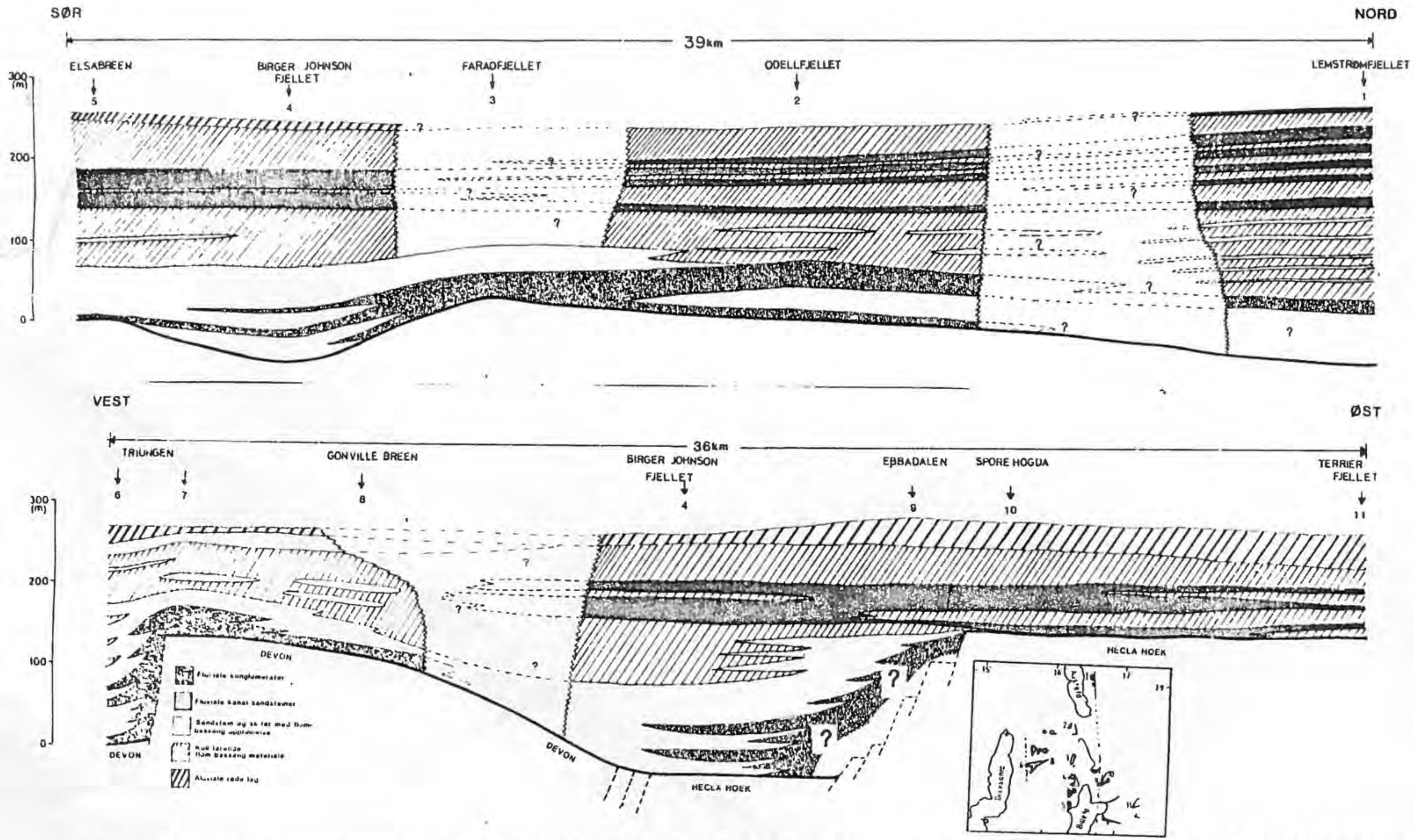

Fig. 8.1.3. Diagrammer Ø-V og N-S som viser utviklingen av Hørbybreen- og Svenbreen formasjonen. Basert på Fig. 8.1.1 og 8.1.2. (Modifisert og utvidet av Aakvik og Gjelberg, 1979).