

The geological evolution of Bjørnøya, Arctic Norway: implications for the Barents Shelf

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Extended abstract

The small island of Bjørnøya ("Bear Island"), situated in the Barents Sea almost midway between northern Norway and Spitsbergen, displays a Precambrian to Triassic succession in a continuous series of spectacular cliff exposures. These exposures provide a key not only to the evolution of the Stappen High (on which Bjørnøya rests) but also to the development of analogous structures along the major lineaments that subsequently contributed to the formation of both the Norwegian-Greenland Sea and the Arctic Ocean.

Precambrian to Ordovician dolomites, limestones, quartzites and shales form the basement on which the Upper Palaeozoic succession of Bjørnøya was deposited. In latest Devonian and early Carboniferous times the area subsided asymmetrically, probably in response to NE-SW extension; a southwestwards down-tilted half-graben developed over the present-day island, with the basinal axis dipping gently NNW. Some 600 m of sandstones, coals and shales are preserved in two upward coarsening sequences. These represent the repeated progradations of sandy fan systems over floodplains with lakes and northward meandering river channels. Mid-Carboniferous (Serpukhovian) uplift was followed by renewed rifting and the same western hinterland again shed debris over its faulted eastern margins. A shift from humid to a semi-arid climate is reflected by the predominantly red colouration of the resultant 200 m thick succession of conglomerates, sandstones and shales, with caliche horizons. Penecon-

temporaneous regional sea level rise resulted in the gradual replacement of the alluvial floodbasin deposits by shallow marine siliciclastics and carbonates of shoreline, tidal flat and shallow shelf origin. Continued transgression through the Moscovian, perhaps also with decreasing subsidence rates and only intermittent tectonism, is indicated by the gradual change to a marine carbonate-dominated succession, with cherty biomicrites reflecting the establishment of an open carbonate shelf over the entire area.

A marked rejuvenation of tectonic activity in the late Moscovian established a different depositional mosaic - faulting affected exposures on the present island along N-S to NE-SW lineaments, with differential subsidence down to the west. This produced erosion of earlier deposits over the eastern part of Bjørnøya and deposition of conglomerates, sandstones, shales and dolomites in alluvial gully, coastal and shallow shelf environments to the west. A 200 m thick succession is preserved in western areas and eroded remnants are also preserved as outliers elsewhere on the island. Conglomerate clasts indicate derivation by successive stripping and redeposition of mid-Carboniferous to uppermost Devonian and then basement strata. By the latest Carboniferous the region had again stabilized and platform carbonate deposition resumed, with the development of paleoaplysiniid carbonate build-ups. Early Permian flexuring, uplift and peneplanation followed, probably with some transpressive movements. The highly condensed mid- to Upper Permian marine succession of mixed siliciclastics and carbonates oversteps all older strata. The Stap-

pen High then remained a positive feature through to the late Triassic, the youngest beds preserved being of Carnian age. The high subsequently subsided significantly during the Mesozoic, but it again became a positive feature as a result of one or more phases of uplift during the Cenozoic.

Much of the Carboniferous succession of Bjørnøya, with non-marine rifted sequences giving way in the mid-Carboniferous to a marine carbonate shelf development, mirrors time-equivalent successions throughout the Barents Shelf, northeastern Greenland and the Sverdrup Basin. Late Carboniferous and early Permian faulting, flexuring and uplift, and the development of overlying, condensed and stratigraphically incomplete Upper Permian/Lower Triassic platform sequences are however atypical features – only found on local structural highs which together form elements of a major circum-Arctic fault complex along which Paleogene continental separation took place. A better understanding of the late Palaeozoic evolution of these highs may contribute significantly to further hydrocarbon exploration in this frontier petroleum province.

Introduction

The Barents Sea covers an extensive shelf area that extends northwards from the Arctic coasts of Norway and Russia to the margins of the Arctic Ocean (Fig. 1). It was long suspected that this area had a different geological history from the Precambrian and Caledonide Baltic Shield to the south. Ongoing hydrocarbon exploration in the last 20 years has demonstrated a complex structural development, with several major subprovinces containing varied Upper Palaeozoic to Cenozoic sedimentary successions (e.g. Rønnevik et al. 1982; Rønnevik & Jacobsen 1984; Faleide et al. 1984; Johansen et al. 1992, Nøttvedt et al. 1992, Gudlaugsson et al. 1998). Exploration wells in the Norwegian sector (over 50 to date) have rapidly increased our knowledge of the area's stratigraphy. However, critical integration of knowledge from onshore exposures with offshore well and seismic data is still crucial for a better understanding of the Barents Shelf's development.

The small island of Bjørnøya, only 178 km² in area, is situated on the Stappen High, near the Barents shelf's western margin and approximately midway between mainland Norway and Spitsbergen. (Fig. 1). The Stappen High as defined by Gabrielsen et al. (1990) is an elongate structure trending N-S from 73° 30' to 75° 30' N at 18 to 19° E latitude, with Bjørnøya forming its highest point. This high was a positive Late Palaeozoic feature; it then subsided in the Mesozoic and was again uplifted in the Cenozoic. Seismic data suggest that exposures on Bjørnøya are representative of the Stap-

pen High as a whole. Prior to the drilling of offshore wells, exposures on this rugged, mist-shrouded and inhospitable island offered the only concrete information on the geological evolution of this significant sector of the Arctic. The sedimentary succession exposed on the island ranges from the Upper Precambrian to the Upper Triassic, with a composite thickness approaching 3 km (Fig. 2). Significant unconformities define the boundaries between three main depositional complexes: viz. the Pre-Devonian economic basement, the Late Palaeozoic basin and the Permo-Triassic platform.

Bjørnøya itself comprises two topographically distinct areas, each directly related to its underlying geology (Fig. 3). The extensive northern plain generally undulates between 20 and 50 m above sea level, with a labyrinth of rock fields, marshes and small lakes - all of which make walking and reconnaissance difficult. The few poor inland exposures give little information on the complexity of the underlying Upper Palaeozoic sequence and this succession is best studied in the coastal cliffs. The exposures there are excellent, but field-work is often hazardous. The south and southeastern part of the island is a rugged mountainous terrain dominated by basement exposures, and more than 400 m high cliffs rise precipitously from the sea. Mountaintops in this area show almost flat-lying exposures of the Permo-Triassic platform sequence unconformably overlying all older units; however Late Palaeozoic half-grabens are locally developed, cutting into the basement but predating the platform units (Fig. 4). Triassic strata - the youngest pre-Quaternary deposits preserved on the island - are exposed in three conical peaks on the Miseryfjellet massif, with youngest Carnian deposits preserved at 536 m above sea level.

Swedish expeditions in the latter half of the 19th century made the first general survey of the island, culminating in the major work of Andersson (1900). Upper Devonian and Lower Carboniferous coals were then the main objects of geological and economic interest, although other minerals were also investigated. Mining operations started in 1916, but were abandoned as uneconomical in 1925 - a conclusion confirmed by the evaluation of Horn & Orvin (1928). This report concentrated on the coal-bearing strata, but it also reviewed other geological work and presented a 1:50 000 bedrock map. Following the abandonment of economic exploitation, the island was largely bypassed by geologists in the ensuing 50 years and only isolated aspects of its palaeontology and geology were described. Biostratigraphically important contributions from this period include studies of Late Palaeozoic brachiopods (Gobbett 1963), palynofloras (Kaiser 1970, 1971), and corals (Fedorowski 1975). Siedlecka (1972, 1975) and Folk & Siedlecka (1974) also presented significant petrographical interpretations of selected Permian sections.

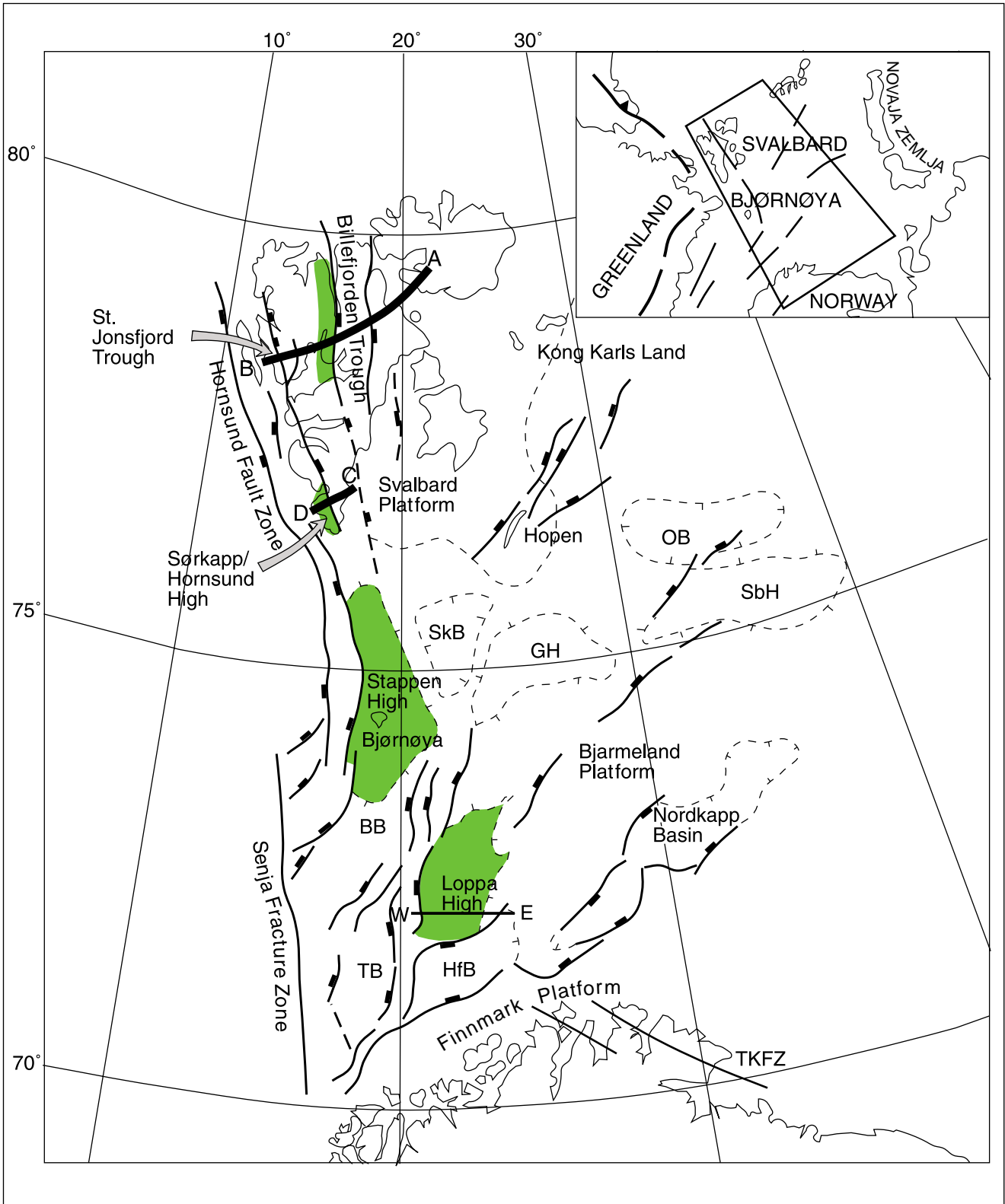


Fig. 1. Regional map of the western Barents Sea with major structural elements, Arctic overview inset (Abbreviations: TKFZ, Troms-Kommager Fault Zone, HfB, Hammerfest Basin; TB, Tromsø Basin; BB, Bjørnøya Basin; SkB, Sørkapp Basin; GH, Garderbanken High; SbH: Sentralbank; OB, Olga Basin; A-B, C-D and W-E - lines of schematic cross-sections in Figs. 24 & 26.

AGE		m	Members	Formations (old unit names)	Group		
TRIASSIC		200		Skuld Urd			
PERMIAN	? Kazanian	11		Miseryfjellet (Spirifer Lst)	TEMPEL - FJORDEN		
	Kungurian						
	Artinskian ?Sakmarian	50		Hambergfjellet (Cora Lst)	BJARME- LAND		
CARBONIFEROUS	Asselian	90		Kapp Dunér (Fusulina Lst)	GIPSDALEN		
	Gzelian	145		Kapp Hanna (Yellow Sst)			
	Kasimovian						
	Moscovian	45		Kobbekbukta			
		80		Efuglvika		Kapp Kåre (Ambigua Lst)	
		90		Bogevika			
	Bashkirian	145				Landnørdingsvika (Red Cgl)	
	Serpukhovian						
	Visean	230				Nordkapp "Culm"	BILLEFJORDEN
	DEVONIAN	Tournaisian		80		Tunheim	
Famennian		80	Kapp Levin				
		200	Vesalstranda	Røedvika "Ursa Sst"			
Ordoician to late Precambrian	~1100	Hecla Hoek					

Fig. 2. Composite stratigraphical column for Bjørnøya's Upper Palaeozoic succession, comparing present and earlier nomenclatures.

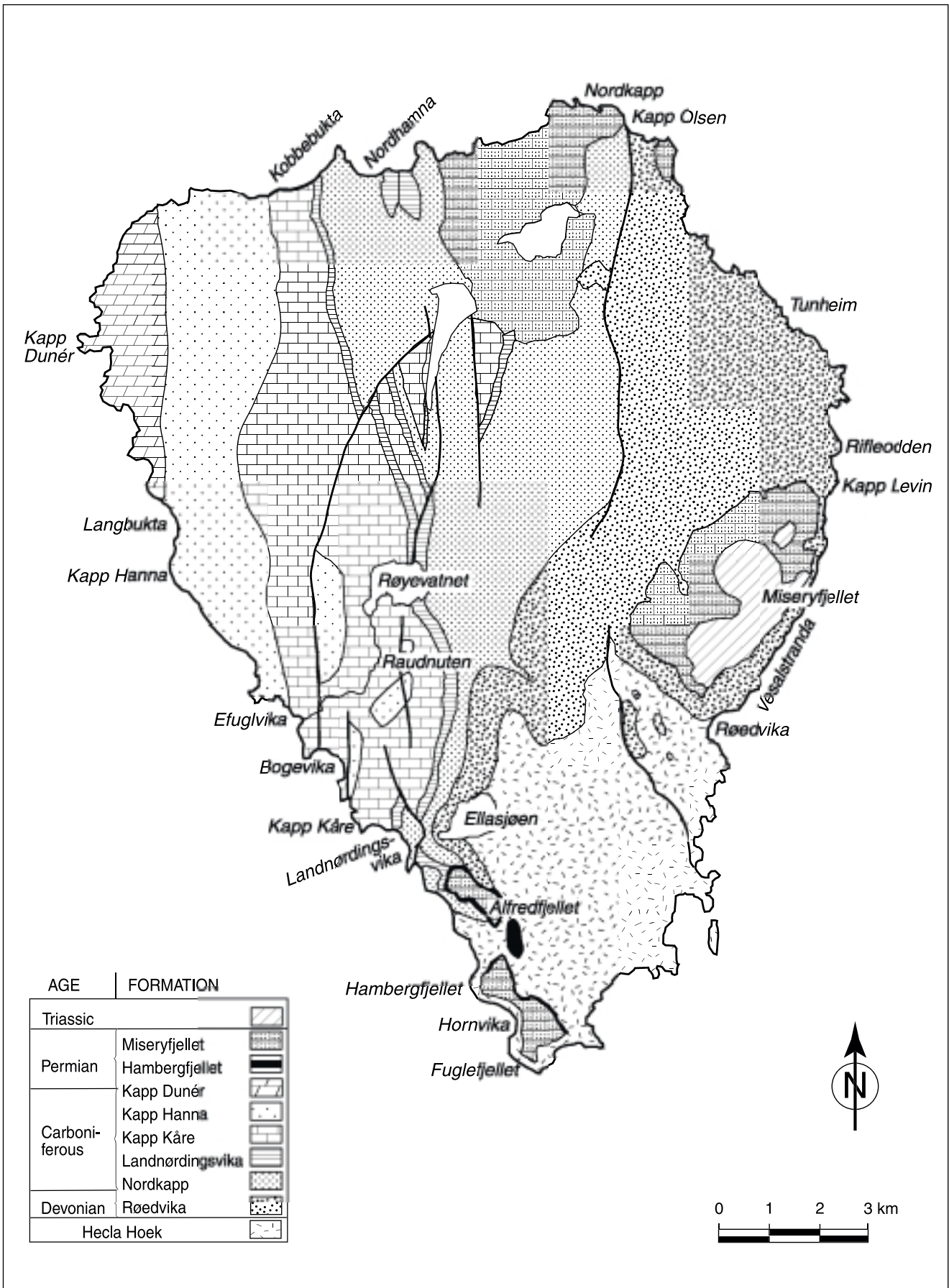
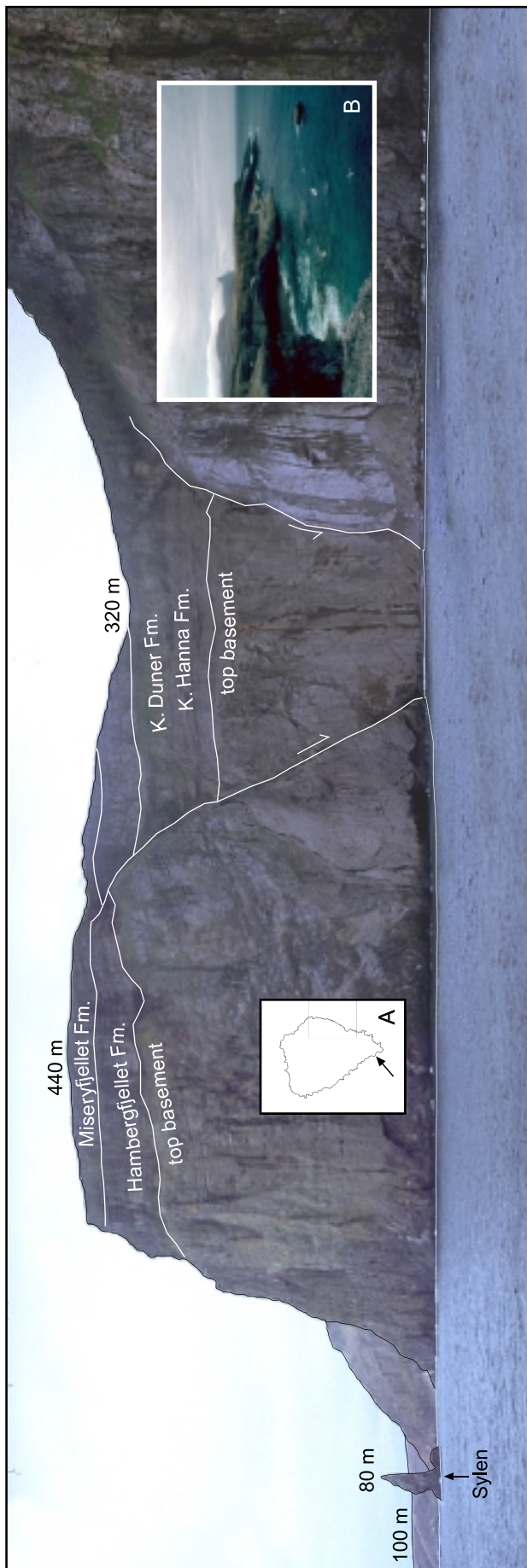


Fig. 3. Simplified geological map of Bjørnøya.



General surveys by Soviet and Norwegian geologists resulted in a description of the island's Triassic succession by Pchelina (1972), a general tectonic synthesis by Krasilscikov & Livsic (1974) and a stratigraphical and palaeoenvironmental review of the Upper Palaeozoic succession by Worsley & Edwards (1976). This new generation of activity sparked a series of detailed studies on the entire Upper Palaeozoic and Triassic succession, involving staff and research students at the Norwegian universities of Bergen and Oslo. Resultant theses (Gjelberg 1978a; Kirkemo 1979; Agdestein 1980) and publications (Gjelberg 1978b, 1981; Worsley & Gjelberg 1980; Gjelberg and Steel 1981, 1983; Bjørøy et al. 1983) were followed by detailed biostratigraphical appraisals of both fusulinids (Simonsen 1988) and palynomorphs (Vigran 1991) throughout the succession. Other recent contributions include detailed studies of parts of the succession (Lønøy 1988; Stemmerik & Larssen 1993; Stemmerik et al. 1994, 1998; Stemmerik & Worsley 2000), a brief review of Late Palaeozoic structural regimes (Lepvrier et al. 1989) and by evaluations of the area's burial history (Ritter et al. 1996). An important contribution was the new 1:50 000 geological map of Dallmann and Krasilscikov (1996). The general review in Harland (1997) is mainly based on pre-existing literature and several of the conclusions presented there will be supplemented and/or modified by the present contribution.

A synthesis of both published and unpublished recent work is presented here. Following initial general reviews of the palaeogeographical evolution of the entire Svalbard archipelago (Steel & Worsley 1984; Worsley et al. 1986) and more recent reviews of various aspects of the Late Palaeozoic regional development (Bruce & Toomey 1992; Cecchi 1992; Gerhard & Buhrig 1990; Nilsen et al. 1992; Stemmerik & Worsley 1989, 1995), it is now relevant to present such a synthesis and compare and contrast the development of Bjørnøya with the remainder of the Barents Shelf. By combining this information with our present geophysical understanding of the area, it may be possible to give more refined prognoses of the subsurface development and economic potential of analogous structures in this extensive and still little explored hydrocarbon province.

Pre-Devonian Basement

In common with the remainder of Svalbard, this sequence is often referred to as "Hecla Hoek"; it was described by Holtedahl (1920) and Krasilscikov & Livsic

Fig. 4. The cliffs of Hambergfjellet from Hornvika with (Inset A) locality map and (Inset B) view of southern massif from northern coast. Note the 80 m high stack of Sylen ("The needle") for scale.

(1974) presented new information on its stratigraphy and structural geology. A comparison of the two works is shown in Table 1 where the Soviet "suitja" are assigned formational rank.

Holtedahl (1920)		Krasilscikov & Livsic (1974)	
Unit	Min. thickness	Unit	Thickness
Tetradium Limestone Series	> 240 m	Ymerdalen Fm	> 450 m
Younger Dolomite Series	> 400 m		
Slate-Quartzite Series	> 175 m	Sørhamna Fm	ca 120 m
Older Dolomite Series	> 400 m	Russehamna Fm	> 500 m

Holtedahl (1920) recognized the biostratigraphical affinities of his two younger series to the Canadian and Black Rock sequences of North America. He correctly correlated Bjørnøya's "Older Dolomite" with the Porsanger Dolomite of northern Norway but mistakenly believed both these units to be of Cambrian age. Subsequent work has suggested that both of Holtedahl's two older series are of late Precambrian age. This conclusion is based on datings of algae and stromatolites in the dolomites of the Russehamna Formation (Milstein & Golovanov 1979) and on lithological correlation of the clastic sequence of the Sørhamna Formation with the Varangian glacial deposits of northern Norway and Spitsbergen (Harland & Gayer 1972; Harland 1978, Harland et al. 1993).

Krasilscikov & Livsic (1974) asserted that the younger and older units represent two different structural regimes: according to these workers the Precambrian sequence shows metamorphic and deformation styles reminiscent of the late Precambrian Baikaldes of Timan and northern Norway. In contrast, they described the Ordovician sequence as showing little sign of metamorphism or deformation and characterized it as lacking "typical" Caledonide features. The authors therefore suggested that Bjørnøya was situated on the southwestern corner of a massif that covered much of the present Barents Sea during the main Caledonide deformation phase. A marked cleavage seen in the Ordovician strata was attributed to overthrusting of Upper Palaeozoic units (presumably in association with Tertiary crustal deformation).

Other workers (Harland & Gayer 1972; Renard & Malod 1974) have also discussed or advocated the possible existence of a Lower Palaeozoic cratonic block in the Barents Sea following late Precambrian orogenesis. Harland & Wright (1979) suggested that Bjørnøya's Hecla Hoek sequence contrasts strongly with the rest of Svalbard; although noting that a Cambrian hiatus accompanied by minor folding has also been suggested for southern Spitsbergen, they emphasized the apparently almost undisturbed nature of the overlying

Ordovician succession. In contrast, Birkenmajer (1981) suggested closer similarities between the Hecla Hoek sequences of Bjørnøya with those of northeastern rather than southern Spitsbergen, a conclusion very much open to discussion. If we accept the extent of late Caledonian transcurrent movements as suggested by Harland & Wright (1979) and by Harland et al. (1984), then Bjørnøya may indeed have been situated nearer to NE Spitsbergen immediately following the main Caledonian orogeny in the late Silurian/early Devonian. However, recent work (e.g. Doré 1991) disputes that such large-scale movements have in fact occurred.

Many of these references to Bjørnøya's basement geology are based on literature studies and this entire succession needs detailed reappraisal. One feature that is undisputed is the prominence of SE-NW trending faults, which are overlapped by younger Palaeozoic units. Reconnaissance work in 1988 by D. Worsley and J. Sales of Mobil Exploration recognized a major thrust zone in Sørhamna on the SW coast of Bjørnøya, indicating that the relationship between the older and younger dolomites is tectonic rather than stratigraphic; thrusting has been taken up in the less competent phylitic beds of the Sørhamna Formation. An analysis of this thrust complex has been carried out recently and forms the subject of a separate contribution (Braathen et al. 1999), while the general structural development of the basement complex is still being worked on (Braathen pers. comm.). Large-scale compressive structures of presumed Caledonian origin have also been recognized recently in seismic data both east and north of Bjørnøya on the Stappen High (Gudlaugsson et al. 1998). This Caledonide thrust complex may well have provided the foundation for the tectonic development of the area in the Late Palaeozoic.

Late Palaeozoic development

No Old Red Sandstone or Lower to mid-Devonian equivalents are found on Bjørnøya, or in any offshore Barents Sea borehole drilled to date in the Norwegian sector. The oldest part of the island's Upper Palaeozoic succession is of Famennian age, with a depositional history and tectonic setting typical of contemporaneous sequences seen elsewhere in Svalbard and on the Barents Shelf. The various formational units recognized in the Upper Devonian to Upper Permian succession of Bjørnøya are shown in Fig. 2. These can be assigned to the three lithostratigraphical groups recognized elsewhere on the Svalbard archipelago (Cutbill & Challinor 1965). Group boundaries reflect major changes in depositional environments resulting from shifts in regional palaeoclimates, large-scale drainage patterns, relative sea level, and tectonic setting:

- Billefjorden Group, (Famennian to Viséan) with coal-bearing non-marine siliciclastics, deposited in the humid alluvial fan and flood-plain environments represented by the Røedvika and Nordkapp formations.
- Gipsdalen Group, (Serpukhovian/Bashkirian to Asselian) dominated on Spitsbergen by shallow marine carbonates and evaporites with subordinate mixed carbonates and siliciclastics, all deposited in semi-arid to arid palaeoclimatic settings. The group is represented on Bjørnøya by the Landørdingsvika, Kapp Kåre, Kapp Hanna and Kapp Dunér formations.
- Bjarmeland and Tempelfjorden groups (Artinskian to Upper Permian), with silica-rich mixed siliciclastics and carbonates of the Hambergfjellet and Miseryfjellet formations, suggesting regional submergence and the development of more temperate climates with deeper and cooler water hydrographic regimes. The Hambergfjellet Formation has generally been assigned to the Gipsdalen Group; our reassignment will now be discussed in more detail.

These formational units were first described in general terms by Andersson (1900) and Horn & Orvin (1928). Presently accepted lithostratigraphical nomenclature as accepted by Dallmann (1999) is based on work by Cutbill & Challinor (1965), Krasilscikov & Livsic (1974) and Worsley & Edwards (1976).

The Famennian to mid-Moscovian succession of Bjørnøya displays a similar depositional history to contemporaneous strata in central Spitsbergen, but the Upper Moscovian and younger rocks show striking differences to these better known areas. Whereas the late Carboniferous to early Permian history of most of central Spitsbergen shows the establishment of a relatively stable carbonate and evaporite platform, Bjørnøya at the same time suffered renewed and repeated tectonic activity, producing extensive faulting (Fig. 4).

We will discuss the late Devonian to Permian history of Bjørnøya in terms of six major evolutionary phases. Palynological and faunal evidence for our datings of these phases are summarized in Fig. 5, based on Simonsen (1988), Vigran (1991), Nilsson (1993, 1994) and J.O. Vigran (pers. comm. 1999). Palaeogeographical sketch maps showing our main conclusions are displayed in Fig. 6. We will subsequently compare this development with the contemporaneous evolution of adjacent Arctic areas, and then discuss possible implications for hydrocarbon exploration in the region.

The Famennian to Bashkirian West Bjørnøya Basin

Bjørnøya in Famennian to Bashkirian times was situated near the western margin of a NNW-trending asymmetric rift basin, which Gjelberg & Steel (1983) considered to be bounded to the WSW by a major tectonic lineament - their "West Bjørnøya Fault". The siliclastic deposits of the Røedvika, Nordkapp and Landørdingsvika formations (Figs. 7, 8 & 9) show a maximum composite thickness of up to 800 metres. This succession consists of three coarsening upward sequences of differing origin and development.

Røedvika and Nordkapp humid clastics -- The lower and middle parts of the Røedvika Formation form a single coarsening upward motif from the coal-bearing Vesalstranda Member to the coarser Kapp Levin Member, both deposited during the Famennian. The base of the Vesalstranda Member is marked by thin intermittent conglomerates in a siliclastic succession which onlaps the underlying basement. The angular unconformity between these units is well displayed on the eastern cliffs of Miseryfjellet where it is dissected by small normal faults, thus refuting the suggestion by Krasilscikov & Livsic (1974) of later modification by thrusting; the strongly discordant appearance of the contact seen in outcrop results from the marked onlap relationship combined with some deformation in the less competent basal beds of the Røedvika Formation. The Vesalstranda Member itself consists largely of fine-grained, dominantly grey flood-plain sediments, with fining upward sandstone bodies deposited in the channels of meandering streams. In addition, the lower and middle parts of the member contain small coarsening upward sequences, which represent the progradation of small lacustrine deltas (see Gjelberg 1981 for details). Lacustrine and fluvial facies thus alternate in the lower parts of the succession, but fluvial deposits become more common upwards and there is a gradual transition to the more sandy and coarser grained sediments of the overlying Kapp Levin Member. The latter were deposited mainly by low sinuosity streams in the member's lower part; these pass upwards into more typical braided river systems.

Palaeocurrents in the Vesalstranda Member suggest northwestwards flowing meandering streams, while flow directions in the Kapp Levin Member were towards the east and northeast. The overall change in depositional environment and palaeocurrent distribution seen through this upward coarsening sequence is probably related to the increasing dominance with time of alluvial fan systems that built out from the southwestern uplifted footwall margin of the basin. These fans prograded eastwards over the older northwest-flowing axial fluvial systems (Worsley & Edwards 1976; Gjelberg 1978a, b, 1981; Gjelberg & Steel 1981, Fig. 6 herein).

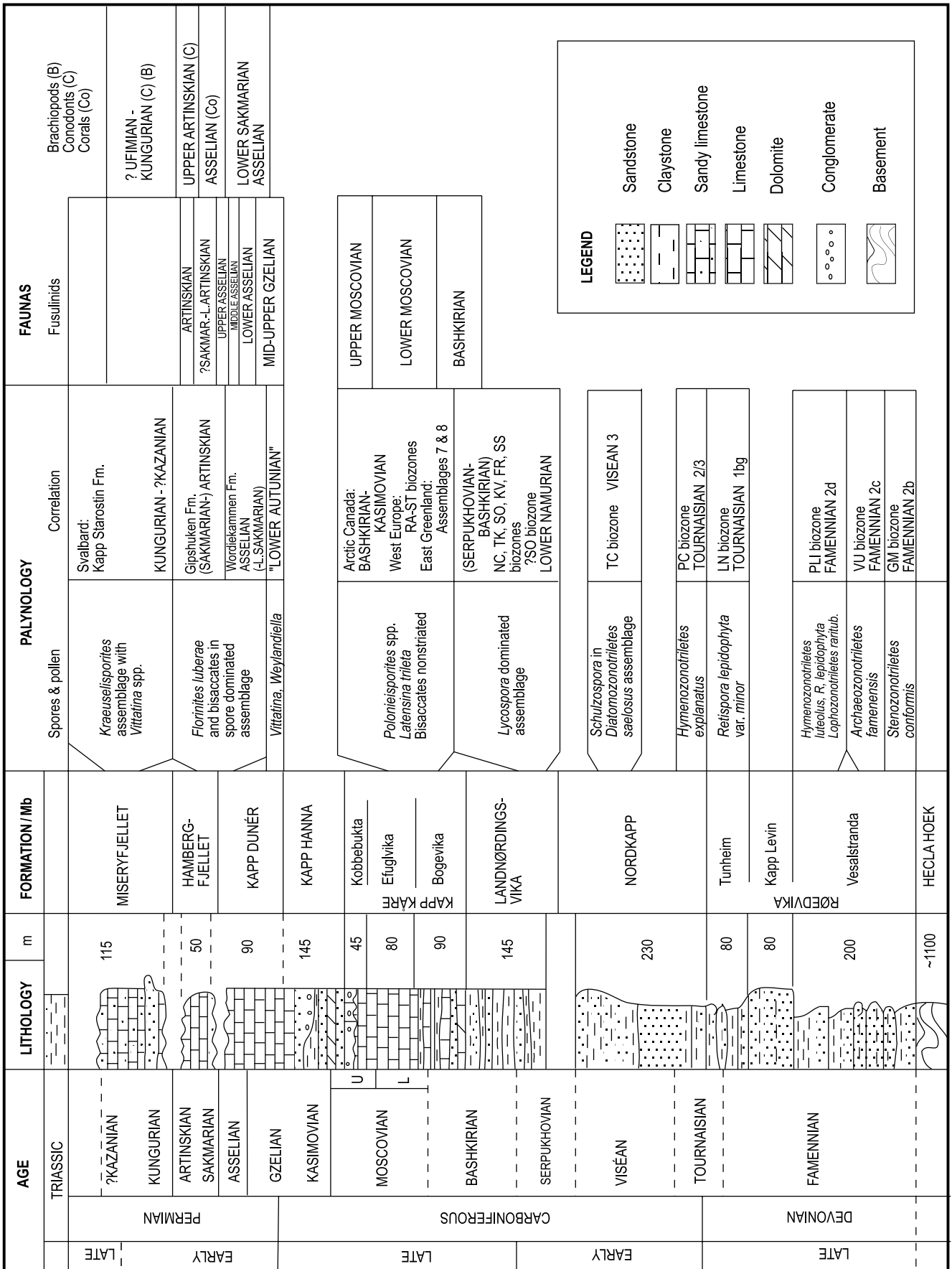


Fig. 5. Review of biostratigraphic evidence for age relationships in the Upper Palaeozoic succession, comparing evidence from palynofloras with that of micro- and macrofaunas.

The renewed development of fine-grained deposits at the top of the Kapp Levin Member marks an abrupt change in depositional environment around the Famennian/Tournaisian transition. The basin was suddenly covered by a standing water body, probably because of a sudden rise of base level as a response to faulting and basin-floor tilting. This water body was then infilled by

coarse-grained prograding fan deltas. The overlying Tunheim Member represents the re-establishment of flood-plain environments in which meandering streams again flowed largely towards the northwest. The lower unit of the member comprises a multistorey and multi-lateral channel sequence with individual components containing features typical of high sinuosity channels.

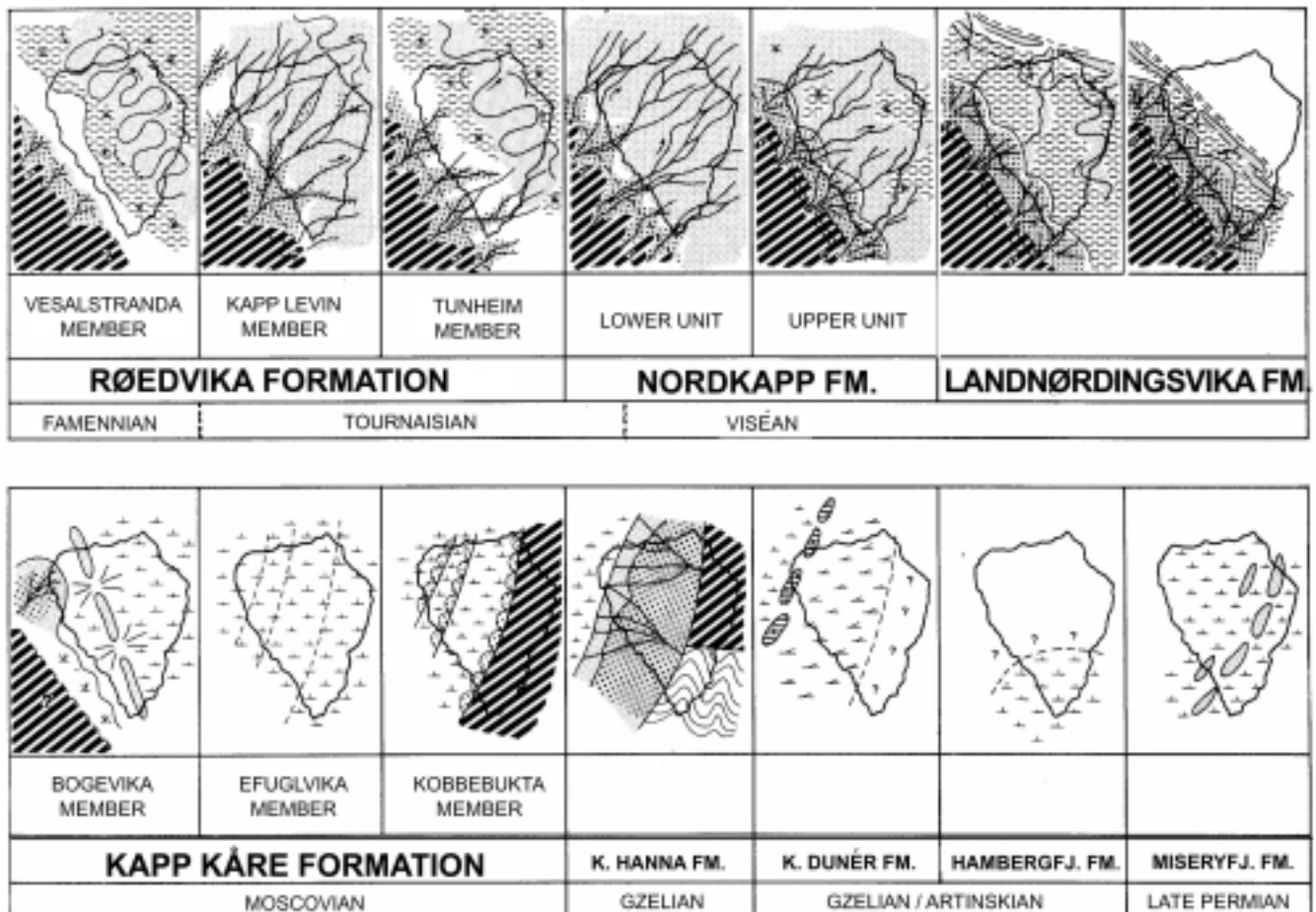


Fig. 6. Palaeogeographic summary maps for main late Palaeozoic depositional phases.

The amount of sandstone decreases dramatically in the upper part of the member, and mudstones, siltstones and coals become more common. This may reflect increased rates of subsidence, as also suggested by coal seam splitting and a general increase in thickness northwards.

The boundary between the Røedvika and Nordkapp formations (the “Ursa sandstone” and “Culm” respectively of early workers) was defined on palaeobotanical grounds by Antevs & Nathorst (1917) and although Horn & Orvin (1928) noted that “when the formations are viewed as a whole, there is a distinct lithological difference” the transition was poorly understood. The formational boundary (as redefined by Gjelberg 1981) is

stratigraphically lower than the unit boundary in these earlier accounts and probably represents a depositional break within the Tournaisian; faults in the underlying unit are apparently truncated and overlapped by the cross-stratified sandstones that dominate the lower parts of the Nordkapp Formation. These sands indicate the re-establishment of eastwards flowing braided streams on large alluvial fans which prograded out from the West Bjørnøya Fault Zone (Fig. 6). Spectacular large-scale (several metres thick) zones of soft sediment deformation suggest earthquake shocks and tectonic activity at this time. This thick succession of alluvial sandstones passes up into prominent conglomerates of stream-flood

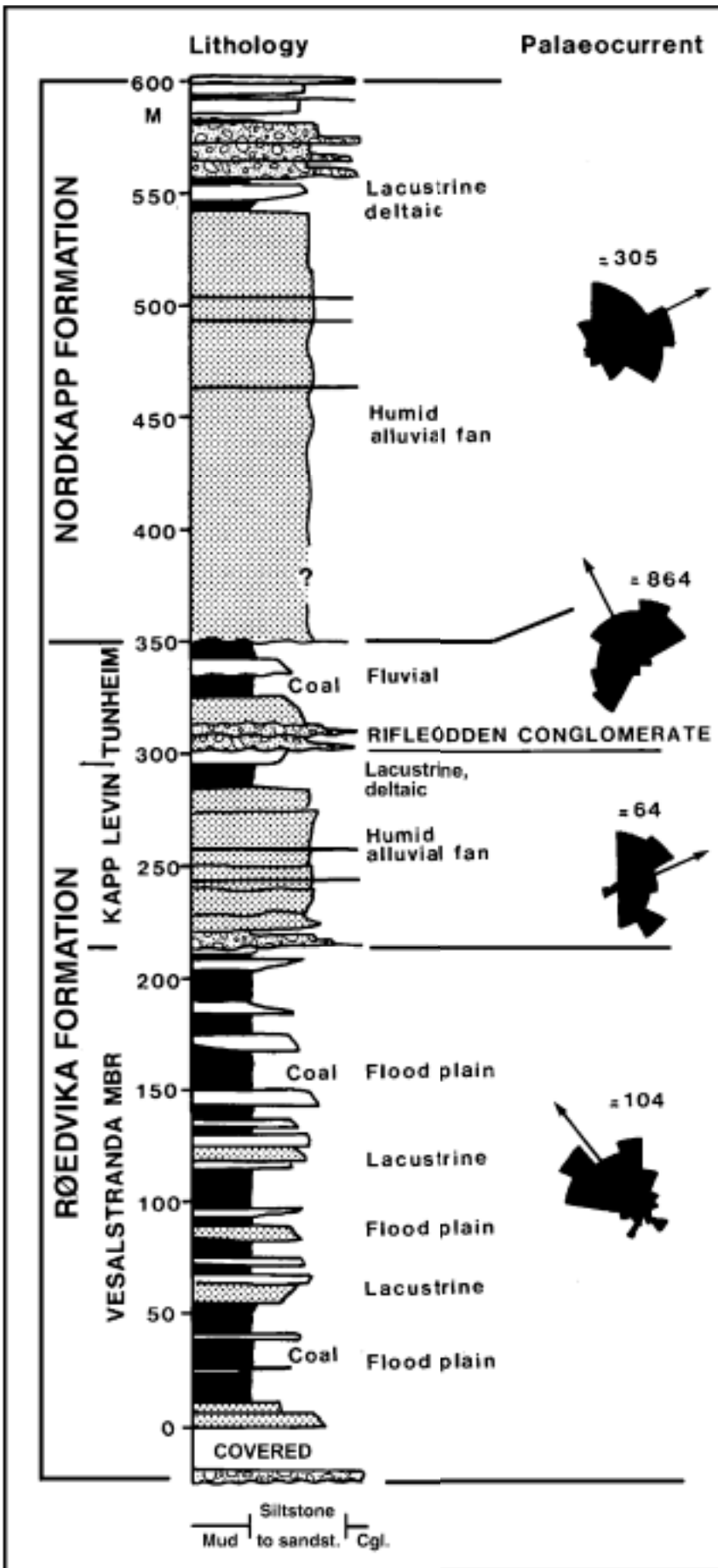


Fig. 7. Interpretative composite log through the Røedvika and Nordkapp formations, based on Gjelberg (1981).

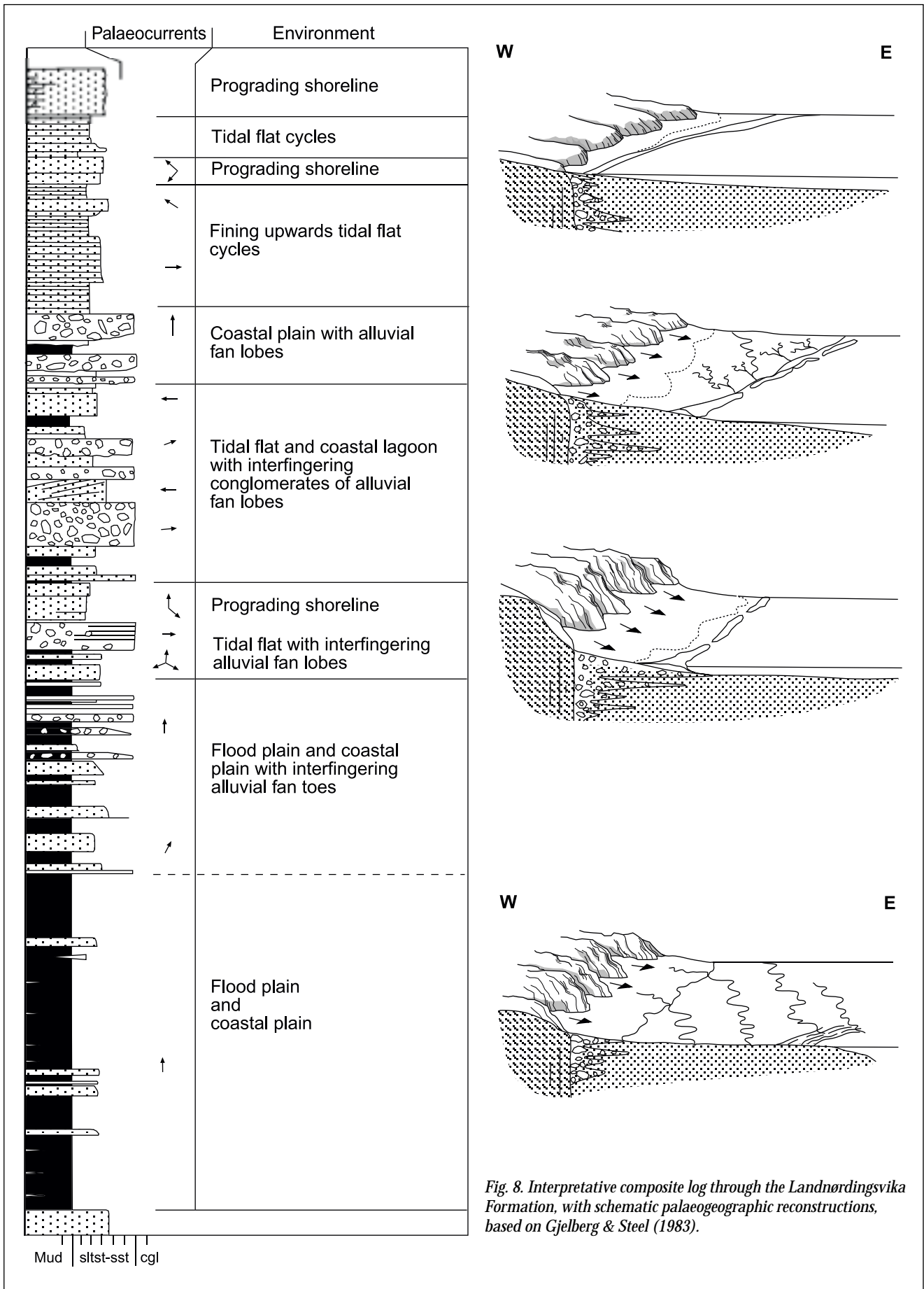


Fig. 8. Interpretative composite log through the Landnørdingsvika Formation, with schematic palaeogeographic reconstructions, based on Gjelberg & Steel (1983).

and mass-flow origin, interbedded with black coaly shales. These contrast sharply with the underlying monotonous quartzitic sandstone succession and are thought to represent renewed large-scale rifting.

Climatic shift to Landnørdingsvika redbeds -- The entire succession reviewed so far is typified by lithofacies suggesting deposition in moist climates on floodplains with a high water table and a low substrate Eh. The transition between the Nordkapp and Landnørdingsvika formations marks a dramatic shift to semi-arid or arid climatic conditions. Worsley & Edwards (1976) noted a sharp break between the grey sandstones of the former and the red mudstone of the latter in exposures on the southwest coast, although some secondary reddening of the underlying unit has occurred. Recent palynological studies (J.O. Vigran, pers. comm. 1995) indicate a Tournaisian to Viséan age for the Nordkapp Formation and a youngest Serpukhovian to Bashkirian age for the overlying red beds. The significant Serpukhovian depositional break above an upward coarsening fluvial succession has been recognized throughout the Arctic and may represent a period of general uplift separating early and mid-Carboniferous rifting phases.

The Landnørdingsvika Formation (Figs 2, 8 & 9), the uppermost of the three clastic units in this early basin infill, consists of interbedded red mudstones, drab yellow-brown sandstones and red conglomerates that together represent an intricate interfingering of flood-plain, alluvial fan and marginal marine sediments (Figs. 8 & 9, see also Gjelberg & Steel 1981, 1983). The presence of calcrete paleosols contrasts with the development of coals in the underlying units. Floodplain and coastal plain deposits dominate the lower parts of the unit, but pass up first into alluvial conglomerates and then into interbedded marginal marine clastics and carbonates, the latter becoming increasingly common upwards. The transition from humid to arid climatic conditions, probably during the Serpukhovian hiatus, was thus followed first by renewed rifting along the pre-existing West Bjørnøya Fault, and then by a long term rise in sea level, giving a gradual transition to the next depositional phase during the late Bashkirian.

Bashkirian to Moscovian transgression

The transitional base of the 215 m thick Kapp Kåre Formation is defined at the disappearance of conglomerates and the development of mixed clastic and carbonate sequences. The first fusulinids found near this transition have a late Bashkirian aspect. The transition from clastic- to carbonate- dominated sedimentation and the generally upward fining trend shown by the two lower members of this formation reflect the continuing effects of regional transgression - perhaps combined with more intermittent tectonic activity.

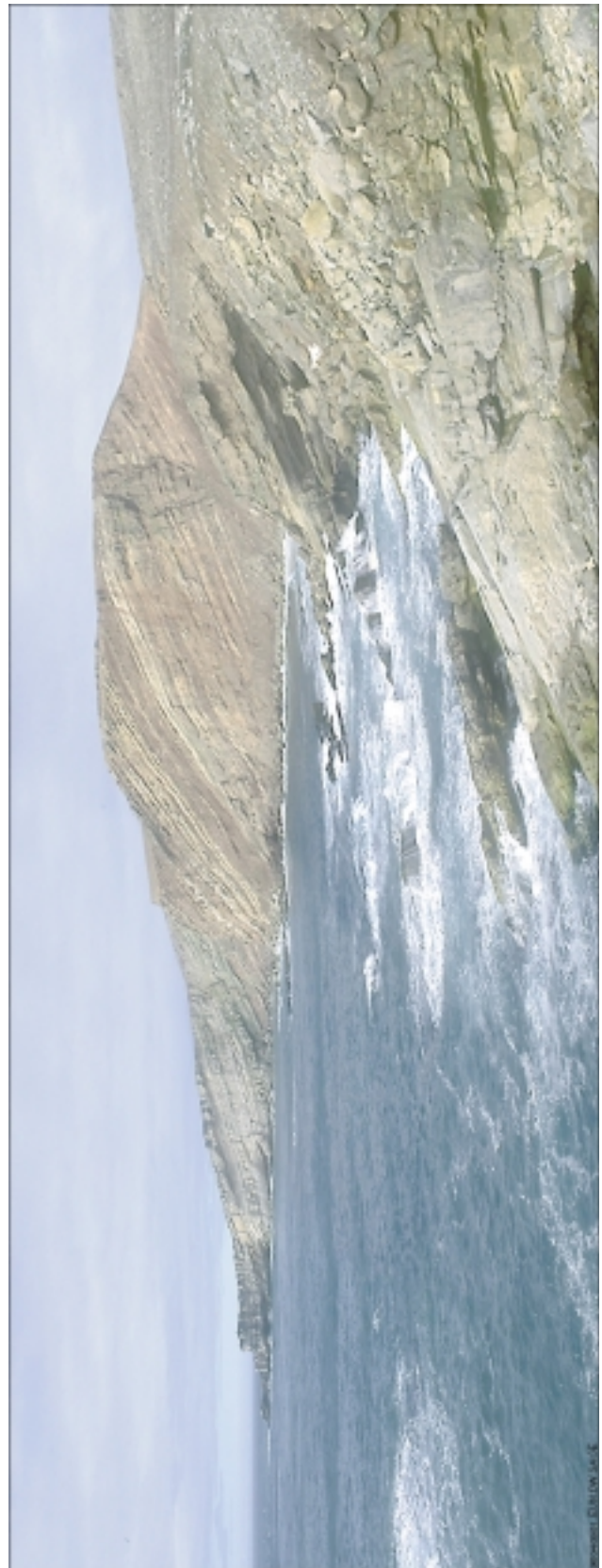


Fig. 9. View of the Landnørdingsvika Formation in its type locality: note the grey sandstones of the Nordkapp Formation (right foreground), the marked change to red mudstones and yellow coarse clastics of the Landnørdingsvika Formation (highest point on the cliff about 120 m) and the transition to the grey carbonate-dominated succession of the Kapp Kåre Formation (far left lower cliffs).

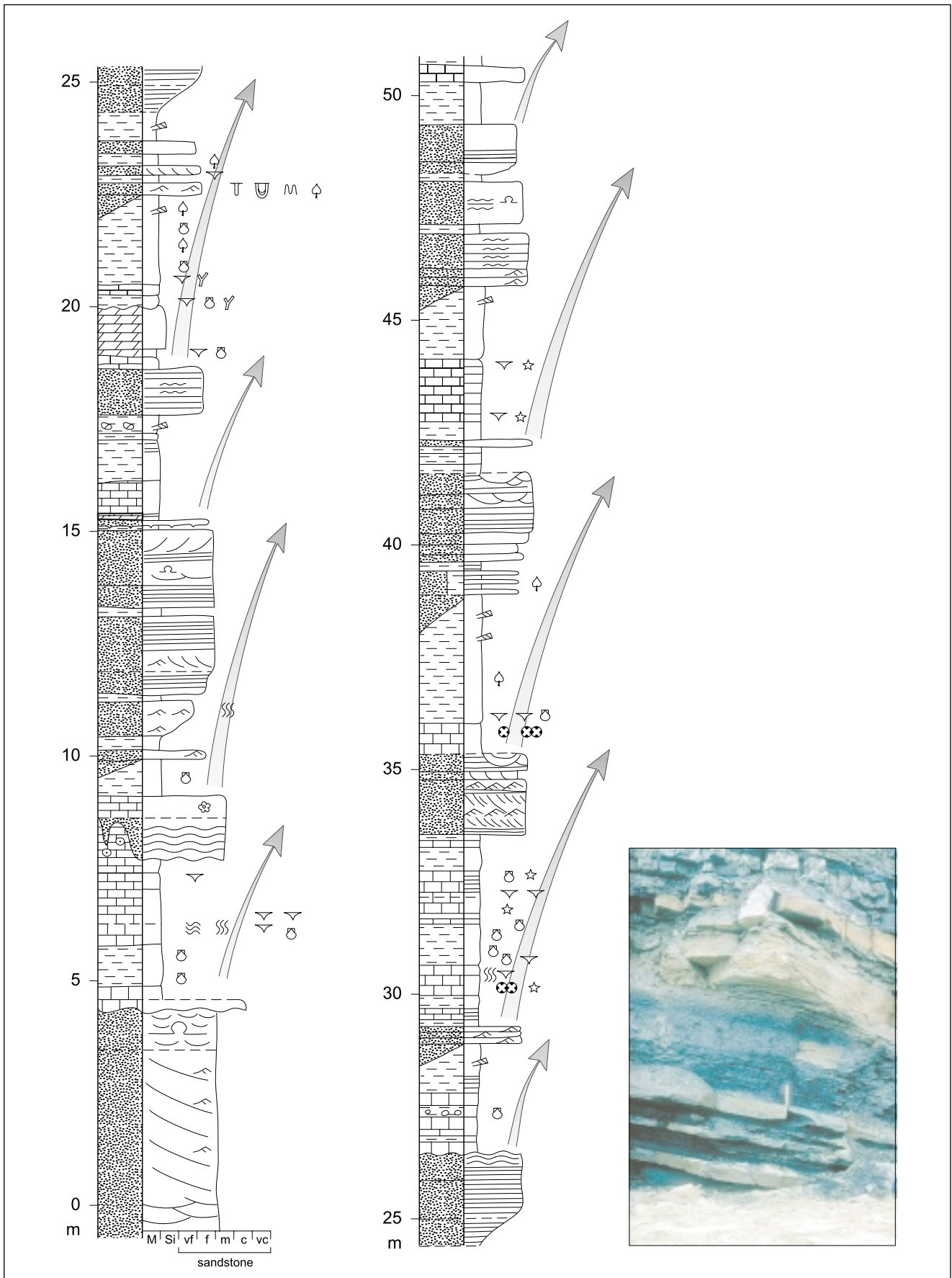


Fig. 10. Small-scale rhythms in the Bogevika Member of the Kapp Kåre Formation showing the general coarsening upwards motifs, combined with an inset photo of a single rhythm in the middle of the member. Legend in Fig. 21.

Bogevika Member rhythms -- The Bogevika Member (Fig. 10) consists of limestones, shales and sandstones apparently organized in a series of small-scale (< 10 m thick) shoaling upward rhythms (Stemmerik et al. 1998; Stemmerik & Worsley 2000). Each rhythm typically shows an upward transition from oncolitic to coralgall limestones or marine shales (often organic rich) into siltstones and sandstones with either brackish water faunas or plants and roots. Upper contacts are usually sharp and show desiccation cracks, calcrete horizons or an erosional surface under the basal limestone or shale of the overlying rhythm. Marked discontinuities and karst surfaces are also relatively common within and on tops of individual limestone units in these sequences. Red beds and coarser clastics are more common in southern exposures, while grey shales and marine limestone incursions are more characteristic of the northern coast. The entire

development reflects deposition in tidally influenced marginal marine environments, with the upward coarsening units representing repeated shoreline progradations into both restricted and open marine depositional sites (Stemmerik & Worsley 2000). The abundance of karst and other discontinuities suggests that the rhythmic development is not a purely autocyclic phenomenon but may rather reflect an interplay of continued local tectonic activity, ongoing regional transgression and glacially influenced eustatic sea-level fluctuations (c.f. Stemmerik & Worsley 1989). Sporadic palaeocurrent indicators reflect both long-shore and bimodally directed on/offshore current patterns in this complex regime. Sandstones become less common upwards, as decreasing clastic input accompanied submergence of the western upland provenance areas. The gradual transition through limestone and shale intercalations to the overlying

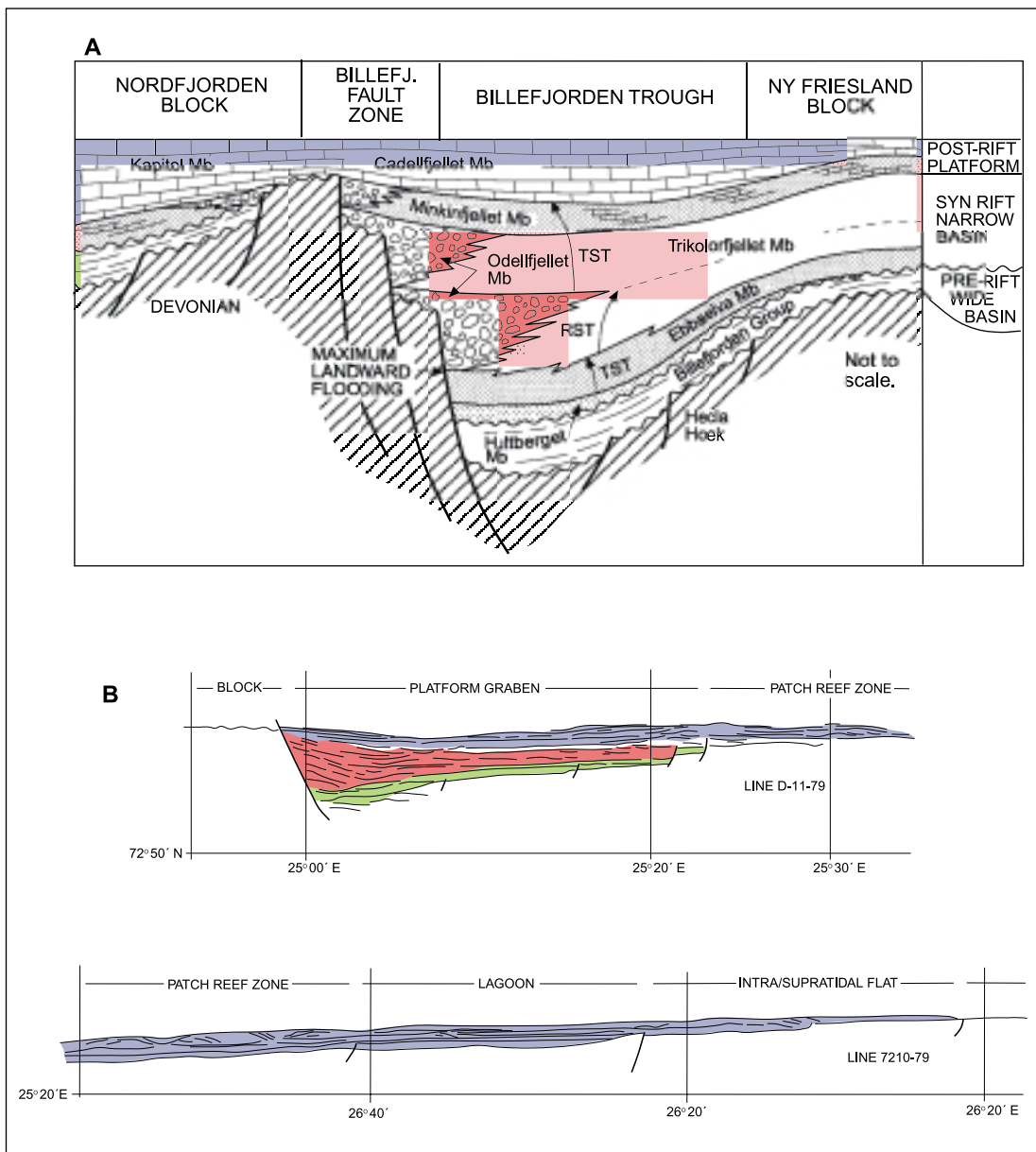


Fig. 11. Interpreted seismic example of Carboniferous half-graben development on the central Barents Shelf (B) and simplified geosection through the Billefjorden Trough of central Spitsbergen (A).

carbonate-dominated Efulgvika Member reflects the establishment of carbonate shelf sedimentation throughout the entire area by the early Moscovian. Similar transitions in local troughs and transgression of large platform areas are typical of the whole Barents Shelf at this time. The best-documented example is the Billefjorden Trough in central Spitsbergen (Holliday & Cutbill 1972; Johannessen & Steel 1992) but similar situations can also be recognized locally in the western Barents Shelf's subsurface (Fig. 11).

Efulgvika platform carbonates -- The 80 m thick Efulgvika Member is dominated by white to grey, thinly to massively bedded and variably cherty limestones with textures ranging from grainstone to wackestone. Both microfacies and stenohaline faunas suggest deposition on an open marine shelf of moderate depth. Exposures show a series of shoaling-upwards rhythms passing from bioturbated chert-rich wackestones with *Thalassinoides* burrows into chert-free grainstones, sometimes with erosive or karstified tops (Stemmerik et al. 1998, Stemmerik & Worsley 2000). The cyclicity seen lower in the succession thus continued, but clastic input decreased as transgression covered available provenance areas. The rhythmic development, the karstic surfaces and the cherts themselves suggest some measure of continued tectonic activity during sedimentation. The chert both fills *Thalassinoides* burrows and occurs in various morphotypes indicative of "diapiric" movement within the unconsolidated sediments. The resultant chert masses vary in form from bulbous to sheet-like "dykes" sub-perpendicular to the bedding. These elongate structures follow NE-SW and NW-SE trending zones of deformation. Large-scale fractures with penecontemporaneous sediment infill also crosscut the bedding subvertically with a NE-SW trend. The fractures and the chert bodies are thought to be related to subaerial exposure and karstification: a few discontinuity surfaces show clear microkarstic features and bedding truncations and angular unconformities are occasionally associated with these surfaces. These phenomena collectively suggest intermittent syn- and early post-sedimentational tectonism, the chert deformation being preconsolidation in age and the fractures postconsolidational; this tectonism is more clearly shown by the facies of the overlying units.

Late Moscovian to Gzelian tectonism

Worsley & Edwards (1976) noted the existence of intraformational conglomerates uppermost in the Kapp Kåre Formation. Subsequent work has shown how these beds mark a change of tectonic activity on Bjørnøya in the Late Moscovian. We interpret the top surface of the Efulgvika Member as representing a pronounced erosional break with clear karstification. The overlying Kobbekbukta Member (Kirkemo 1979), where present, consists of interbedded marine limestones, shales and

conglomerates (Figs. 12 & 13). The latter contain mostly intraformational chert and limestone clasts - in contrast to the significant extrabasinal components that characterize the coarse clastic units of the overlying Kapp Hanna Formation. The conglomerates of the Kobbekbukta Member were deposited by both subaerial and submarine debris flows triggered by renewed syn-depositional tectonism. However, these flows originated from fault blocks over eastern parts of present-day Bjørnøya, producing apparent partial inversion of the earlier basin (Figs. 6 & 14), superimposed over the northerly trend of the underlying Caledonide thrust system. Two sets of brittle fracture systems with calcitic slickensides observed in the Røedvika and Nordkapp formations suggest post-early Carboniferous but pre-mid Permian movements characterized by predominantly normal dip-slip extension followed by minor lateral movements. The late Moscovian basinal inversion appears to be represented by the normal extensional fractures, which began to form penecontemporaneously with the dykes and fractures described above in the Efulgvika Member. Major block controls seem to have been exerted by the dominantly N-S trending faults, while minor cross-cutting roughly ESE-WNW and ENE-WSW trending sets controlled flow of eroded material from the uplifted flanks of the graben westwards into accommodation areas on the hanging wall of the West Bjørnøya Fault.

A spectacular facies development seen on the northern coast within the Kobbekbukta Member (mentioned briefly by Worsley & Edwards 1976) is interpreted as marking the site of repeated synsedimentary small-scale fault activity along such a WSW-ENE trending fault scarp (Fig. 12). Debris flows drape over the faulted margin, but the main feature of the downthrown side is a sequence of shales and turbidites, the latter deposited by currents flowing westwards and paralleling the micro-fault scarp (Stemmerik & Worsley 2000). The overlying conglomerates show no lateral variation over the fault-line trace, implying cessation of movement on this particular feature immediately below the boundary with the Kapp Hanna Formation. Faulting obscures the boundary itself; conglomerates, which apparently drape over the poorly exposed critical fault separating the two formations, may suggest ongoing synsedimentational tectonism. Southern outcrops show a highly varied development at this level (Fig. 13). Debris flows uppermost in the formation just south of Efulgvika form thin veneers (less than 1 m thick) on the eroded top of the Efulgvika Member whereas only 1.5 km further north along the coast, extrabasinal Kapp Hanna conglomerates directly infill broad channels cutting at least 5 m down into the Efulgvika Member.

Additional evidence of tectonism -- Significant additional information is given by several critical inland exposures and by analysis of photomosaics of the generally inaccessible southern cliffs:

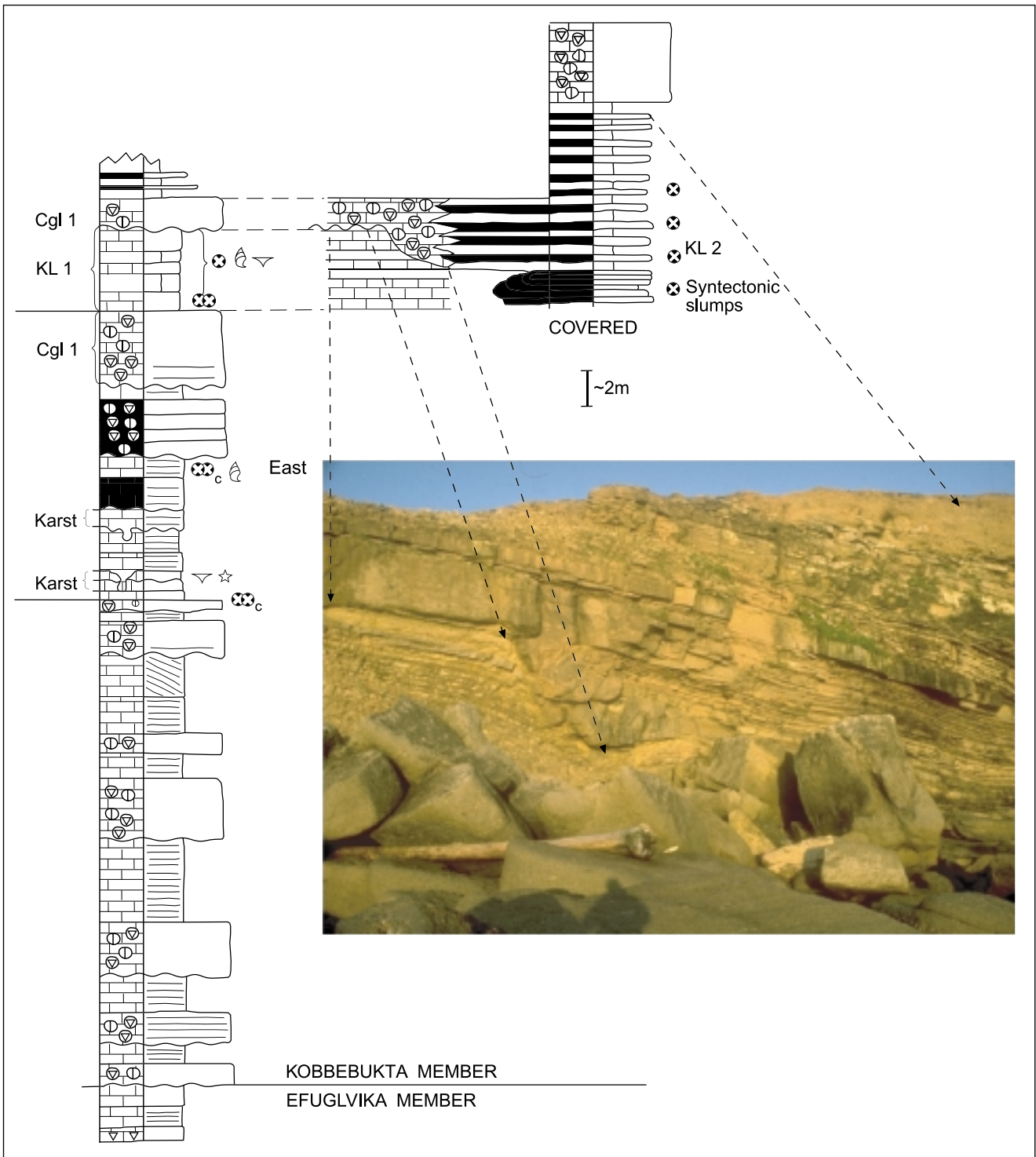


Fig. 12. Intraformational conglomerates in the Kobbekukta Member, uppermost Kapp Kåre Formation: combined section logs and photcollage show a syndepositional fault – this reflects renewed tectonic activity producing small half-grabens which then channelled debris flows and turbidites from the newly emergent eastern high. Legend in Fig. 21.

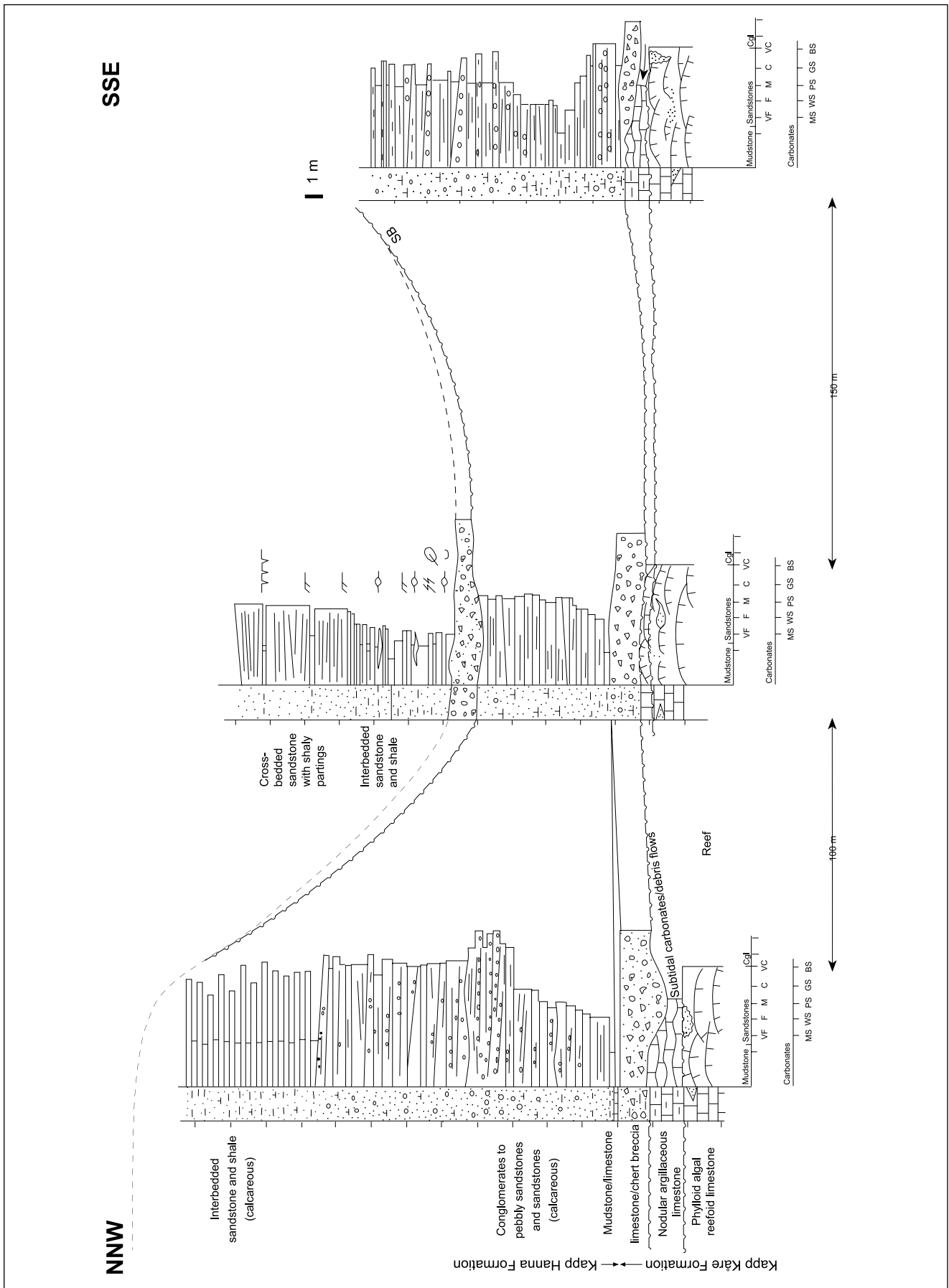


Fig. 13. The Kapp Kåre to Kapp Hanna formational boundary in the area around Efulgvika, sections showing the complex lateral variation at this level.

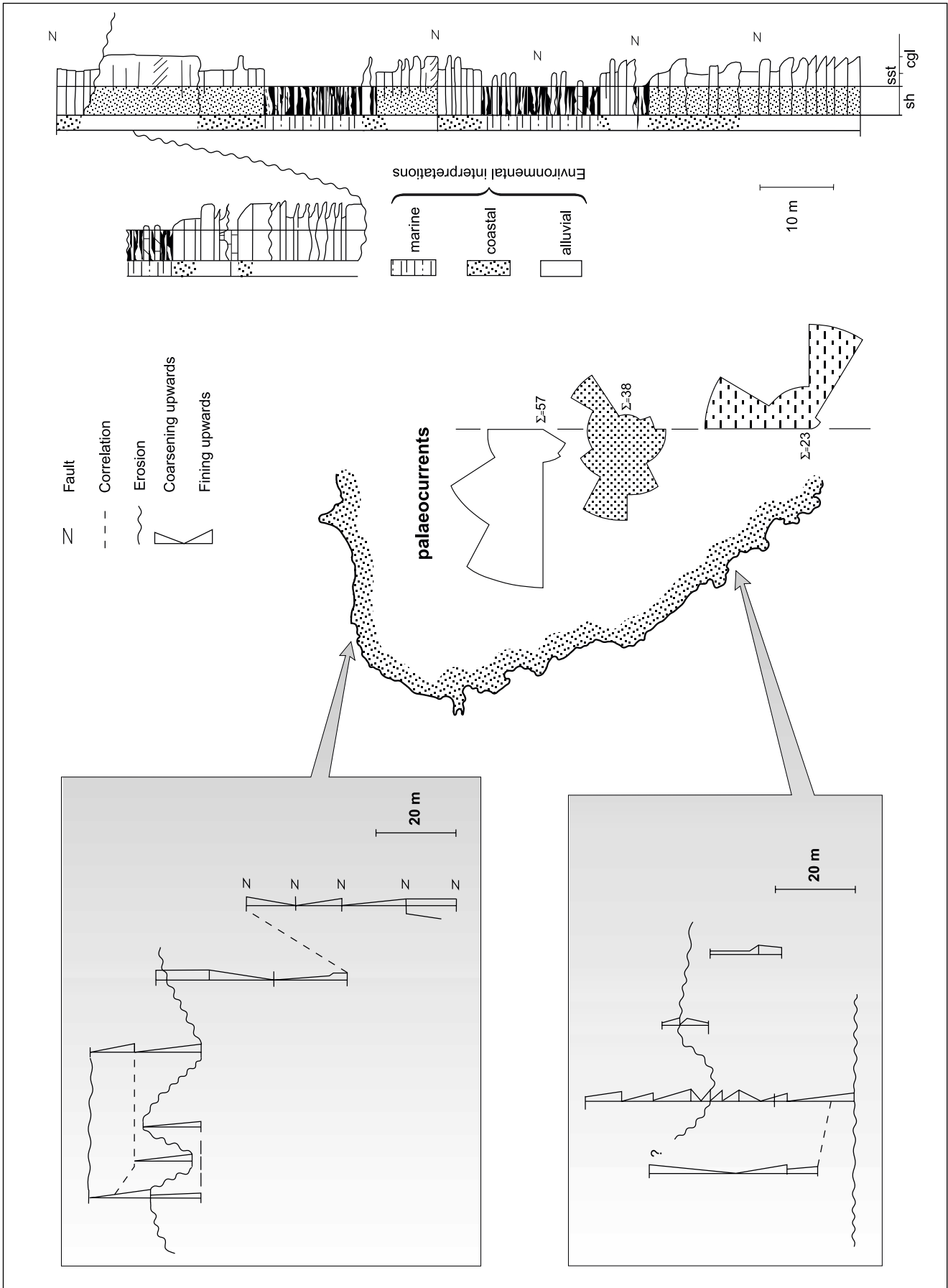


Fig. 14. Composed interpretative logs through the Kapp Hanna Formation, indicating the complex local variations in facies developments, but with clear relationships between lithofacies and palaeocurrent directions.

- Inland exposures on the hill of Raudnuten near the west coast show complex relations: on eastern hill-sides almost flatlying Efulgvika carbonates are erosively overlain by a cm-scale veneer of conglomerates, while western slopes show a monoclinical flexure in the top of the Efulgvika Member before these dip steeply to the west. ENE - WSW trending fractures and minor faults dissect the N-S axis of the monocline and define an erosional relief infilled by up to 10 m thick coarse conglomerates of the Kapp Hanna Formation. The relief shown by the faulted and eroded top of the Efulgvika Member is clearly a late Moscovian phenomenon - isolated thin outliers on the hilltop contain limestones with fusulinids assignable to the overlying Kapp Dunér Formation of late Asselian age (see also below) and these limestones overlap the whole of the underlying irregular relief,
- Earlier workers mapped inland exposures south of Miseryfjellet near the southeastern coast as containing basal Røedvika Formation conglomerates. These are now interpreted as Kapp Hanna conglomerates deposited directly on eroded basement; they pass up into carbonates which have not yet been dated,
- Southernmost cliffs show almost 400 m sheer exposures of basement, generally with a thin overlapping mid- to Upper Permian overlying sequence; three local half-grabens which have been identified in these cliffs show a presumed Kapp Hanna to Kapp Dunér wedge infill resting directly on an abutting basement; the uppermost Permian overlaps and is not involved in the graben infill (Fig. 4).
- Coastal exposures of the Kapp Hanna Formation, of latest Moscovian to Kasimovian age, display laterally variable alternations of conglomerates, sandstones, shales and dolomites. The complex development, in numerous small fault blocks on the western and northwestern coasts and in scattered poorly exposed outliers inland, makes lateral correlation extremely difficult but detailed studies suggest a composite maximum thickness of around 145 m (Fig. 14). Most of the coastal exposures display both fining and coarsening upward packages in which alluvial, coastal and marginal marine environments are represented. However, several localities show shallow marine dolomite and shale units cut by valley forms with up to 20 m observed relief; these valleys also trend generally ESE-WNW and are controlled by minor syndepositional faults. These incised valleys are infilled by thinly interbedded sequences of conglomerates and sandstones of stream-flood origin. Abundant palaeocurrent data in the alluvial sequences indicate a clear eastern source and flow directions along the valley floor to the WNW; similar directions are seen in the isolated inland exposures described above.

Desiccation cracks found in shaly laminae on bedding planes throughout the conglomerates indicate repeated subaerial exposure between intermittent depositional episodes. Other features indicative of local tectonic activity include fissures infilled with clastic material and intraformational angular unconformities of up to 5° overlain by conglomerates containing angular clasts of the underlying penecontemporaneous sandstones.

Tectonic summary -- The total association of unusual features displayed by exposures of the Kobbekbukta Member and the Kapp Hanna Formation strongly suggest intrabasinal tilting which uplifted the eastern flanks of the earlier West Bjørnøya depositional graben. Older Carboniferous and Devonian deposits must have already been well consolidated so that the flanks were dissected into a series of N-S trending fault blocks now exposed over eastern parts of present-day Bjørnøya (Figs. 15 & 16). Subaerial erosion of this newly created structural high complex produced the conglomeratic material infilling the incised valleys in the Kapp Kåre and Kapp Hanna formations. Fault trends and paleocurrent directions associated with these events indicate main movements along N-S to NNE-SSW directed lineaments with a different alignment from the NW-SE trending Early Carboniferous West Bjørnøya Fault. Conjugate sets of minor faults controlled the general westerly trend of the incised valleys themselves.

Analyses of sandstone mineralogy and conglomerate clast composition in the Kapp Hanna Formation provide additional evidence for basinal evolution at this time (Fig. 15). The clasts were derived from older local units and both clasts and matrix show a well-developed inverse stratigraphy, reflecting the progressive erosion of these units on the newly uplifted graben flanks. The marked dominance of Hecla Hoek clasts in southwestern exposures contrasts with the dominantly Lower Carboniferous clast content of the northwest exposures. This suggests that unroofing and erosion of Hecla Hoek rocks in the south and southeast of the island happened largely during deposition of the Kapp Hanna Formation, so that this syntectonic depositional phase apparently involved tilting and creation of most accommodation space in the north and northwest. This interpretation is supported by the inland outliers of coarse Kapp Hanna conglomerates and by several features in the Kapp Dunér Formation discussed below; this also suggests that much of the present exposure pattern on the island essentially reflects Late Carboniferous faulting, subsequently modified by early Permian uplift and peneplanation of the entire area (Fig. 16).

The incised valleys and the irregular relief produced by this tectonic phase were not completely infilled during the Gzelian: uppermost fine clastic beds in valley fills in Nordvestbukta (Fig. 17), for example, contain fusulinids with a clear Asselian aspect; these beds apparently correlate with carbonates from the upper parts of the overlying Kapp Dunér Formation in westernmost

exposures. Similar deposits occur above thin Kapp Hanna lithologies on Raudnuten, possibly also in isolated localities south of Miseryfjellet and in at least one of the half-grabens described from the southern cliffs

(Fig. 4), suggesting that the Kapp Hanna Formation was only locally deposited over most of the eastern and southern parts of the island - and then only in the fault-defined incised valleys.

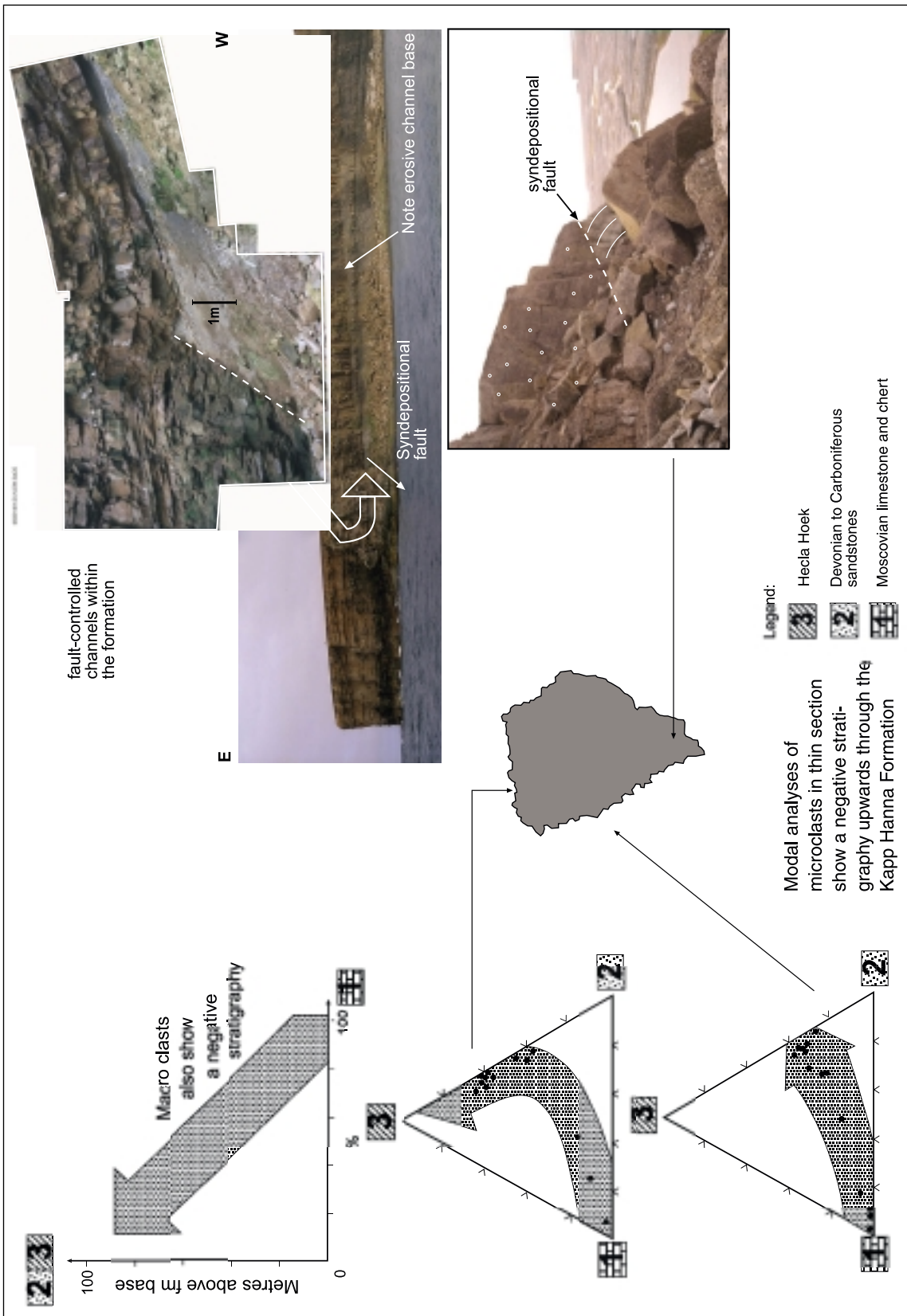


Fig. 15. Clast compositions in Kapp Hanna Formation conglomerates, showing variations upwards in the formation, in mosaic with other critical exposures showing channelling in the formation.

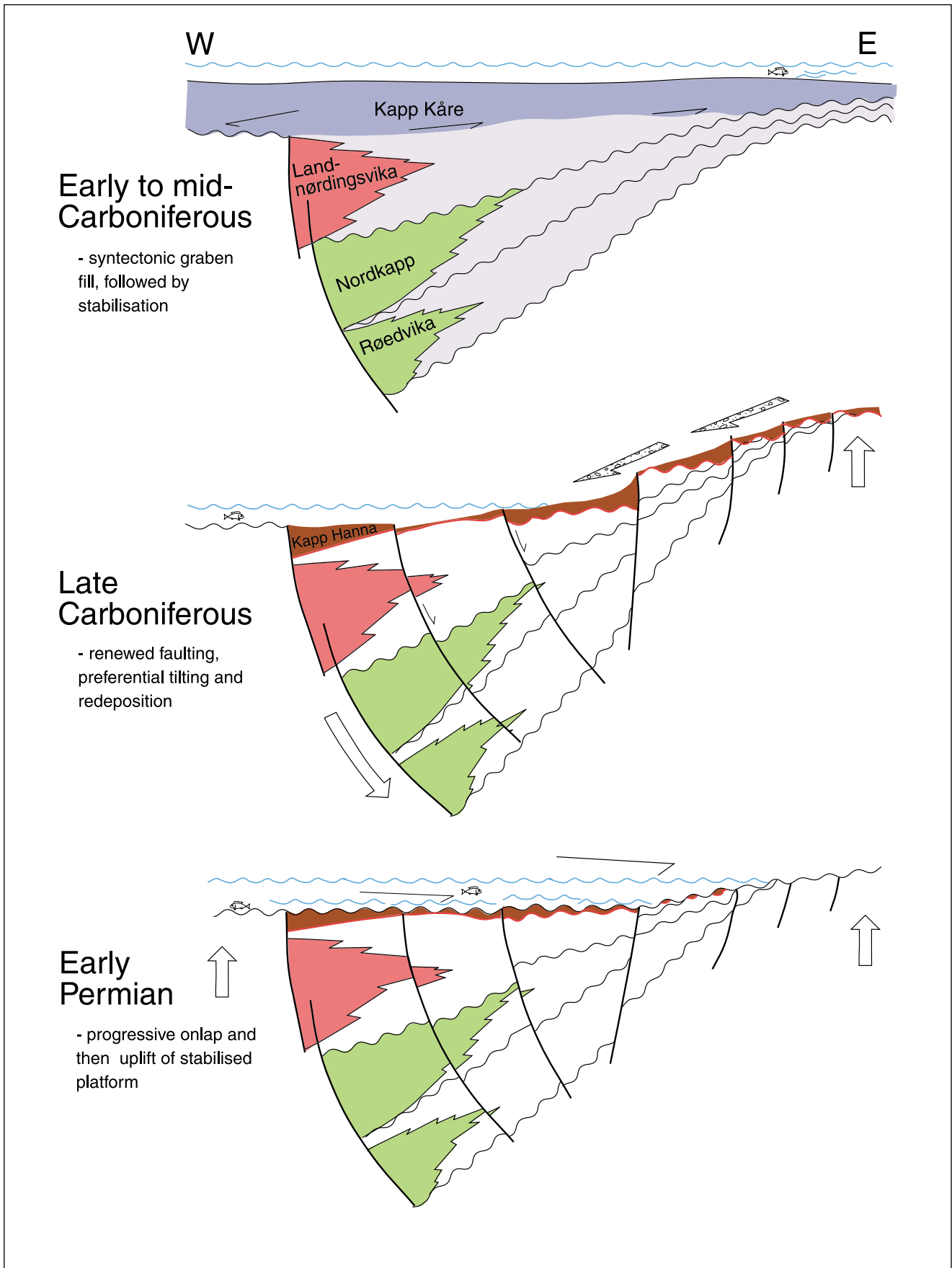


Fig. 16. Schematic cross-section to illustrate the early Carboniferous to early Permian development of Bjørnøya as suggested in our new interpretations presented herein.

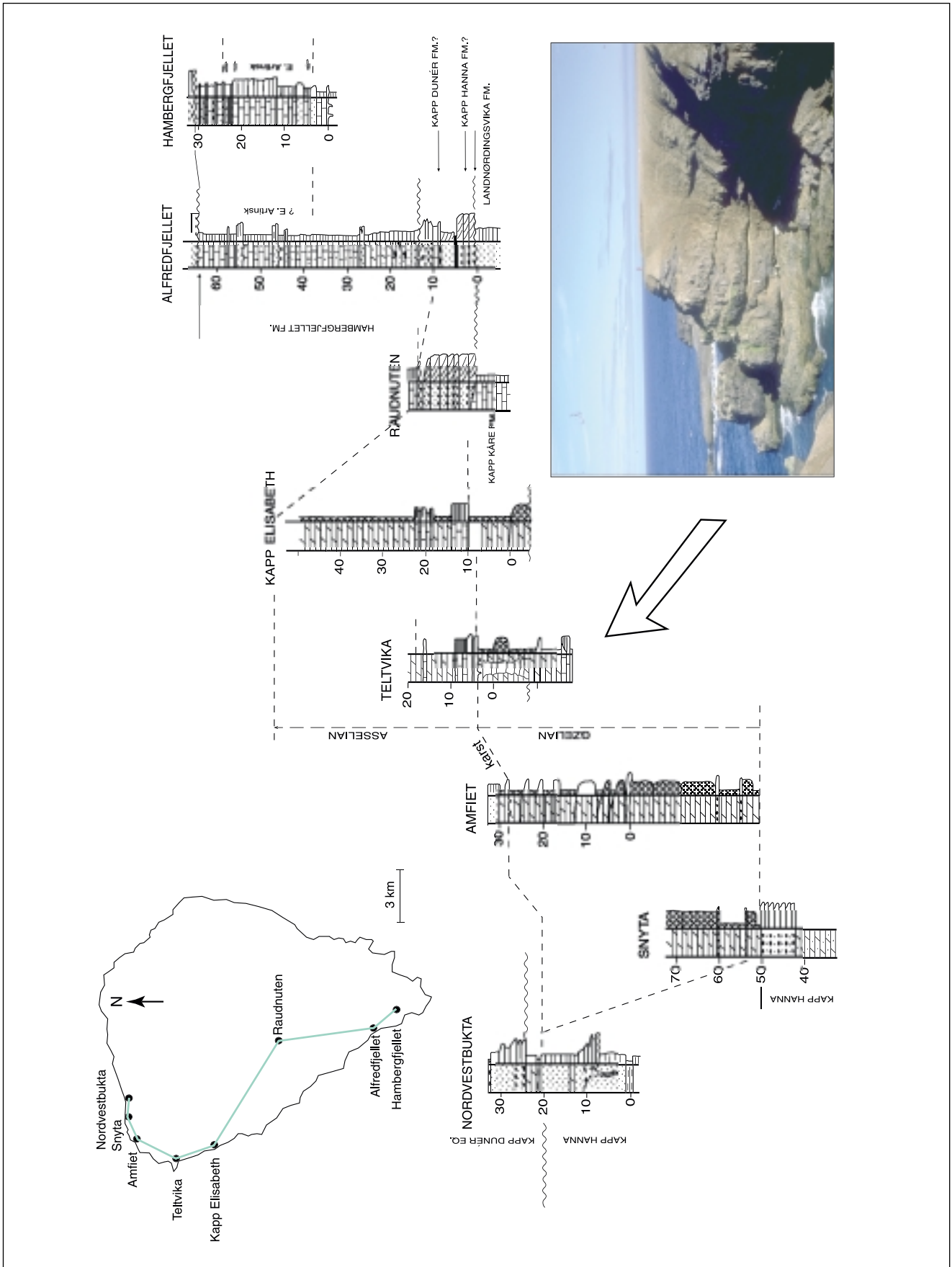


Fig. 17. Correlation of several partial sections through the Kapp Dunér Formation with (inset) an example of stacked palaeoaplysineid buildups.

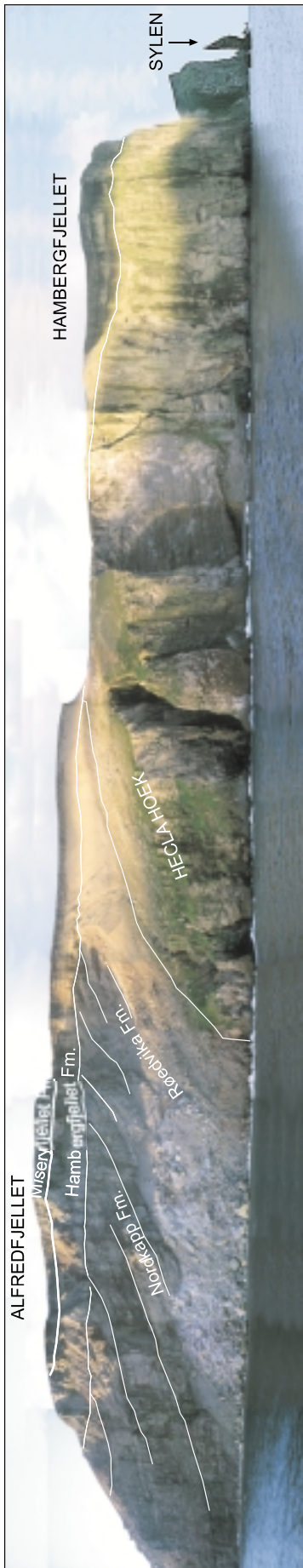
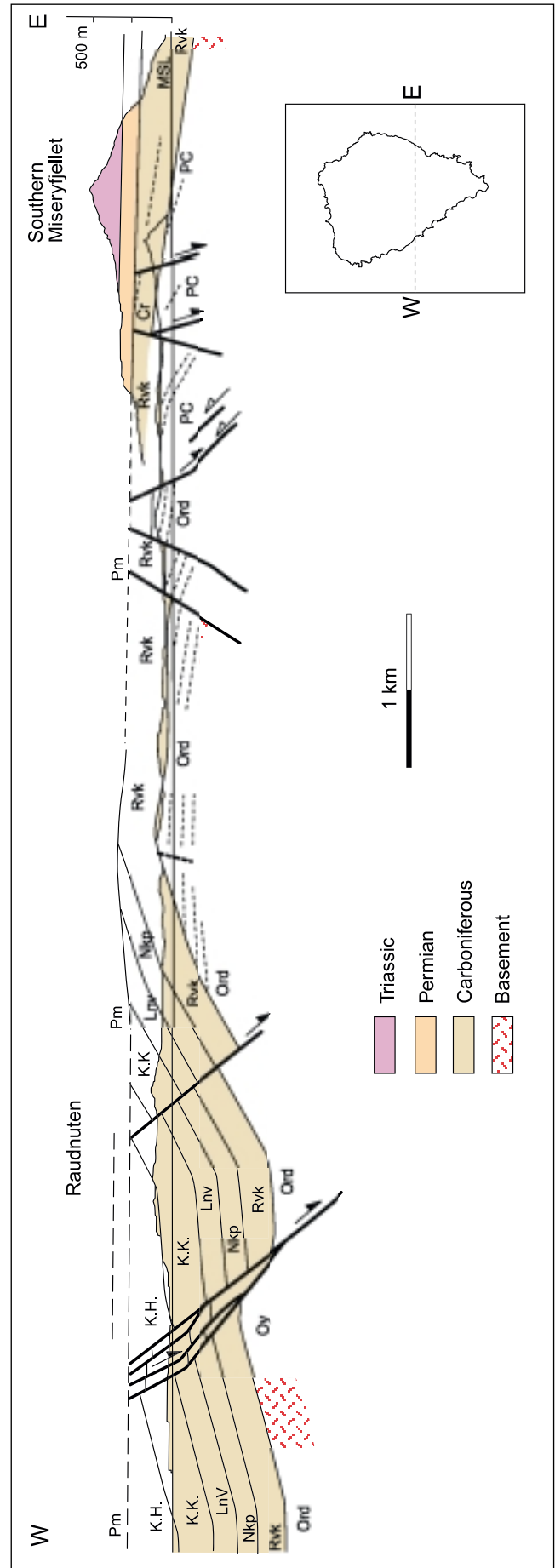


Fig. 18. A digital photo-mosaic of the southwestern cliffs of Alfredfjellet based on a photo-series taken in August 1995 in unusually clear weather shows the relationships between various Carboniferous to Permian units and the Hecla Hoek basement.

Fig. 19. A reinterpreted W-E cross-section through Bjørnøya by H. Maher (pers. comm. 1996), which should be compared with that of Horn & Orvin (1928).



Mid-Gzelian to Asselian stabilization

The upper parts of the Kapp Hanna Formation show a marked fining trend into interbedded thin sandstones and dolomitic mudstones, reflecting increasing local tectonic stability and a relative rise in sea level. The transition to the carbonates of the Kapp Dunér Formation is marked by the development of two thick beds of massive dolomite intercalated with thinly bedded dolomitic mudstones, wackestones and packstones (Fig. 17). The former are interpreted as highly dolomitized tabular bioherms and biostromes; they show striking similarities to the contemporaneous paleoaplysiniid build-ups of central Spitsbergen described by Skaug et al. (1982).

Kapp Dunér mounds -- The two lowermost tabular mound sets are overlain by a karstic surface with 2 m relief before deposition of more paleoaplysiniid build-ups with a lenticular cross-section. Pronounced long axes in these lenticular structures show a NNE-SSW trend (Fig. 6) and individual 5-7 m thick build-ups are dominated by large-scale accretionary surfaces directed perpendicularly to this trend both to the WNW and ESE. These represent a flank facies formed by lateral migration of the structures following vertical growth to the surf zone. Talus washed from the build-ups' core was stabilized on the flanks by the building activity of framework organisms such as corals, bryozoans and stromatoporoids; back-reef facies to the east of the buildups are characterised by lagoonal wackestones and mudstones. Although binding organisms and other faunas are seen only as vague ghosts, some of these structures appear to show a marked ecological succession from base to top, frame-building organisms increasing from 20 % to 60 % upwards in each build-up. Bituminous limestones and dolomites are common in the inter- and back-mound sequences; Siedlecka (1972, 1975) and Folk & Siedlecka (1984) have described the "schizohaline" environments represented by parts of these sequences: faunas and petrography suggest both restricted hypersaline and open marine environments.

This total association, described in detail by Lønøy (1988), Stemmerik & Larssen (1993) and Stemmerik et al. (1994), is similar to that of the penecontemporaneous Brucebyen Bed of central Spitsbergen (Skaug et al. 1982), although the Bjørnøya sequence is more highly dolomitized. In both areas build-ups developed in sites which had been tectonically active in the Carboniferous. In central Spitsbergen, build-ups developed parallel to the Billefjorden Lineament along the earlier Nordfjorden Block's eastern margins; they also extended some distance out into the adjacent basin. We cannot establish the original lateral extent of the build-ups in the Bjørnøya area, but both axial and accretionary trends conform to the basinal pattern suggested by the underlying Kapp Hanna sequences.

Ongoing Asselian transgression -- Uppermost lenticular mound horizons are overlain by another pronounced karstic surface. The overlying 40 metres of the formation

consist of bedded dolomites without build-ups; these beds represent deposition in lagoonal to restricted shelf environments through the Late Asselian. Deposition in the west was accompanied by onlap of the positive and still emergent areas to the east and southeast; the entire high was probably transgressed before renewed tectonism and uplift in the Sakmarian. The present-day exposed top of the Kapp Dunér Formation on the western coast probably approximates to the eroded surface resulting from these Sakmarian movements; fractures and fissures up to about 10 m deep are filled with clasts and sediments of presumed mid- to Late Permian age.

The major erosional surface overlying the mounds in the middle of the formation is correlated with a regional relative fall in sea level in the Late Gzelian now recognised over large areas of the Barents Shelf (*c.f.* Cecchi 1992). The subsequent Asselian transgression progressively overlapped the entire Bjørnøya area, as shown by the crucial exposures in Nordvestbukta, on Raudnuten and in the southern cliffs (Fig. 4). As mentioned previously, the incised valley observed in the Kapp Hanna Formation in Nordvestbukta has an uppermost infill of Asselian age, directly overlying? Kasimovian coarse clastics. On Raudnuten (Simonsen 1988; Stemmerik et al. 1994), fusulinids in thin limestone beds that directly overlie both Kapp Kåre and Kapp Hanna Formation lithologies indicate late Asselian age. At least one of the previously unrecognized small graben structures in the southern cliffs contains bedded carbonates which we consider to be lateral equivalents to the upper parts of the Kapp Dunér Formation in its main exposure area (Figs. 4 & 17), with fusulinids confirming the model presented above for onlap and evening of fault and erosional relief during the late Asselian. Smaller scale variations in the entire formation, with numerous karstic surfaces, probably also reflect high-frequency local tectonic pulses (Stemmerik & Larssen 1993).

Present exposures of the Kapp Dunér Formation in the western and northwestern cliffs of Bjørnøya are at least 90 m thick, but uppermost beds exposed dip seawards and the unit appears to thicken in the same direction on the limited seismic lines available so that the exposures onland may represent just the easternmost proximal part of a larger complex. The formation apparently outcrops on the seafloor up to 3 km off the western coast before passing up into presumed mid- to Upper Permian sequences further offshore.

Early to mid-Permian uplift and peneplanation

Renewed uplift during the Sakmarian and/or early Artinskian resulted in the final sculpting of the entire area, producing a broad, apparently gentle and slightly asymmetric anticline which is cut by large numbers of N-S trending largely normal faults. The axis of this structure corresponds roughly to the margins of the Late Carboniferous high, with the more steeply dipping western limb containing the Upper Carboniferous to lower-

most Permian basinal sequences. Our new model suggests that most of the structuring of the area occurred in the late Carboniferous rather than the early Permian.

Largely extensional faulting affects the Carboniferous sequence, with a N-S direction and dip-slip westerly downthrow. The large-scale compressional features advocated by Krasilscikov & Livsic (1974) as being Tertiary in origin could equally well be reverse drag phenomena, produced by movements along listric normal faults during the late Carboniferous (Fig. 16). Although some lateral movement with a compressional element may be suggested by isolated faults, and by the small-scale horizontal slickensides cross-cutting the earlier phase of dip-slip movements, these are minor in comparison to the bulk of the faulting. The following salient points should be noted:

- No major faults affecting the Upper Devonian to Lower Permian succession extend upwards into the Upper Permian strata,
- Horizontal slickensides post-date other indicators of movement, but again are not observed in Upper Permian strata,
- Fault frequency in outcrop decreases markedly upwards stratigraphically and very few minor faults can be demonstrated to affect the relatively large coastal exposure line of the Kapp Dunér Formation, as compared to the high fault frequency observed in the Kapp Hanna and Kapp Kåre formations.

Using this interpretation, early to mid-Permian uplift, peneplanation and erosion was probably minor, on the scale of up to 100 to 200 m in the eastern and southern parts of the island, rather than the 1 - 2 km apparently suggested by cross sections of earlier workers (notably Horn & Orvin 1928), which did not recognize the nature and extent of the Late Carboniferous tectonism. These eastern and southern areas were thus essentially sites of uplift and erosion from Late Moscovian Kobbekbukta Member time onwards, penecontemporaneous with deposition immediately further west; these areas were only demonstrably transgressed during the Late Asselian immediately prior to regional uplift.

Stabilization of the Stappen High

Major tectonic movements had ceased prior to the deposition of the carbonates of the Hambergfjellet Formation, so that neither this nor younger units are affected by any significant faulting or show large-scale angular unconformities.

The *Hambergfjellet Formation* forms an up to 60 m thick sedimentary wedge, which is preserved only on the island's southwestern mountaintops (Fig. 18). The unit thins rapidly northwards and eastwards: it oversteps all older sequences before itself being overstepped by the

mid- to upper Permian Miseryfjellet Formation. There is a minor angular unconformity between the two formations, so that some additional rotation did occur between these two depositional phases. Rotation was accompanied by some local, probably slide-induced contortion of the Hambergfjellet Formation; this is seen most clearly in the half-grabens noted earlier, where there was small-scale renewed movement before deposition of the overlying Miseryfjellet Formation. Only one of these structures (on Alfredfjellet) shows pronounced faulting affecting the Hambergfjellet Formation and extending down into the underlying Nordkapp Formation (Fig. 4).

The largely inaccessible cliff exposures of the Hambergfjellet Formation have not yet been studied in any detail. Basal fossiliferous sandstones pass up into sandy packstones and grainstones with a rich and varied marine fauna of bryozoans, crinoids and brachiopods. The fauna is similar to that found in the upper parts of the Gipsbukta Formation of Spitsbergen, generally thought to be latest Sakmarian to Artinskian in age. This correlation suggests a regional transgression which elsewhere resulted in deposition of open marine limestones over a thick sequence of platform dolomites and/or sabkha evaporites. Even thicker equivalents in offshore wells in the Barents Sea (Fig. 20) show a packstone/wackestone limestone development with no dolomites, contrasting to the underlying dolomites and evaporites (Larsen et al. in press). Faunas are also markedly different and offshore wells have penetrated prominent carbonate build-ups containing bryozoans and *Tubiphytes*, in contrast to the underlying paleoaplysiniid and algal build-ups. These and other biota suggest a transition to the cooler water conditions of the Late Permian (Stemmerik 1997). Although no reefal facies are seen in the thin onlapping development of the Hambergfjellet Formation on Bjørnøya, cooler water biotic elements are common and skeletal remains are often partially silicified. Although lacking the pervasive silicification of the overlying beds, all of these features prompt our allocation of the unit to the newly defined Bjarmeland Group (Dallmann 1999) rather than the Gipsdalen Group. A strikingly similar development is shown by the contemporaneous Great Bear Cape Formation of the Sverdrup Basin (Beauchamp et al. 1989; Beauchamp & Henderson 1994) and the lowermost Kim Fjelde Formation of North Greenland (Håkansson & Stemmerik 1989; Stemmerik et al. 1996; Stemmerik 1997).

The Hambergfjellet Formation may have primarily been deposited over the whole Bjørnøya area and then preferentially eroded in the north during tilting prior to deposition of the Miseryfjellet Formation. Equally, the present wedge may be a primary depositional feature, perhaps reflecting preferential subsidence of the southern part of the newly formed Stappen High. Neither remnants nor clasts of Hambergfjellet lithologies are found at the unconformable contact between the Nordkapp and Miseryfjellet formations in the northern parts

PERIOD	AGE	GROUP	FORM.	BJØRNØYA	ESSE	SAGA	STATOIL
PERMIAN	ARTINSKIAN - GAZEL	GIPSDALEN	KAPPE HANNA, KAPPE KÅPE, KAPPE HANNA, KAPPE HANNA, KAPPE HANNA	SHALLOW MUDDY SHELF	OPEN MARINE	BASINAL	BASINAL
				SHALLOW MARINE AND COASTAL PLAIN	OPEN MARINE	OPEN MARINE PLATFORM	OPEN MARINE PLATFORM
CARBONIFEROUS	VISÉAN - MOSCOV	BILLEFJORDEN	NORDKAPPE, LANDNØRDSINGVYKA	SHALLOW MARINE AND COASTAL PLAIN	OPEN MARINE	BASINAL	BASINAL
				SHALLOW MARINE AND COASTAL PLAIN	OPEN MARINE	OPEN MARINE PLATFORM	OPEN MARINE PLATFORM
DEVONIAN	FAMENNIAN	RØDVIKA	HECLA HØEK	SHALLOW MARINE AND COASTAL PLAIN	OPEN MARINE	BASINAL	BASINAL
				SHALLOW MARINE AND COASTAL PLAIN	OPEN MARINE	OPEN MARINE PLATFORM	OPEN MARINE PLATFORM
PRE-DEVONIAN				SHALLOW MARINE AND COASTAL PLAIN	OPEN MARINE	BASINAL	BASINAL

Fig. 20. Correlation of the Late Palaeozoic succession of Bjørnøya to offshore wells on the southwestern Barents Shelf, including 7120/2-1 in a near-crestal position on the Loppa High, passing eastwards into three wells drilled in more normal platform situations.

of the island. It may also be significant that conglomerates with clasts similar to those in the Miseryfjellet Formation directly infill karstic fissures in the present-day truncated top surface of the Kapp Dunér Formation on the NW coast. These features together suggest that the northern parts of present-day Bjørnøya were not the site of deposition of any significant Hambergfjellet equivalents.

The Miseryfjellet Formation consists of a 115 m thick sequence of silica-cemented sandstones and limestones (Fig. 21), which unconformably overlie all older units exposed on the island. Although clearly assignable to the Tempelfjorden Group, the sequence lacks the typical development of spiculitic shale seen in the more basinal situations represented by the Kapp Starostin Formation of central Spitsbergen. Both litho- and biofacies suggest shallow, high energy depositional environments on the newly stabilized and submerged - but still positive - structural high which had developed after the cessation of faulting activity earlier in the Permian.

As mentioned above, karstic features are seen in exposures of the uppermost Kapp Dunér Formation. These are up to 10 m deep and 1.5 m wide, and they postdate both consolidation and tilting of the older unit. The structures are infilled with clasts typical of the basal development of the Miseryfjellet Formation seen elsewhere on the island. Occasional small hillocks of frost-shattered sandstone blocks are seen scattered on the northern plain of Bjørnøya. We interpret these as eroded outliers of the Miseryfjellet Formation's basal sequence rather than primarily ice-moved material as previously assumed (*c.f.* Horn & Orvin 1928, Salvigsen & Slette-mark 1995). Thus the entire northern plain of the present-day island approximates to the peneplain upon which the basal sandstones of the Miseryfjellet Formation were deposited.

The karst features show that the dolomites of the Kapp Dunér Formation were well cemented by the onset of the Late Permian transgression. In contrast, basal sandstones of the Miseryfjellet Formation in northeastern exposures show vertical burrows of *Skolithos* extending down into the underlying sandstones of the Nordkapp Formation. This indicates that at least the near-surface of these sands was poorly consolidated in the mid-Permian, although exposures only a few metres beneath the contact show faulting and fracturing with slickensides indicating, as discussed earlier, brittle deformation in at least two phases between the early Carboniferous and mid-Permian. The poorly consolidated sands must reflect early Permian subaerial erosion of exposed and previously cemented sandstones rather than poor consolidation of the entire formation at the time.

The Miseryfjellet Formation's basal conglomerates and sandstones pass up into irregularly bedded sandy packstones and grainstones with distinctive silica cement. These shallow shelf limestones contain a rich shelly fauna, including unusually large individuals of

the same brachiopod taxa found elsewhere in the Upper Permian Kapp Starostin Formation of Svalbard. An up to 20 m thick sandstone developed in the middle of the formation contains both tabular and low-angle cross-bedding and *Skolithos* burrows (Fig. 21). This unit is interpreted as a shoal complex paralleling the margins of the earlier Gzelian high, suggesting continued subtle tectonic controls on facies patterns in the area (Fig. 6). These exposures represent a very condensed development of the Tempelfjorden Group, comparable to the even more highly attenuated few metre thick succession seen along the eastern margins of the Sørkapp-Hornsund High in southern Spitsbergen (Hellem & Worsley 1978). The continued positive nature of the Bjørnøya area throughout the Late Permian is therefore clear.

Triassic sediments

The shale-dominated Triassic sequence, exposed on the highest peaks in the SE of the island, is approximately 200 m thick and rests disconformably on the uppermost resistant limestones of the Miseryfjellet Formation (Figs. 21 & 22). The lowermost 65 m (the Urd Formation of Pchelina 1972; Mørk et al. 1982) is assigned to the Sasendalen Group - elsewhere in Svalbard assigned to the early to mid-Triassic. Basal beds contain erosional products of underlying Permian sediments, a similar basal development to that seen on Edgeøya. Palynological studies indicate that the earliest Triassic is not represented - oldest datings suggest a Dienerian age (Mørk et al. 1990, 1992). A poorly preserved ammonoid fauna of Smithian age occurs in the middle and upper parts of the formation (Pchelina 1972). The lack of Spathian and Anisian palynomorphs indicates sporadic deposition, with major breaks, through to the Late Ladinian.

The Urd Formation comprises silty marine shales comparable in thickness and development to the condensed Lower Triassic sequences seen on the Sørkapp-Hornsund High of southern Spitsbergen. A significant marker at the top of the formation is the Verdande Bed - a 20 cm thick bed of remanié phosphorite concretions, some with the distinctive "petroliferous odour" noted by Hoel & Orvin (1928). This bed is correlated with the organic rich shales with phosphorites deposited elsewhere in Svalbard during the mid-Triassic. The remanié clasts suggest that deposits initially formed during a regionally widespread Anisian transgression were subsequently locally uplifted and eroded. However, no similar condensed units are seen elsewhere at this horizon - indeed this was a time when there were fewer and smaller differences between basinal and block subsidence patterns than either earlier or later in the region's evolution. The remanié bed itself may represent the basal transgressive conglomerates of the Upper Triassic sequence, although its lithology has led it to be included in the Urd Formation by Pchelina (1972, 1983) and by Mørk et al. (1989, 1990, 1992).

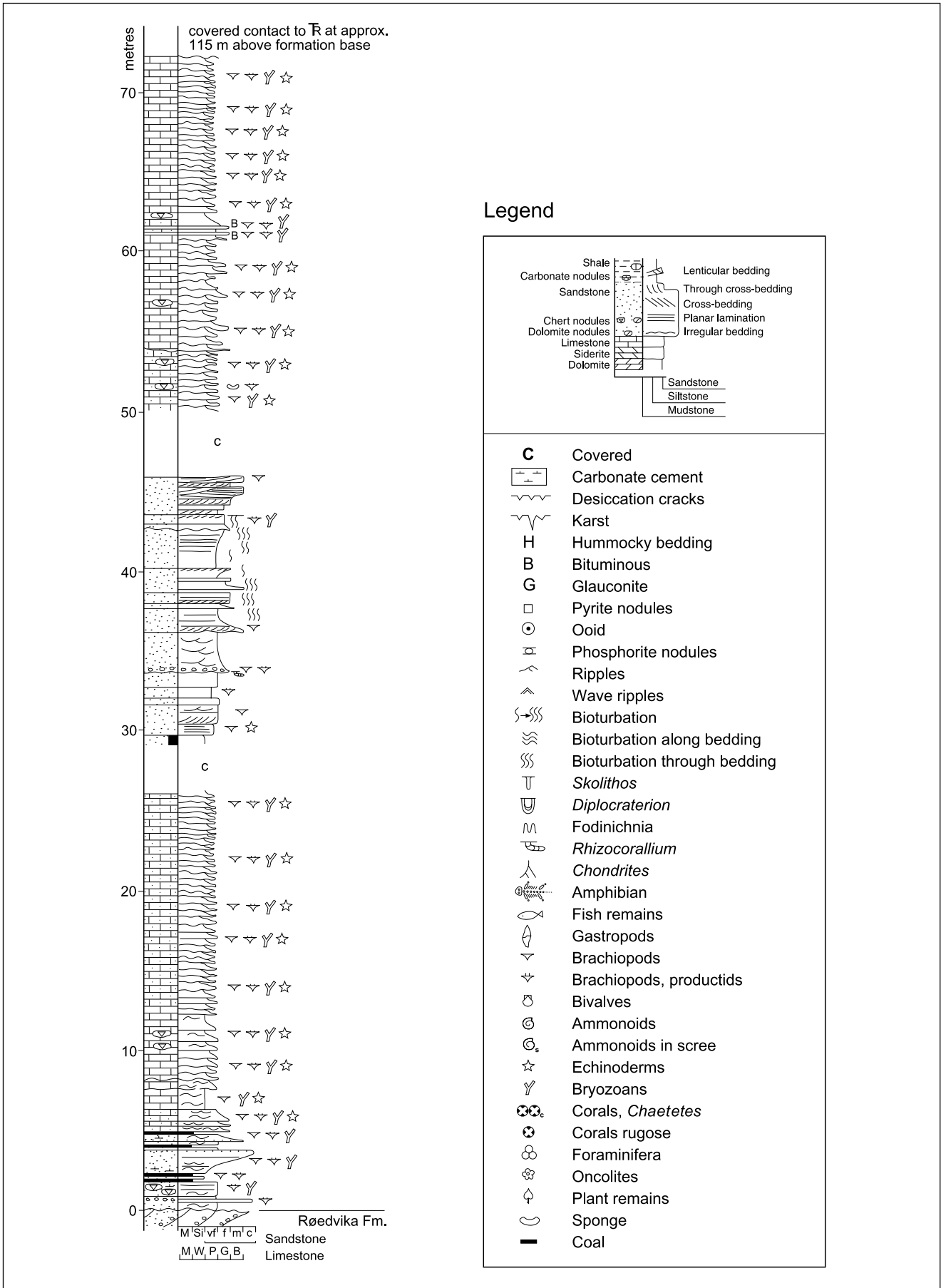


Fig. 21. A summary log through the Miseryfjellet Formation in its type area.

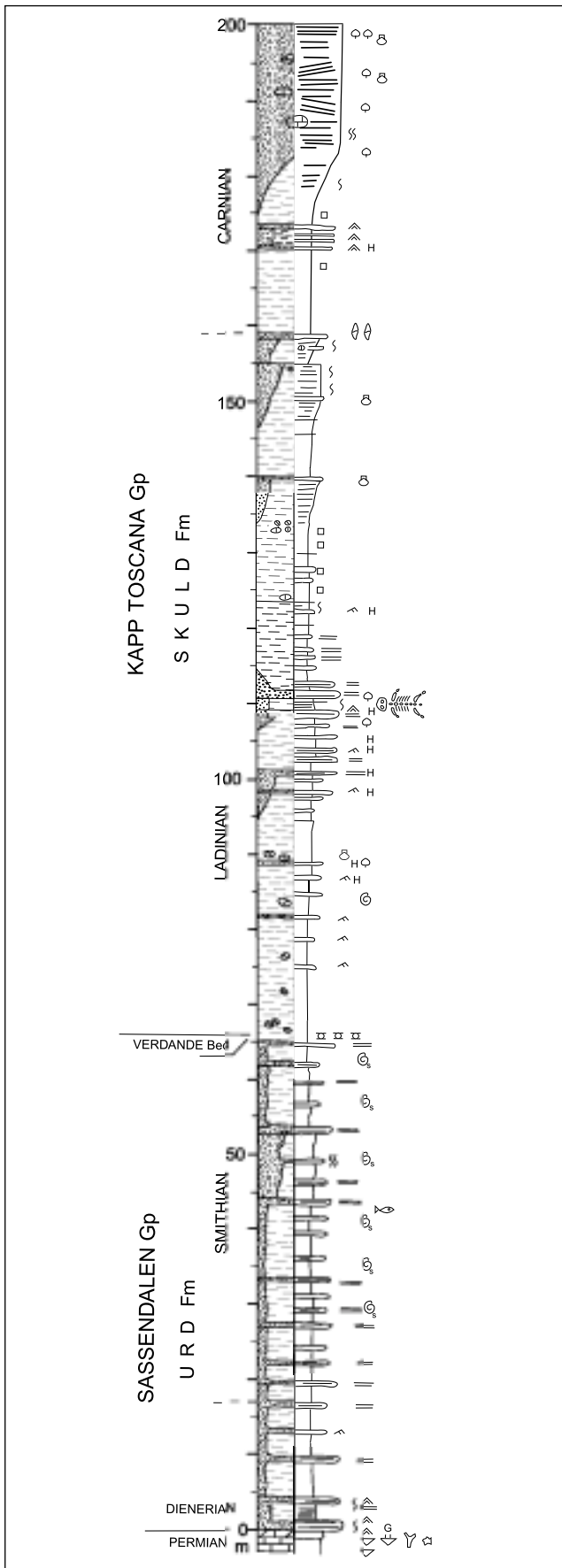


Fig. 22. A summary log through the Triassic succession in the Miseryfjellet area, based on Mørk et al. (1990). Legend in Fig. 21.

The 135 m thick Skuld Formation, which is preserved on uppermost mountain peaks, forms a major coarsening upward succession defined by several minor rhythms (Mørk et al. 1990, 1992). The basal beds consist of bluish-grey shales with purple weathering siderite nodules similar to those seen in the Tschermakfjellet Formation elsewhere on Svalbard. The basal beds (of Late Ladinian age) represent a shallowing upwards pro-deltaic facies. Rippled thin sandstone-shale alternations in the middle part of the formation have yielded a three metre long amphibian (Lowy 1949; Mørk et al. 1990); hummocky bedding and wave ripples and occasional marine fossils indicate deposition in shallow shelf environments. An ammonoid fauna found in the upper part of the formation is diagnostic of the Ladinian/Carnian transition (Dagys et al. 1993). The top of the formation, on the highest peak of Miseryfjellet, consists of a 20 m thick sandstone of Carnian age. The development of the Skuld Formation is not remarkably different, either in thickness or facies development, from the lower parts of other penecontemporaneous coarsening and shallowing upwards sequences seen throughout Svalbard. Comparisons with the Austjøkelen Formation (c.f. Mørk et al. 1982) of southern Spitsbergen, for example, suggest that the Skuld sequence originally passed up into deltaic deposits only a matter of metres above the present youngest preserved exposures.

Subsequent history

The broad features of the subsequent evolution of the area can be partially reconstructed from the results of organic geochemical and other thermal maturation studies (Bjørøy et al. 1983; Ritter et al. 1996) and by comparisons with the history shown by geophysical studies of the adjacent shelf (Rønnevik et al. 1982; Rønnevik & Jacobsen 1984; Faleide et al. 1984; Nøttvedt et al. 1992). Bjørøy et al. (1983) suggested a post-Triassic overburden in the range of "a few kilometres" based on vitrinite reflectance data ranging from 0.9 to 1.5 % R_o in the upper part of the oil window. Ritter et al. (1996) used these and additional vitrinite reflectance data to estimate maximum burial temperatures to somewhat over 160 °C on the north coast and 150 to 160 °C further south on the island. These apparent local variations may either reflect early oxidation (perhaps related to Late Carboniferous uplift) or slightly varying depths of maximum burial at some post-Triassic stage in the island's development. The present-day base of the Miseryfjellet Formation outcrops between 200 and 350 m above sea level on Miseryfjellet and in the southern cliffs, while it is near sea-level in outliers on the northern plain; this is a result of gentle northerly downtilting of the entire platform, away from the highest point on the Stappen High represented by the basement massif in the south of Bjørnøya; this differential is enough to have produced these variations - if the present tilting also reflects varying maximum burial at some stage in the late Mesozoic or Palaeogene.

Palaeogeothermal gradients estimated from the vertical vitrinite reflectance profile at Miseryfjellet range from less than 10 °C/km to over 40 °C/km. A geothermal gradient of 30 °C/km (not unreasonable in view of nearby measurements of present-day heatflow by Sættem et al. 1994) would indicate that 4 to 5 km of post-Permian overburden has been eroded; extrapolations based on sonic velocities in the Triassic shales indicates about 3 to 4 km of eroded section. Apatite fission track data indicate cooling below ~100 °C, beginning at some time during the late Cretaceous to early Tertiary (60 to 90 Ma). Ritter et al. (1996) used all of the available data (including fluid inclusions in the Nordkapp Formation's sandstones) to construct an "optimal" thermal history. However, their reconstructed burial curve for the base Røedvika Formation takes no account of the complex block development through the Late Carboniferous and indicates massive and - in our belief - unrealistic mid-Permian uplift. Figure 23 presents a reinterpreted burial curve based on the tectonic models proposed here.

The total maximum post-Palaeozoic overburden suggested by these studies is thus in the range 3 to 5 km. Axial parts of the Tertiary Central Basin of Spitsbergen appear to have had a maximum total primary thickness of about 3 km of Mesozoic sediments, while estimates suggest thicknesses in the order of 10 km in the central

parts of the Bjørnøya Basin to the SE of the Stappen High. In comparison, Triassic to lowermost Jurassic exposures in several northern areas of the Svalbard archipelago show very low (< 0.3 % Ro) vitrinite reflectances, implying minimal later overburden. The estimate for Bjørnøya is therefore "mid-range" and in no way suggests that the area remained a structural high throughout the Mesozoic. The present-day horst structure of the Stappen High therefore probably represents final moulding by the early to mid-Tertiary transpressive movements that preceded the opening of the Norwegian-Greenland Sea. These movements rejuvenated the Late Palaeozoic high, leading to erosion of an appreciable cover of Upper Triassic and younger Mesozoic sediments.

We reiterate that the complex faulting and fracturing seen to affect the Carboniferous to Lower Permian succession of Bjørnøya was a result of pre-Late Permian tectonism. There is no evidence of faults or extensive fracturing affecting Upper Permian or younger units wherever these overlie older rocks. The essential fault patterns displayed on Bjørnøya are therefore not a result of Tertiary tectonism - as has been suggested in several regional reviews: such Tertiary movements seem to have been restricted to the master faults along the Stappen High's present margins.

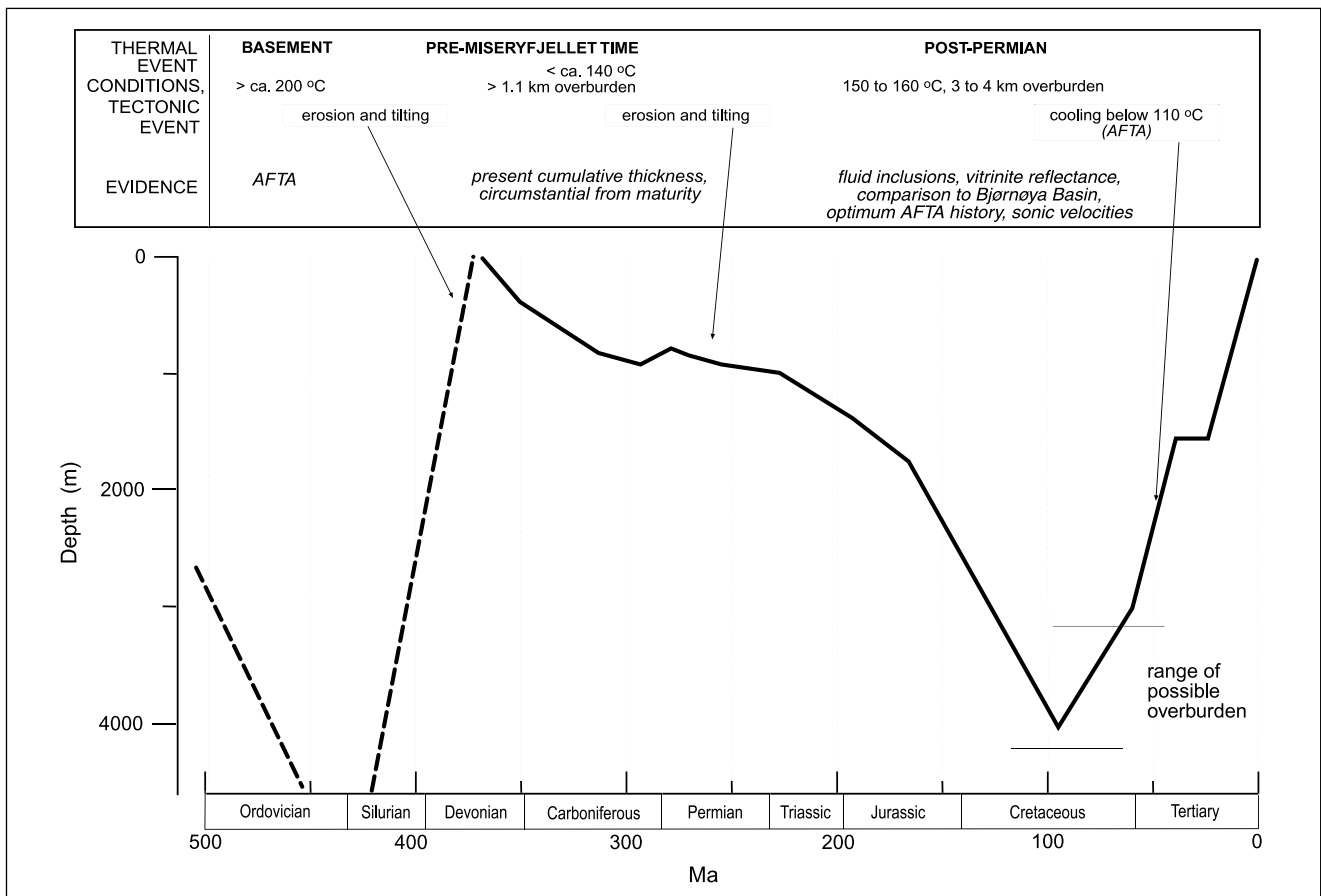


Fig. 23. Modelled post-Triassic depositional and thermal history based on all available data, modified from Ritter et al. (1996).

Comparisons with adjacent areas

In general terms, the Upper Palaeozoic and Triassic succession of Bjørnøya shows many of the same lithofacies seen elsewhere on the Barents Shelf and in the Svalbard archipelago - and indeed in the Wandel Sea (north Greenland) and Sverdrup (Arctic Canada) basins. However, Bjørnøya and some other specific areas show significant differences in their Late Palaeozoic tectonic and sedimentational evolution from the region as a whole.

Spitsbergen

The Billefjorden area of central Spitsbergen (Figs. 11 & 24) was the site of active fault-controlled sedimentation in the early to mid-Carboniferous. Deposition commenced in local narrow basins along the eastern parts of the earlier Old Red Sandstone basin. Inversion in the Tournaisian produced the uplifted Nordfjorden Block on the site of the former Devonian basin, and this was a positive feature throughout the remainder of the Carboniferous. Subsidence along the Billefjorden Fault on the block's eastern margins was at a maximum in the mid-Carboniferous, producing a tilted half-graben (Holliday & Cutbill 1972; Harland et al. 1974; Gjelberg & Steel 1981; Johannessen & Steel 1992). Sediments range from coarse alluvial fans along the graben's westerly faulted margins to playa and sabkha deposits axially. This is a very similar development to that shown by the Landnørdingsvika Formation on Bjørnøya. However, lineamental activity decreased in Billefjorden from the mid-Carboniferous onwards and Upper Carboniferous to Lower Permian carbonate sequences show only small thickness variations between the earlier block and trough, although lateral facies changes suggest continued subtle tectonic controls on sedimentation. Bjørnøya's history of inversion and renewed tectonism is not seen in this area.

Permo-Carboniferous exposures between St. Jonsfjorden and Hornsund on the western coast of Spitsbergen show a different history. These exposures have been poorly understood until recently, partly because of their inaccessibility, but also because Tertiary compression and deformation have obscured primary lateral facies relationships in the area. Steel & Worsley (1984) suggested the development of two or possibly more "en echelon" basins during the mid-Carboniferous. In common with Billefjorden, northwestern areas stabilized through the Carboniferous; however, Harmon Maher (pers. comm. 1995) has noted the existence of conglomerates interbedded with carbonates in the ?upper Carboniferous succession of St. Jonsfjorden. By the Permian there seems to have been one continuous basin, also a westwards tilted half-graben, flanking the eastern margins of a presumed high off the western coast of present-day Spitsbergen; this most likely represented a northerly extension of the Hornsund-Sørkapp High, which is interpreted as actively controlling Late Palaeozoic sedimentation over southern Spitsbergen.

The evolution of the Sørkapp-Hornsund High itself (Figs. 1, 24 & 25) is directly relevant to Bjørnøya. Unfortunately, the few critical exposures in southernmost Spitsbergen are also difficult to interpret because of significant Tertiary deformation. A horst developed in the Bashkirian by the inversion of a wide shallow basin that apparently had covered southern Spitsbergen in the early Carboniferous. Fan deltas were deposited over the horst's eastern margins into the Inner Hornsund Basin in the early Permian (Kleinspehn et al. 1984); these marginal basinal areas were subsequently uplifted before renewed Late Permian sedimentation produced a major progradational wedge of marine siliciclastics, spilling out eastwards into the basin from the high. Thick Upper Permian sequences preserved off the western margins of the high are extensively tectonized and their original depositional site is uncertain. Attenuated Upper Permian sequences are seen locally on the high's eastern margins, but the main part of the structure was not transgressed before the early Triassic. Dienerian basal conglomerates overlie Hecla Hoek, Devonian and Lower Carboniferous sequences in isolated localities on the high itself. Enigmatic exposures on islands and skerries south of the southernmost tip of Spitsbergen indicate that the high continues southwards so that Upper Permian or Triassic strata may rest directly on Lower Carboniferous fluvials there. The highly schematic cross-section of Fig. 25 indicates the main stages in the high's development following basinal inversion in the mid-Carboniferous.

A comparison of Figs. 18/19 and 24/25 highlights the structural similarities between Sørkapp Land and Bjørnøya. The late Palaeozoic fault zones in Sørkapp Land later became the focus of Tertiary tectonism whereas the Stappen High remained a largely stable positive feature in the Mesozoic and Cenozoic and, as noted earlier there is no evidence of major post-Palaeozoic faulting on Bjørnøya. This comparison may also shed some light on the structure which we might expect in the shelf subsurface between southernmost Spitsbergen and Bjørnøya - in general terms the western margin of the Stappen High (the "West Bjørnøya Fault" of Gjelberg & Steel 1983) may represent a strand of the Hornsund Fault Zone, while the high's eastern margins roughly correspond with the expected continuation of the Billefjorden Lineament.

Regional tectonic trends

The relationship between the Svalbard platform, the Stappen High and the southern areas of the Barents Shelf in the Late Palaeozoic is still unclear. Immediately south of Bjørnøya, the Bjørnøya and Tromsø basins (Fig. 1) seem to mark a transition to yet another structural setting which was characterized by more northeasterly basinal trends at the time (Rønnevik et al. 1982; Gudlaugsson et al. 1998). More work is needed to clarify the tectonic relations between these basins and those of the Svalbard Platform. However, seismic studies in these other areas suggest the presence of strikingly similar features to those we

have described from Bjørnøya. The Bjørnøya Basin is bounded to the east by the major Bjørnøya Fault Complex that separates the basin from the Loppa High, a shallow eastwards tilting block. This high was tectonically active throughout the Late Palaeozoic, with repeated movement into the Late Permian (Faleide et al. 1984; Gudlaugsson et al. 1998) and was then progressively onlapped by a condensed Lower to Middle Triassic sequence (Fig. 26). Main depositional units and tectonic events displayed by wells and seismic data on the Loppa High suggest a closely similar but mirror image development to that of the Stappen High: the mid-Permian to Triassic history of the Loppa

High, which can be better documented with the seismic coverage available, is predominantly one of tilting rather than active faulting within the high itself, confirming the similarity to Bjørnøya. The Late Palaeozoic development of these areas may reflect uplift and tectonism over and along the western and eastern flanks of the embryonic Bjørnøya Basin, although major subsidence of the basin itself is a predominantly Mesozoic feature. Indeed some seismic lines in the shallow northern part of the Bjørnøya Basin may suggest that the entire area was uplifted prior to mid-Permian transgression and onset of the rifting which produced the basin itself.

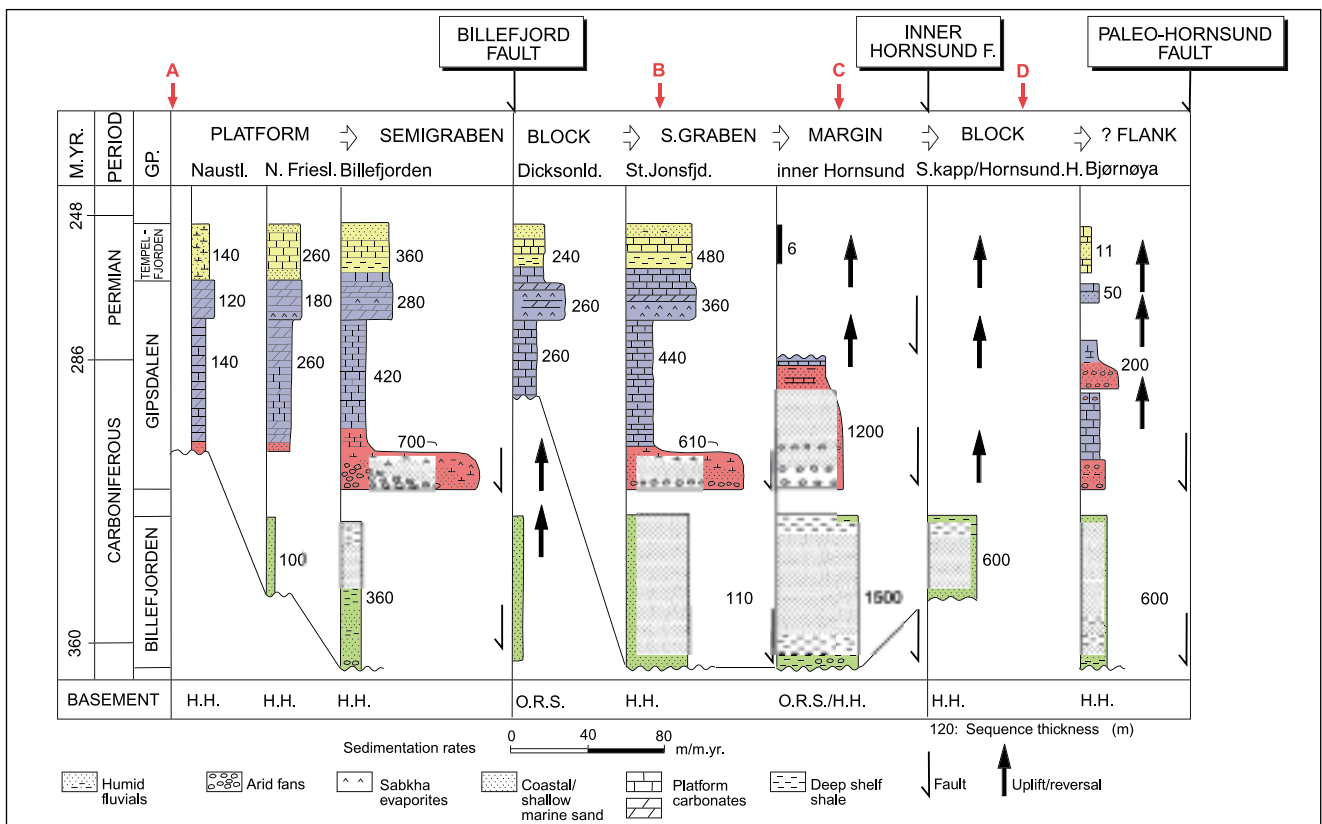


Fig. 24. Comparison of Bjørnøya (right) with schematic cross-sections through central Spitsbergen (A to B), and the Hornsund area (C to D) showing relationships of sediment thicknesses and sedimentation rates between highs and troughs: for positions of Spitsbergen cross-sections, see Fig. 1.

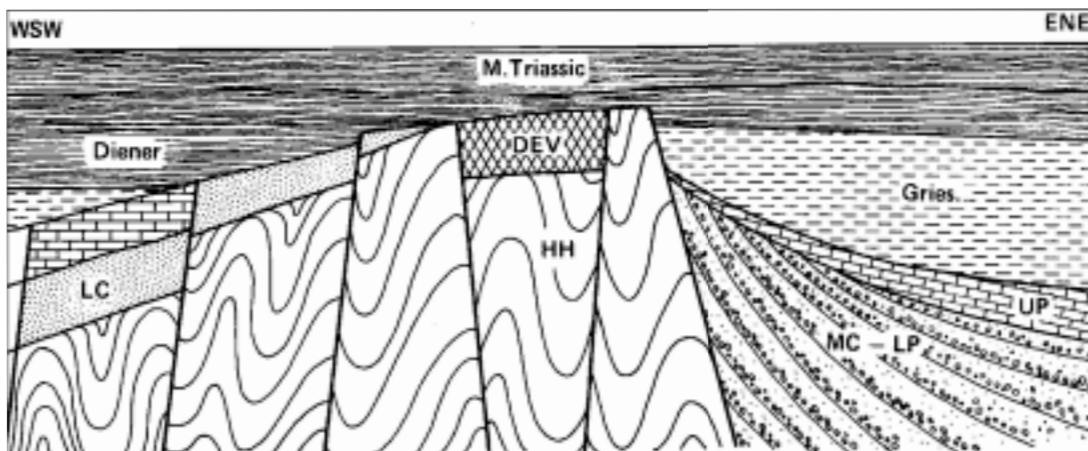


Fig. 25. Highly schematic cross-section indicating possible late Palaeozoic configuration of the Sørkapp-Hornsund High.

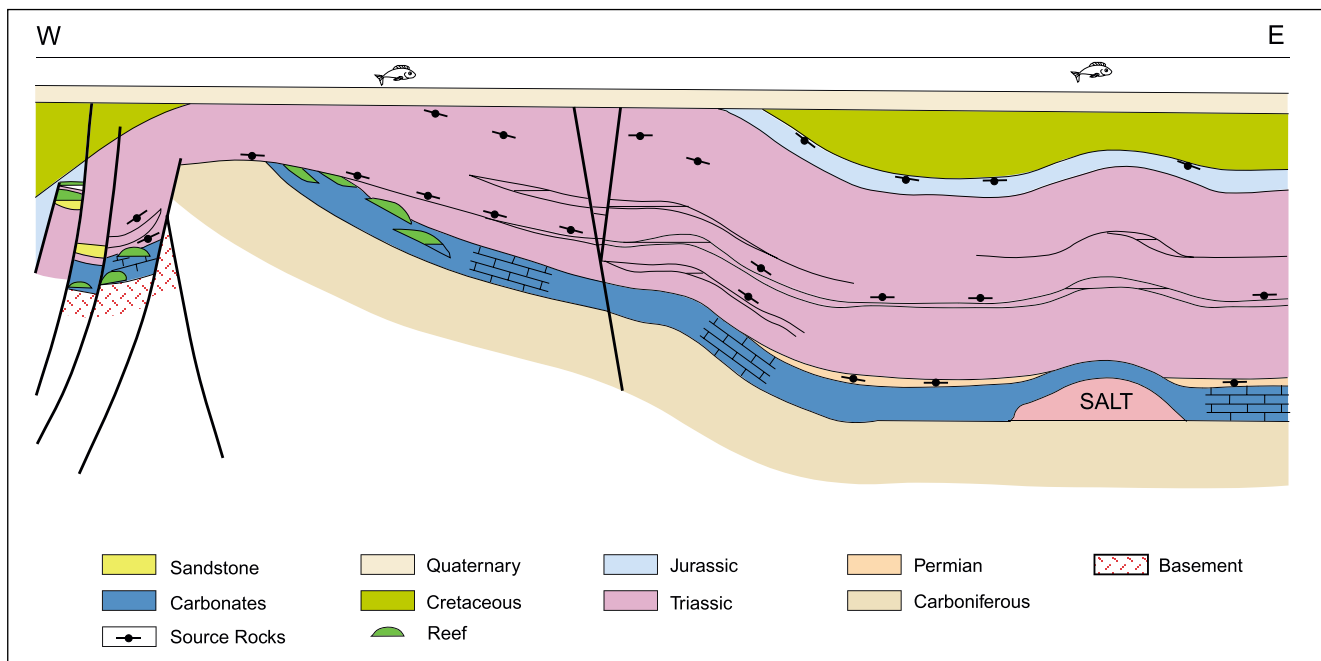


Fig. 26. Condensed and schematic geosection through the Loppa High (W-E as in Fig. 1).

All of these areas parallel and comprise strands of the "Senja-Hornsund alignment" which, as pointed out by Doré (1991), has significant connections to northern Greenland and the Sverdrup Margin, perhaps into the Kaltag Fault Complex of Alaska - representing a long and fundamental line of weakness responsible for repeated major plate movements from the early Palaeozoic to the Cenozoic (Fig. 27). The interplay between this alignment and the Caledonian front systems to the south in the Late Palaeozoic is uncertain, but we should note that marine Carboniferous strata are not known in the Caledonide terrains between subcrops on the southern margins of the Barents Shelf (Bugge et al. 1995) and outcrops in Britain and Poland - apart from highly significant thin Moscovian carbonates preserved in the Oslo Rift (Olaussen et al. 1994). The only known deposits of Carboniferous age along the Norwegian-Greenland margin are the continental sequences of East Greenland (Stemmerik et al. 1992), unconformably overlain by Upper Permian carbonates (following early Permian uplift and erosion). The Greenland exposures and several wells demonstrate the mid-Permian transgression and formation of an intracratonic rift system southwards over the earlier Caledonide chain, giving rise to the Zechstein seaway between the Boreal regions and the evaporitic basins of Central Europe. The penecontemporaneous shift to sediments of the Tempelfjorden Group on the Barents Shelf is related to this major realignment and to major Uralian movements to the east. Bjørnøya represents a significant site near the junction between the two major lineamental systems reflected by the Senja-Hornsund alignment and the proto-Norwegian/-Greenland Rift.

The newly documented evidence of Caledonide thrusting on Bjørnøya and the Stappen High (Gudlaugsson et al. 1998, Braathen et al. 1999) sheds light on the ongoing discussions of relations between Caledonide and Baikalian/Timanide structural grains and their influence on the later geological evolution of the Barents Shelf. Prominent crosscutting trends such as the Trollfjord-Komagelv Fault Complex (Figs. 1 & 27) and related structures with a NW/WNW trend were active through to the early/mid-Carboniferous (Lippard & Roberts 1987; Lippard & Prestvik 1997; Gudlaugsson et al. 1998) and evidently constrained and controlled the development and morphology of the Nordkapp and Hammerfest basins. However, there were only minor movements along these trends after the mid-Carboniferous and active tectonism such as displayed on Bjørnøya is limited to the North-South trending strands of the Senja-Hornsund alignment.

Wandel Sea and Sverdrup basins

Other relevant aspects of Late Palaeozoic activity along the projected extensions of the Senja-Hornsund alignment and its expected related lineaments should also be noted:

- The Upper Palaeozoic succession of the Wandel Sea Basin in northern Greenland has earlier been compared in general terms to that of Svalbard and the Barents Sea (Stemmerik & Worsley 1989). Recent work (Stemmerik et al. 1996) suggests that the entire area was subjected to uplift from the Asselian to the Artinskian. Significant thickness and facies variations in both under- and overlying units are related to movements along the Trolle Land and Harder Fjord Fault complexes (Håkansson 1979; Håkansson &

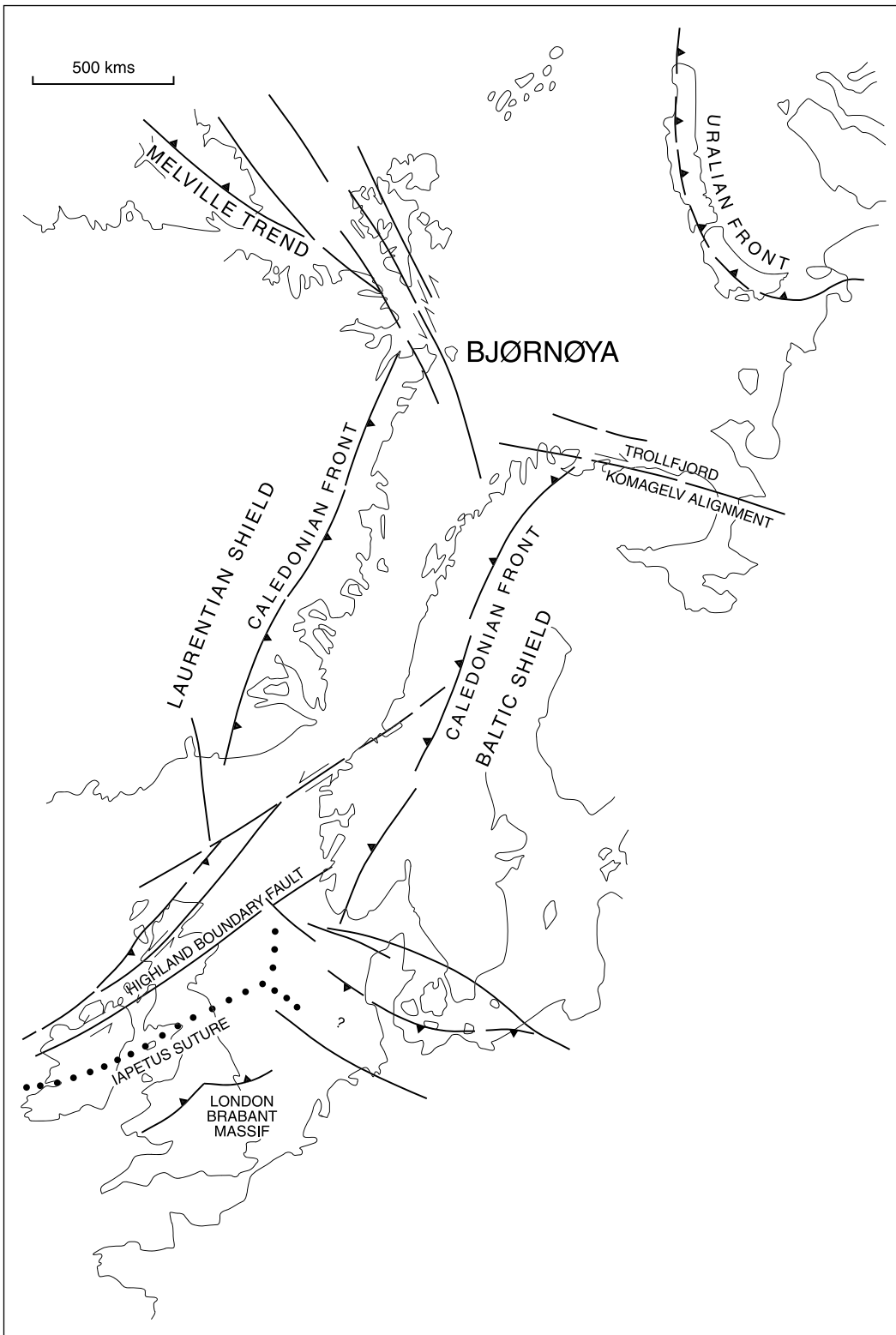


Fig. 27. Arctic summary map indicating Bjørnøya's possible palaeoalignment in relation to major tectonic sutures, including the "Senja-Hornsund-St Jonsfjord-Wandel-Melville trend".

Stemmerik 1984, 1989; Stemmerik & Håkansson 1991), which represent probable continuations of the Senja Hornsund alignment.

- The Sverdrup Basin margins experienced several periods of faulting during the Carboniferous and early Permian (Stephenson et al. 1987; Beauchamp et

al. 1989); Mayr (1992) described thick Upper Carboniferous siliciclastic sequences along the basin's northwestern margins. The mid-Permian saw a change from active fault control to passive subsidence, but the transition was marked by the ?Kungurian "Melvillian Disturbance" - an episode of reactivation accompanied by some strike-slip deformation

- somewhat in the same style as the Sakmarian events on Bjørnøya. The Tanquary Structural High in the northeastern part of the Sverdrup Basin was apparently actively uplifted in the Late Permian to Triassic (Mayr 1992); this feature thus shows an interesting analogy to the Loppa, Stappen and Sørkapp-Hornsund highs.

Summary and Conclusions

In summary:

- The Stappen High was the site of fluvial sedimentation in a NNW trending half-graben from the late Devonian to early Carboniferous,
- Mid-Carboniferous uplift was accompanied by a climatic shift to arid conditions and followed by renewed rifting along a master fault to the west of present exposures on Bjørnøya,
- Bashkirian and Moscovian sea-level rise led to carbonate deposition over the entire area, in common with the rest of the Barents Shelf,
- Renewed tectonism in the late Carboniferous produced the faulted configuration seen today,
- The early Permian was characterized by onlap and then uplift of the newly created high,
- Upper Permian and Triassic sequences progressively onlapped the high before the entire area subsided from the late Triassic to late Mesozoic or Paleogene.

The complex development shown by the Upper Palaeozoic succession of Bjørnøya is noteworthy in view of the immense amount of information that can be derived from this small area. The structural development of the Stappen High is in no way unique, but the spectacular exposures offer an impressive documentation of the ongoing tectonism that characterized the present-day western margins of the Barents Shelf during the Late Palaeozoic. Bjørnøya is especially interesting in that the Late Palaeozoic tectonism can be differentiated from the Tertiary overprint, which usually obscures similar movements both in southern and western Spitsbergen and in parts of the Wandel Sea and Sverdrup basins. This development also gives striking examples of the type of plays expected to have great potential for successful hydrocarbon exploration both on the Barents Shelf and in adjacent areas.

Economic implications

Present knowledge suggests the extensive development of Upper Palaeozoic basinal and platform sequences to the east and southeast of Bjørnøya over large areas of the

Barents Shelf, and the following features provide interesting - and as yet poorly explored - targets for hydrocarbon exploration:

- Lower Carboniferous coal-bearing fluvial sequences in local rift basins,
- Upper Carboniferous to Lower Permian platform carbonates and interbedded evaporites, with local structuring related to major lineaments,
- Carbonate build-ups and associated facies along major lineaments and basinal margins,
- Intrabasinal thick evaporites with structuring resulting from halokinetic movements.

The Bjørnøya succession yields important information for the first three of these play types, whereas major basinal evaporites are restricted to the Nordkapp and Tromsø basins.

Sandstones of the coal-bearing Røedvika and Nordkapp formations may have an interesting trapping potential, especially as they show some of the highest porosities of the entire Upper Palaeozoic succession on Bjørnøya (c.f. Grønlie et al. 1980). These sandstones occur in local grabens where they may provide combinations of stratigraphical (pinch-out and truncation) and structural traps, with structuring provided by mid-Carboniferous rifting. Bjørnøya's southwestern cliffs display sections through possible truncation traps related to later Carboniferous and Permian tectonism, with potential seals provided by Permian carbonates; these provide good analogues for geographically restricted but similar structures such as the Loppa High (Figs. 18 & 26). These potential sandstone reservoirs would in general be expected to be sourced by hydrocarbons derived from the adjacent coals and coal shales in the same sequences, but more oil-prone lacustrine units have also been described from comparable fluvial sequences both in the penecontemporaneous Emma Fjord Formation of the Sverdrup Basin (Goodarzi et al. 1987; Davies & Nassichuk 1988) the Billefjorden Group of Spitsbergen (Nøttvedt et al. 1992) and the Upper Carboniferous of East Greenland (Piasecki et al. 1990).

The overlying conglomerates, sandstones and limestones of the Landnørdingsvika, Kapp Kåre and Kapp Hanna formations are generally tightly calcite cemented in exposures on Bjørnøya, reflecting the predominantly marine diagenetic regimes in spite of repeated uplift and erosion. Similar units deposited in more restricted lagoonal environments or which have been subjected to more drastic uplift and subaerial exposure may show appreciable secondary porosity, either because of dolomitization or by leaching of early marine cements. The bioherms and associated dolomites of the Kapp Dunér Formation are much more porous bodies than the surrounding and overlying sequences, porosities resulting

from early leaching and/or dolomitization linked to repeated subaerial exposure. These carbonate build-ups are furthermore associated with bituminous limestones with an interesting source potential.

The overlying limestones of the Hambergfjellet Formation appear to have been formed in cooler water transgressive regimes and are characterized by pervasive marine calcite cementation leaving no effective reservoir potential (Stemmerik et al. 1999). Indeed in subsurface situations analogous to those shown in Fig. 18, the Hambergfjellet Formation could have acted as an effective seal for hydrocarbons trapped in the underlying truncated units. Large-scale carbonate build-ups associated with Hambergfjellet equivalents over large shelf areas are generally also tight, with no effective reservoir potential. Such build-ups are observed along the tilted flanks of the Loppa High where they were eroded and presumably karstified as a result of repeated uplift in the Late Permian, probably giving good dissolution porosities; they were subsequently directly overlain and sealed by onlapping Triassic shales with a probable source potential (Fig. 26).

Uplift in the latest Permian was apparently accompanied by regional regression and at this time even the silica-cemented sandstones and limestones of the Miseryfjellet Formation and its equivalents may have suffered dissolution and karstification over large areas, giving rise to an interesting mouldic secondary porosity development; this play is especially interesting in areas such as the Finnmark Platform or Loppa High where structuring may put these potential reservoirs in direct contact with possible uppermost Permian or lowermost Triassic potential source intervals which have been tentatively identified in several wells.

Based on these observations the search for significant hydrocarbons in the Upper Palaeozoic succession of the Barents Sea therefore will demand an integrated understanding of the interactions of both local and regional tectonics and sea-level variations together with a detailed understanding of the facies variations produced.

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