8 Svalbard's post-Caledonian strata – an atlas of sedimentational patterns and palaeogeographic evolution

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The Carboniferous to Palaeogene sedimentational history of the Svalbard Archipelago is documented with the help of representative cross-sections, palaeogeographical maps and brief syntheses of major depositional phases.

The succession comprises eight lithostratigraphical groups, with a general composite thickness of more than 7 km, which accumulated between the late Devonian 'Svalbardian' deformation and the Tertiary orogeny. Varying tectonic regime is reflected in the succession by changing patterns of sediment thickness, facies configurations, provenance and transport directions. Climatic changes, resulting largely from northwards palaeocontinental movement, also had a great influence on stratigraphical variation and facies development.

Tectonic activity was concentrated along a series of NNW–SSE lineaments of Caledonian, or earlier, origin. Lineamental instability, with both normal and oblique-slip movements, was most marked in the earliest and latest phases of the depositional epoch. Facies of the Carboniferous and early Permian developed in a horst and graben setting. Early Carboniferous grabens were the sites of equatorial fluviatile deposition, with coal swamps developed on flood-plains and around lakes. Mid-Carboniferous to early Permian red bed, carbonate and sabkha sequences reflect arid terrestrial climates and ongoing stabilization of most lineaments. The transition to more stable platform environments during the Permian probably reflects the relocation of tensional tectonic regimes to intracratonic rift areas west of Svalbard. This transition was accompanied by a regional transgression in the mid-Permian and the establishment of temperate climates in the Svalbard area.

Thickness and facies variations in the Mesozoic clastic sequence demonstrate continued flexuring and down-warping along existing lineaments; active faulting was accompanied by intrusive and extrusive activity in the late Jurassic and early Cretaceous. Periodic northern uplift of the platform became more marked through the Mesozoic, perhaps reflecting mantle expansion related to the evolution of the present Arctic Basin.

Tertiary basins and the West Spitsbergen Orogenic Belt developed from transtensile and transpressive motion between Greenland and Svalbard. Deep basins developed subsequently off western Spitsbergen, with the change from a sheared to a rifted margin, as the Svalbard Platform finally separated from Greenland.

INTRODUCTION

The Svalbard Archipelago comprises all islands in the area 74–81°N, 10–35°E (Fig. 1). The largest islands of Spitsbergen, Nordaustlandet, Barentsøya and Edgeøya, together with innumerable smaller islands and skerries comprise a total land area of 62 000 km^2. Approximately 60% of this area is permanently covered by glaciers and inland ice, but coastal and mountain exposures display a varied and superbly exposed geological succession ranging in age from the Precambrian to the Palaeogene. In view of its extreme latitude the archipelago has a relatively mild climate, and western sea approaches are ice-free most of the year; however, snow cover permits effective geological field work only in the short summer season of July and August. The archipelago has a somewhat unusual status. Originally a political no-man's land, it has been under Norwegian sovereignty since 1925. However, all signatory nations to the treaty which granted that sovereignty have equal rights of exploration and economic exploitation of the area. This unique combination of geological, climatic and political factors has made the Svalbard Archipelago the subject of active international geological research for 150 years.

The Norwegian geologist B.M. Keilhau paid a short visit to the area in 1827, but geological expeditions through the remainder of the 19th century were very much dominated by Swedish expeditions under the leadership of S. Loven and, later, of A.E. Nordenskiold, A.G. Nathorst and G. De Geer. These expeditions established the strati-

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Fig. 1. A location map showing the major geographical features referred to in the text.

graphic framework of the area and resulted in many major contributions on the fossil floras and faunas (see Nathorst, 1910). Significant coal deposits of Carboniferous and Tertiary age were discovered at an early stage of investigation, and exploitation of these started around the turn of the century. This was accompanied by decreasing Swedish activity; from 1906 onwards Norwegian expeditions, led first by G. Isachsen and later by A. Hoel, played an increasingly important role in further work. The early Norwegian expeditions were privately sponsored, but increasing government support led finally to the establishment of 'Norges Svalbard og Ishavets undersøkelser' (later Norsk Polarinstitutt) in 1929. These expeditions contributed to increased knowledge both of coal-bearing sequences and of the palaeontology and biostratigraphy of the entire succession. Of especial note are works on the Festningen section on the southwestern coast of Isfjorden; continuous exposures from the mid-Permian to the basal Tertiary made this area a source of study as a biostratigraphical standard for the entire archipelago (Hoel and Orvin, 1937). Other important palaeontological work was carried out on the Devonian agnathan faunas of northern Spitsbergen; a Norwegian—British—Swedish expedition working in this part of the succession represented the final pre-war scientific effort in the summer of 1939 (Føyn and Heintz, 1943).

Frebold (1935) presented a synthesis of available knowledge on the geology of Spitsbergen, an important milestone after his own earlier presentation of 10 palaeogeographical maps for the Mesozoic succession (Frebold, 1931). A geological map of the archipelago (scale 1:1 000 000) compiled by Orvin (1940) was also accompanied by a general synthesis and Orvin (1947) presented a bibliography of geological and other scientific literature on Spitsbergen up to 1944.

The break in field investigations caused by the Second World War was followed by increasing multi-national activity, which has continued to the present day. Research activities have to some extent reflected interest in the archipelago's petroleum potential (seven boreholes have been drilled to date, most in the 1960s and early 1970s), although petroleum interest in land areas has decreased in recent years and moved to adjacent areas of the Barents and northern Norwegian shelves. Continuing geological studies have produced a gradually more coherent lithostratigraphical scheme for the entire geological column, with increased biostratigraphical refinements using microfaunas and palynofloras. Understanding of Svalbard's geology has also increased significantly in the last 20 years as a result of increased activity in the less accessible parts of the archipelago. Three 1:500 000 geological maps have now been published covering southern and northern Spitsbergen and Barentsøya/Edgeøya (Flood *et al.*, 1971; Winsnes and Worsley, 1981; Hjelle and Lauritzen, 1982) and the final sheet for northeastern areas is now in preparation.

Important studies which have led to a better conceptual understanding of Svalbard's geological history have discussed the major NNW—SSE trending lineaments on Svalbard (Fig. 2). Early studies centred on the Billefjorden Fault of central Spitsbergen (Harland *et al.*, 1974) but later work has shown the importance of other structures in the late Palaeozoic (Gjelberg and Steel, 1981, 1983) and Mesozoic (Mørk *et al.*, 1982). Several lineaments were rejuvenated in the Palaeogene transform or Neogene rift regions during the development of this segment of the Greenland and Spitsbergen continental margins. The implications of some of these Tertiary movements for the evolution of Spitsbergen have been discussed by Birkenmajer (1972), Kellogg (1975), and Steel *et al.* (1981). Geophysical investigations in the Norweigian-Greenland Sea (Talwani and Eldholm, 1977) and along the Spitsbergen Continental Margin to the west and north of the archipelago (Myhre *et al.*, 1982) have complemented geological work on land. Increasing geophysical activity on the Barents Shelf, both to the south and east of Spitsbergen in recent years, has also given important general information on the structure of this important region (Schlüter and Hinz, 1978; Marty *et al.*, 1979). However, recent reconstructions of regional geology (e.g. Rønnevik, 1981) are still almost as much hampered by the lack of relevant information from onshore Svalbard as was the first pioneering attempt at a synthesis of the Barents Shelf evolution by Frebold (1951). In spite of syntheses in recent years (e.g. Harland 1969, 1972; Birkenmajer 1981) there is still no published information on spatial and temporal variations in bio- and lithofacies or interpretations of the palaeogeographical and tectonic controls on these which permit extrapolations from land to adjacent shelf areas.

This chapter is intended as a first step towards

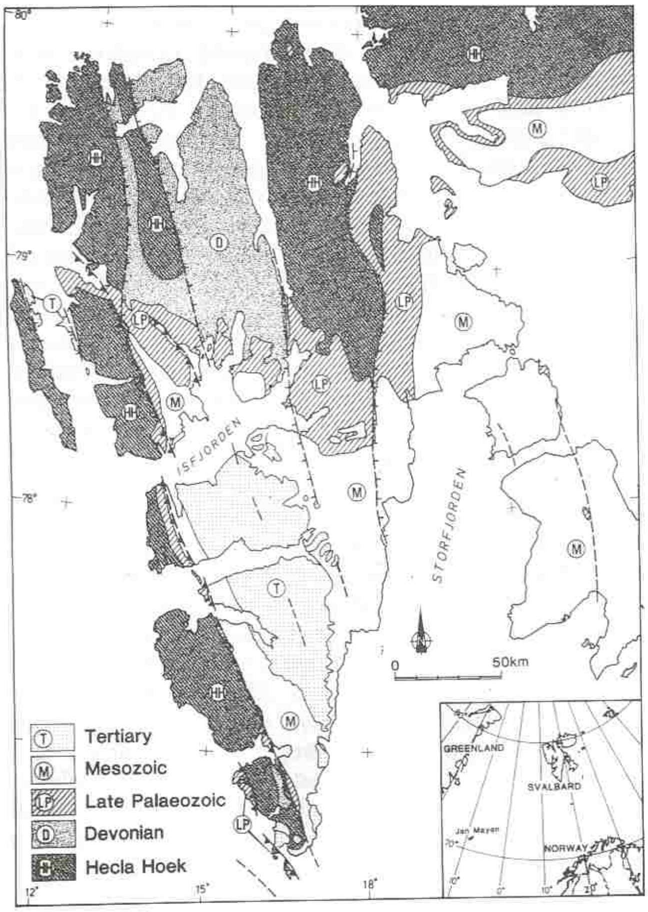

Fig. 2. A simplified geological map of Spitsbergen and adjacent areas.

a more detailed synthesis which will, hopefully, fill this gap in our knowledge. Using illustrative sections and reconstructions, we intend to summarize the results of detailed studies carried out since 1975 on the Carboniferous to Palaeogene strata of Svalbard by both staff and students at the Universities of Bergen and Oslo. This work has included sedimentological and palaeogeographical analyses of the post-Caledonian succession (see Appendix 1 for a list of theses from these Norwegian universities). With the notable exception of Devonian facies and basin analyses by Friend and Moody-Stuart (1972), this type of work had not been attempted previously; the efforts of the Norwegian universities have therefore heralded a new phase in the study of Svalbard's strata. Prior to the presentation of detailed results of this work we would also note that syntheses of single geological periods or lithostratigraphical groups are also being produced (e.g. Steel *et al.*, 1981; Mørk *et al.*, 1982; Hellem and Worsley, in press). Work is also in progress on a synthesis of the late Palaeozoic evolution of Bjørnøya; although we do not include Bjørnøya on our palaeogeographical maps, points of regional significance provided by this island are noted in the text.

STRATIGRAPHICAL SCHEME

The most recent total review of stratigraphical units from Svalbard was presented by Major *et al.* (1956). Increasing research activity and the general adoption of evolving international recommendations on stratigraphical nomenclature during the last 20 years has led to the development of a coherent lithostratigraphical scheme for most units of post-Caledonian strata on Svalbard. In view of the international engagement in research on the archipelago, conflicting stratigraphical proposals and use of synonomous units has perhaps been inevitable. A definitive revision of all lithostratigraphical terms now in use must await the recommendations of the newly established Norwegian Stratigraphical Committee; in the interim period we largely adhere to the scheme used by the Norwegian Polar Institute in their 1:500 000 Geological Map Series, with some modifications resulting from our own work. Figure 3 presents a schematic review of groups comprising the Carboniferous to Palaeogene sequence of Spitsbergen. Formational and member units assigned to these groups will be referred to in the text: the following short review should make it possible for the interested reader to ascertain the derivation of all stratigraphical units referred to herein. Precise datings of many lithostratigraphical units are still lacking and outstanding correlation problems will be discussed in this section.

The lithostratigraphical scheme for Carboniferous and Permian units assigned to the Billefjorden, Gipsdalen and Tempelfjorden Groups by Cutbill and Challinor (1965) has worn well, although some modifications are necessary. An important change concerns the junction between the Billefjorden and Gipsdalen Groups in the Billefjorden area. We propose that use of the upper Hultberg Member of the Svenbreen Fm should be modified to include only coal and shale sequences found in the lower parts of the member as it is presently defined. A new unit — the Anservika Member — is proposed for overlying red beds, which should now be used to define the base of the overlying Ebbadalen Fm

M.y. B.P.	LITHO LOGY	AGE	MIN./MAX. TH. (M)	GROUP	FACIES
		← TERTIARY DEFORMATION			
		Eocene / Palaeocene	1500+	VAN MIJENFJORDEN	DELTAIC/RESTRICTED MARINE CLASTICS
100					
		Alb./Aptian / Callovian	550/ 1700+	ADVENTDALEN	MARINE CLASTICS, MAJOR PROGRADATION IN L. CRET.
200		Bathonian / Rhaetian / Ladinian	70/510+	KAPP TOSCANA	DELTAIC/SHALLOW MARINE CLASTICS
		Lad. Griesb.	60/870	SASSENDALEN	FG MARINE CLASTICS
		«late P.» / Artinsk.	5/460	TEMPELFJORDEN	SILICIFIED MARINE CLASTICS/LSTS
300		Artinskian / ?Bashkir.	270/ 1800	GIPSDALEN	LSTS/DMS/EVAPORITES, LOCAL CLASTICS ALONG FAULTED BLOCK MARGINS
		?Namur. / Famenn.	0/1250	BILLEFJORDEN	FLUVIAL/ALLUVIAL CLASTICS
		↖ SVALBARDIAN DEFORMATION			

Fig. 3. A schematic lithostratigraphical scheme showing the general development of the seven post-Devonian groups of central Spitsbergen.

of the Gipsdalen Gp. The biostratigraphical basis for the dating and correlation of formational units varies between the three major groups in this succession, reflecting to some degree the different depositional regimes which these represent. The Billefjorden Gp is dated on the basis of palynofloras and important works are those of Playford (1962/1963) for central Spitsbergen, Siedlecki and Turnau (1964) for Hornsund, and Kaiser (1970, 1971) on Bjørnøya. The Gipsdalen Gp has been dated mainly on the basis of fusulinids (Cutbill and Challinor, 1965; Sosipatrova, 1972) with some additional information from brachiopods (Gobbett, 1963). Our main modification to Cutbill and Challinor's datings is assignation of Gipsdalen Gp sequences in southern Spitsbergen and on Nordaustlandet to the entire depositional phase from the Bashkirian/Moscovian to the Artinskian and not just to the early Permian. Brachiopods (Gobbet, 1963), non-fusulinid forams (Sosipatrova, 1972), and conodonts (Szaniawski and Malkowski, 1979) have been used to date the Tempelfjorden Group; there remains much uncertainty as to how far sequences assigned to the group extend into the late Permian and opinions vary considerably; we indicate a ?Kazanian age for the youngest beds and hope that studies of palynomorphs, conodonts and foraminifera now in progress may elucidate this problem.

Buchan *et al.* (1965) introduced a lithostratigraphy for Triassic to early Jurassic units which are now assigned to the Sassendalen and Kapp Toscana Groups. Subsequent extensive studies by several groups have led to a wealth of new proposals for formational and lower rank units and the reader is referred to Mørk *et al.* (1982) for an interim synthesis of present status. These sequences have traditionally been dated on the basis of their molluscan macrofaunas (see reviews of Tozer and Parker, 1968; Korcinskaja, 1973), but subsequent work has proved the potential of palynostratigraphical studies, especially in the upper parts of the Kapp Toscana Gp (see e.g. Bjærke and Manum, 1977). There is, however, doubt on intercorrelation of palynofloras and macrofaunas at some levels, e.g. around the Triassic/Jurassic boundary, and little palynostratigraphical work has been done as yet on early to mid-Triassic sequences. However, extensive palaeontological and palynological studies are now in progress and a refined biostratigraphical zonation of the entire sequence may be expected in coming years.

Mid-Jurassic to early Cretaceous deposits of the Adventdalen Gp were first assigned to a formal lithostratigraphical scheme by Parker (1967), with subsequent modifications and refinements by Nagy (1970) and Major and Nagy (1972). The group has been dated on the basis of molluscan macrofaunas (Sokolov and Bodylevsky, 1931; Frebold, 1930, 1931; Nagy, 1970), augmented by recent palynological studies of the groups Callovian to Hauterivian black shales (Bjærke 1978, 1980). Detailed biostratigraphical studies are now needed in the remaining early Cretaceous sequences in order to test the model of diachronous, northwards younging, deltaic deposition presented herein.

Alternative lithostratigraphical schemes for the Tertiary sequence of central Spitsbergen now assigned to the Van Mijenfjorden Gp have been presented by Norsk Polarinstitutt in a 1:100 000 geological map of the area around Longyearbyen printed in 1964 (later described by Flood *et al.* (1971) and by Major and Nagy (1972)) and by Livsic (1965, 1967, 1974). Elements of both schemes have been used by Steel *et al.* (1981) in a new lithostratigraphical subdivision of the group. Tertiary deposits of northwestern Spitsbergen (the Forlandsundet Gp of Harland (1969) have been reinvestigated by Rye-Larsen (1982)). The deposits there are probably largely of Eocene age, and thus partly time-correlative with the youngest sequences of central Spitsbergen. Still younger Tertiary sequences which lie along Svalbard's rifted margin (Sundvor *et al.*, 1977; Myhre *et al.*, 1982) are the product of uplift, after mid-Oligocene times, of the northwestern corner of the Barents Platform and marginal basin development off western Spitsbergen. Results of Deep Sea Drilling Project, Leg 38 (White, 1976) show the age of the uppermost parts of the offshore succession to be Plio/Pleistocene. Despite some continued uncertainty about the age of the youngest on-shore sequences (see Ravn, 1922; Manum, 1962; Livsic, 1967, 1974; Vonderbank, 1970), we now know that both Palaeogene and Neogene successions are represented on and around Svalbard. The oldest deposits in the central basin may, indeed, extend down into the latest Cretaceous (S.B. Manum, personal communication, 1983).

TECTONIC FRAMEWORK

Tectonic setting has been an important controlling influence on sedimentation patterns of post-Caledonian Svalbard, as in most regions of thick sediment accumulation. Previous reviews of the development of Svalbard have emphasized tectonic 'episodes' or 'movements', particularly in late Devonian and early Tertiary times (e.g. Orvin, 1940; Harland, 1969; Harland *et al.*, 1974; Birkenmajer, 1981). Although recognizing the importance of these two tectonic 'highlights' we are impressed also by the considerable record of tectonic movement seen in the entire post-Caledonian succession of Svalbard. Variation in both local and regional tectonics is reflected by changing patterns of sediment thickness and by varying facies configurations, provenance and transport direction. Better understanding of these changing depositional patterns and of the reasons for major stratal breaks, documents a more complete tectonic record, and gives a better insight of the timing and character of the major deformational episodes themselves.

Svalbard's tectonic framework is dominated by a number of structural lineaments, mostly N—S to NW—SE oriented, across which there has been repeated differential movement or inversion since the Devonian. The most important of these are the Lomfjorden/Agardhbukta, Billefjorden, Inner Hornsund and Palaeo-Hornsund Fault Zones. Tectonic movement along these lineaments varied from slight flexuring to discrete faulting, with the latter varying from dip-slip to strike-slip dominance. Figure 4 outlines how these lineaments have affected sedimentation patterns in post-Devonian Svalbard.

The Carboniferous was characterized by rapid subsidence along or between the major lineaments, with sequences up to 3-km thick accumulating in southern Spitsbergen.

Three marked phases of instability are distinguished:

(1) Tournaisian—Viséan subsidence along narrow (< 30-km wide), isolate zones on both Spitsbergen and Bjørnøya.

(2) Broad, asymmetric Namurian down-warping against the Palaeo-Hornsund Fault, resulting in a thick (< 2 km) clastic wedge which thinned rapidly eastwards.

(3) Bashkirian—Gzhelian return to localized subsidence in a series of narrow zones along the major lineaments. We speculatively suggest that the apparent *en echelon* arrangement of some of the troughs (Fig. 10) may indicate some oblique-slip movement across the region at this time.

A marked feature of Carboniferous tectonics was the tendency of the sense of dip-slip movement across the lineaments to reverse with time. This produced almost total inversion of the early Wedel Jarlsberg Basin in the Namurian, partial inversion of the primitive Billefjorden Basin in the Bashkirian, and Gzhelian to Sakmarian inversion of parts of the Bjørnøya Basin. It is tempting to relate these basinal inversions and the suggested early Carboniferous thrusting in inner Hornsund (Birkenmajer, 1981) to oblique-slip tectonics. Major oblique-slip movements have been proposed for Spitsbergen in the late Devonian (Harland, 1971; Harland *et al.*, 1974) and for the North Atlantic generally in the Carboniferous (Kent and Opdyke, 1979; van der Voo and Scotese, 1981; Ziegler, 1982; Russel and Smythe, 1983). Our own work on a local scale thus strengthens these larger-scale speculations. One consequence of early—mid. Carboniferous strike-slip movements along some of the Svalbard lineaments is that our early Carboniferous maps (Figs. 7 and 8) become more speculative. However, as yet we have no evidence of great movements within Svalbard in Carboniferous times and most of the large-scale translation may have been taken up off western Svalbard, along the Palaeo-Hornsund Fault Zone.

The early Permian to late Cretaceous is characterized by flexuring and minor instability across most lineaments when compared to the preceding and succeeding periods. In late Carboniferous times the Inner Hornsund and, to a lesser extent, the Billefjorden lineaments still divided 'high' areas to the west (Sørkapp-Hornsund High and Nordfjorden Block, respectively) from 'low' areas to the east. Eastwards influx of clastic debris over the Billefjorden lineament had ceased, however, and by the early Permian a relatively stable platform existed throughout most northern areas of Svalbard. In contrast, the Sørkapp—Hornsund High was a positive feature throughout the Permian (Hellem and Worsley, in press). Parts of the western edge of the southerly continuation of the Nordfjord Block were also active, at least into earliest Permian times (Kleinspehn *et al.*, 1983).

Platform conditions persisted through the Mesozoic, although marked thickness and facies variations reflect flexuring and downwarping along earlier lineaments, especially in the early Mesozoic. Differential (?submarine) movement has also been documented along the Lomfjorden-

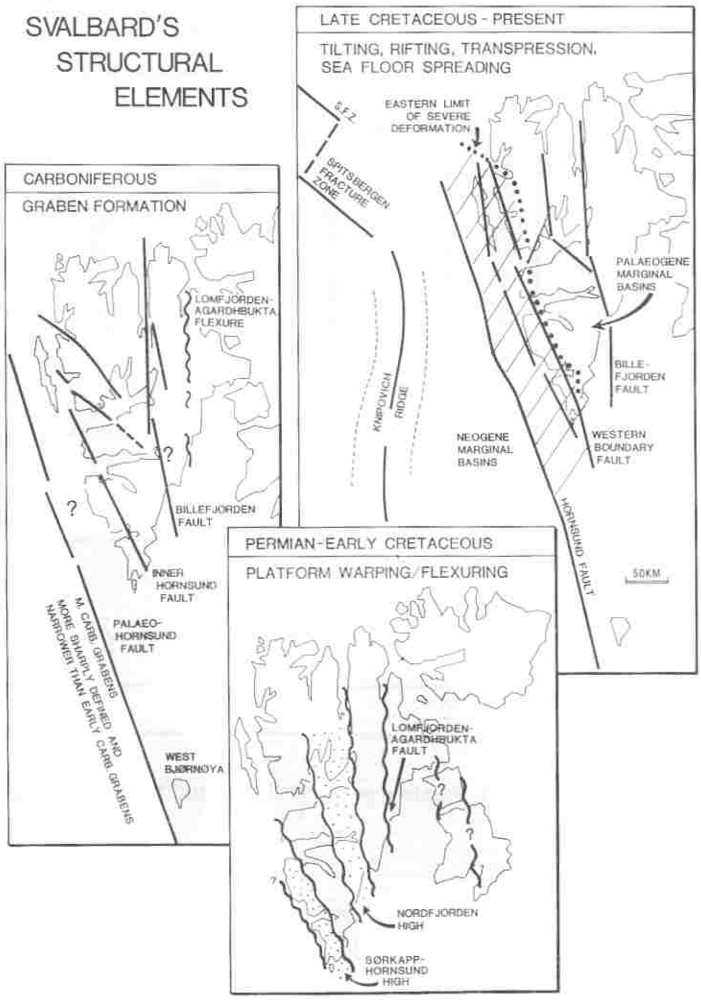

Fig. 4. Svalbard's structural elements during the three main phases of the sedimentary basin's development.

Agardhbukta and Billefjorden lineaments around the Jurassic—Cretaceous boundary. An additional tectonic constraint on deposition, increasingly important through the Mesozoic, was a broad northerly uplift of the platform area. This is evident from sediment transport patterns, and inferred basinal closure to the north from at least Jurassic times. This depositional phase culminated in marked late Cretaceous uplift, with consequent southerly tilting and erosion of the entire Spitsbergen region.

With a marked change in tectonic regime during Tertiary times, the main lineaments again defined the edges of major subsidence zones on Svalbard. They were initially the focus of a continental transform system, then the framework of a new continental margin (Steel *et al.*, 1981). Palaeogene oblique-slip movements along the western lineaments caused up to 3 km of subsidence against the Western Boundary Fault (partly located along the older Inner Hornsund Fault, Fig. 4), and a similar amount of subsidence in a narrow zone (Forlandsundet Graben) east of the Hornsund Fault. Compression across these lineaments also produced major overthrusts on to the flanking basinal areas at this time. The establishment of a sea-floor spreading axis in the Greenland Sea in the

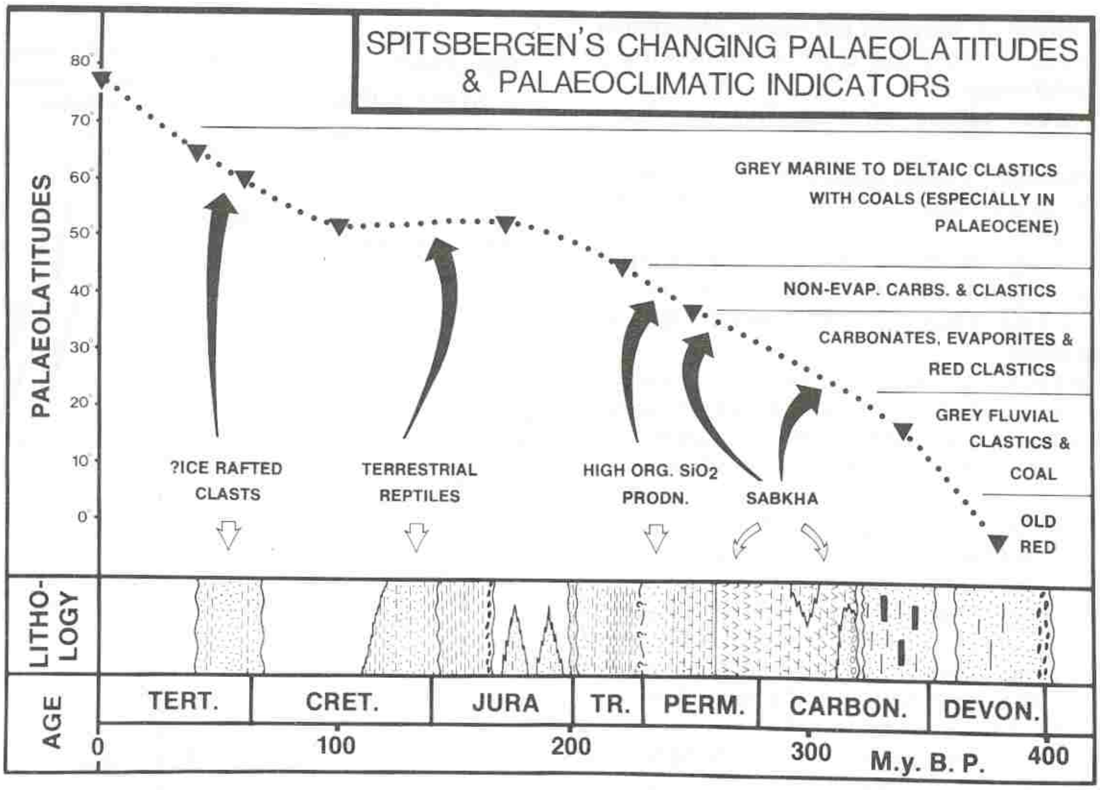

Fig. 5. Possible palaeolatitudes and palaeoclimatic indicators in relation to the major lithofacies observed.

Oligocene shifted the locus of subsidence westwards. The region west of the Hornsund Fault then became the site of Neogene rift basins on the new continental margin of Svalbard.

Changes in tectonic regime clearly reflect different phases in the palaeocontinental evolution of the present Arctic and Norwegian-Greenland Seas. Important information for facies interpretations is also given by relating palaeoclimatic indicators in Svalbard and adjacent basins' strata to possible palaeolatitudes suggested by the global reconstructions of Briden *et al.* (1974) and Smith and Briden (1977). Early Carboniferous coal sequences of the Billefjorden Gp formed in climates comparable to those of today's equatorial humid zone (Fig. 5). Rapid climatic shifts mark the base and top of the Gipsdalen Gp, whose sediments show all the indications of deposition in arid conditions. Although there appears to have been rapid northwards plate movement in the late Carboniferous and early Permian, it is doubtful whether this alone can explain the rapidity of the transition to and from arid conditions. It is probable that additional contributory factors were changing hydrographic regimes related to intracratonic rifting in this sector of the Laurasian Plate at the time.

More humid and temperate conditions persisted from the late Permian to the Cretaceous: terrestrial dinosaurs which inhabited the area in the early Cretaceous indicate continued mild climates at that time (Heintz, 1963; Edwards *et al.*, 1978). Renewed acceleration of movement northwards is suggested in the late Cretaceous, but Palaeocene coals witness a rich vegetation which could not have developed in extreme climatic conditions. However, Dalland (1977) has explained the occurrence of erratic clasts in marine deposits as representing ice-rafting, reflecting freezing of coastal embayments and/or inland lakes in winter months. A major, although elementary point has often been overlooked in interpretations of geophysical data from nearby shelf areas — the climatic shifts noted above did not occur at the same times as in southern Norwegian and North Sea shelf regions; it is therefore unrealistic to expect Triassic red beds in the subsurface of the Barents Shelf, to name only one possible example.

LATE PALAEOZOIC GRABEN DEVELOPMENT

Billefjorden Group

This thick succession of non-marine, coal-bearing strata, lying unconformably on Old Red Sandstone or Hecla Hoek sequences, was early referred to as the 'Kulm' (Nathorst, 1910) or 'Culm' (Orvin, 1940) sandstones. The succession is characterized by plant-bearing quartz arenites, black shales and coals. Early interest in the group was stimulated by the search for coal, now mined only by the Soviet community at Pyramiden. The succession is best known from the type area around Billefjorden, largely through the work of numerous Cambridge University expeditions (summarized by Harland *et al.*, 1976). More recently, the sedimentology of the Billefjorden Gp basins of Svalbard was briefly summarized by Gjelberg and Steel (1981) and a synthesis of Bjørnøya data has been presented by Gjelberg (1982). The tectonic setting of late Devonian to early Carboniferous sedimentation on Svalbard was one of graben development. The main basins were comparable in size to the earlier Old Red Sandstone graben, but lay mainly on the

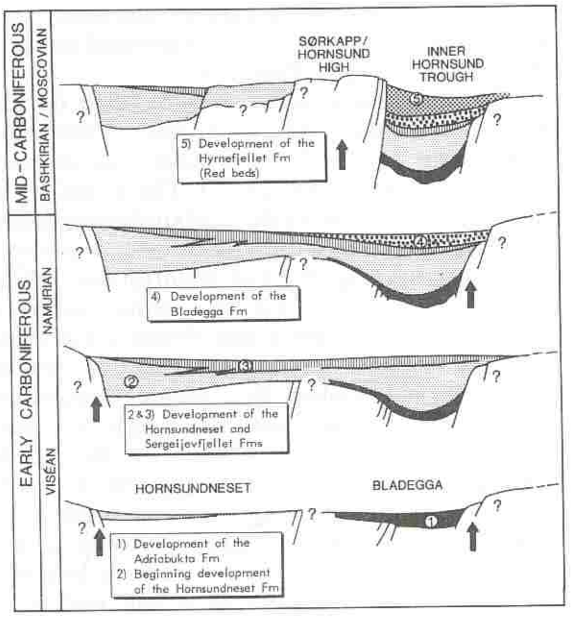

Fig. 6. Early to mid-Carboniferous basinal development in southern Spitsbergen (data by courtesy of J. Gjelberg).

flanks of the latter, which was now partly inverted. This configuration resulted in great thickness variations (0—2000 m) in strata assigned to the Billefjorden Gp (Fig. 6), with major depocentres lying along and east of the Palaeo-Hornsund Fault Zone, off western Spitsbergen and Bjørnøya, and in the Billefjorden area. The palaeogeography was dominated by large, humid alluvial fans which built out from the graben edges into swamps, lakes and river floodplains (Gjelberg and Steel, 1981).

Tournaisian to Visean sequences (extending back into the Fammennian on Bjørnøya, and possibly also elsewhere) are preserved only poorly and exposed on Spitsbergen, but appear to have formed in narrow, elongate, restricted basins (Fig. 7). The Adriabukta Fm (Hornsund and Van Keulenfjorden areas) is about 300 m thick and consists of black shales and a basal conglomerate sequence representing sublacustrine fans which built out from the east. Sedimentation in the Billefjorden area (Hørbyebreen Fm) was dominated by alluvial fans which prograded west and northwestwards into coaly swamps and flood-basins, and partly eastwards into a black shale facies. The Rødevika Fm of Bjørnøya is analogous, representing alternations of fluvial and flood basin deposits (Gjelberg, 1981). Coal seams from these levels were mined until 1925 on Bjørnøya, and are still mined today at Pyramiden.

Namurian times on Svalbard saw the following important changes (Fig. 8):

(1) Basinal areas had significantly increased in size, particularly along the eastern flank of the Palaeo-Hornsund Fault.

(2) Drainage and dominant sediment transport direction was now from westerly regions rather than from the east.

(3) The same spectrum of sedimentary environments was present, but the Namurian braided fans were much larger than earlier systems, probably in

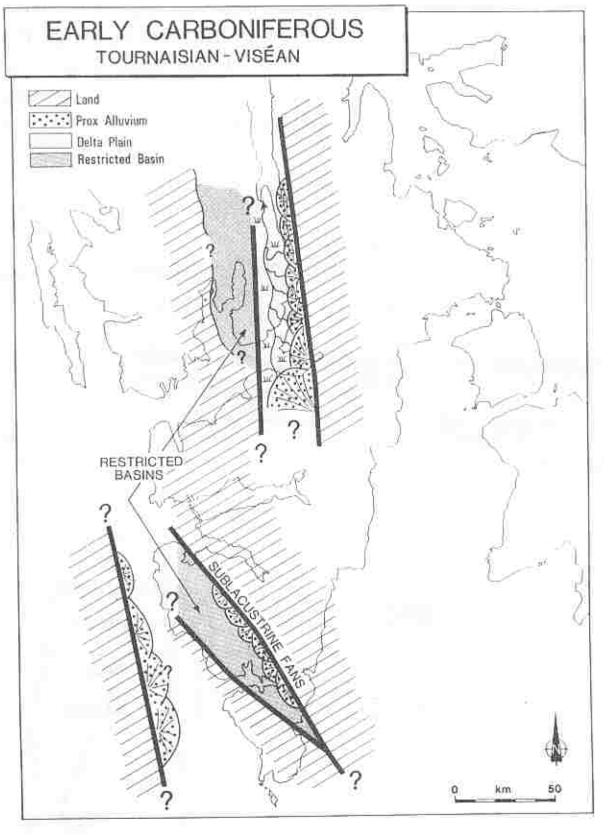

Fig. 7. Tournaisian/Viséan palaeogeography. Map is speculative due to limited data base and to uncertainty as to the relative position of the two basinal areas, due to possible later strike-slip faulting.

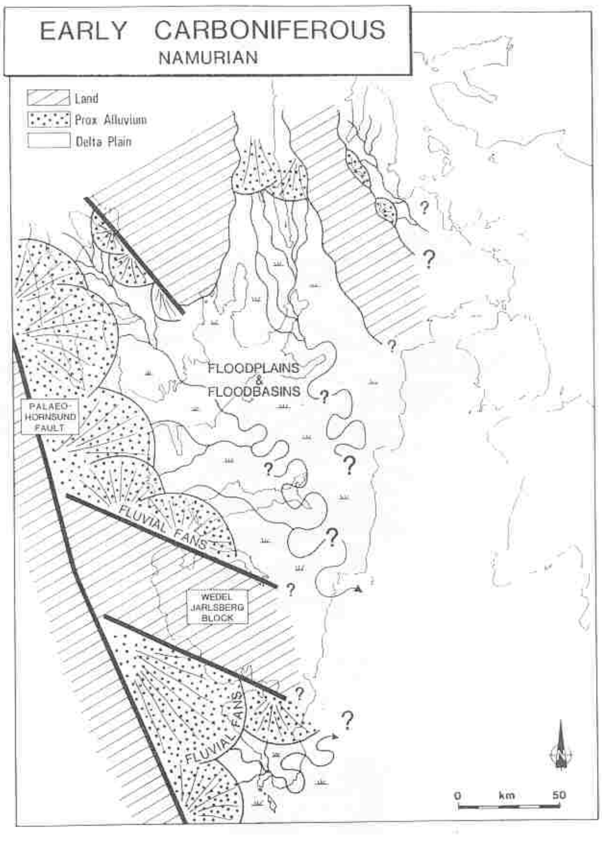

Fig. 8. Namurian palaeogeography. The position of the northeastern area relative to the western area is uncertain, due to possible later strike-slip faulting.

response to increased tectonic activity along western lineaments.

The result of these changes was that thick quartz arenitic successions, largely of braided stream origin, were deposited across Svalbard at this time; these include the Hornsundneset Fm (>1500 m) in areas south of the Wedel Jarlsberg Block and the Orustdalen Fm (>1000 m) in western Spitsbergen north of this block (Fig. 8). Subsidence in the primitive Billefjorden Trough was less impressive, with the deposition of the <100 m sequence of the Sporehøgda Mbr. The analogous Nordkapp Fm on Bjørnøya appears to have developed in the Viséan (Gjelberg, 1981).

Decreased subsidence rates in the late Namurian are suggested by a widespread retreat of the braided fans and their replacement in many areas by fine-grained marsh and flood-plain environments. This produced the youngest Carboniferous coal-bearing sequences of the Sergeijevfjellet Fm in the south, the Vegard Fm in the north, and uppermost part of the Sporehøgda Mbr in the Billefjorden area.

The Gipsdalen Group

Bashkirian times heralded the transition to semi-arid terrestrial climates and a general rise in sea-level. Rapid subsidence and faulting along the main lineaments continued to be important. Although sometimes difficult to define precisely, the junction between the Billefjorden and Gipsdalen Gps in basinal areas is consequently marked by the appearance of red alluvial fan sequences, with their laterally equivalent fan delta deposits, evaporites and carbonates. During trough infilling in northern areas the fault margins were draped and finally overstepped in the late Carboniferous, so that carbonate platform sequences then developed directly upon a basement of Devonian or Hecla Hoek units in the previously positive areas of the Nordfjorden Block and the eastern platform. These areas subsequently show a well-developed regressive trend through the early Permian.

Some of the aspects of the early tectonic development of the group, and facies inter-relationships with changing sea-level, have been discussed by Gjelberg and Steel (1981, 1983). The initial setting was one in which the early Carboniferous basinal system had become subdivided into a series of narrower grabens (Fig. 9). The Billefjorden Trough, often used as a model for the evolution of the entire Svalbard area during this depositional phase, may in reality show an unrepresentative development of the Gipsdalen Gp. Major depositional activity appears to have been situated in a series of *en echelon* arranged basins between the Billefjorden and Palaeo-Hornsund lineaments, possibly reflecting an oblique-slip tectonic regime. These basins are less accessible, and more highly tectonized, than the Billefjorden area, and therefore have tended to be overlooked. Their evolution is still not understood in detail, but a striking feature is a trend of southwestwards directed migration of lineamental instability throughout the depositional phase. By early Permian times tectonic activity had all but ceased along the margins of the Billefjorden and St. Jonsfjorden troughs, although changes in carbonate facies still betray a subtle lineamental influence in these areas. In contrast, the Sørkapp-Hornsund High and the adjacent Inner Hornsund Basin were tectonically active throughout the depositional phase. Bjørnøya shows a complex tectonic development, with alternating periods of stability and faulting; partial basinal inversion occurred in the late Carboniferous and the entire Bjørnøya area was extensively faulted and uplifted in the early Permian. In view of the varied tectonic settings sketched above, we will discuss separately three major depositional systems, *viz.* that of north-

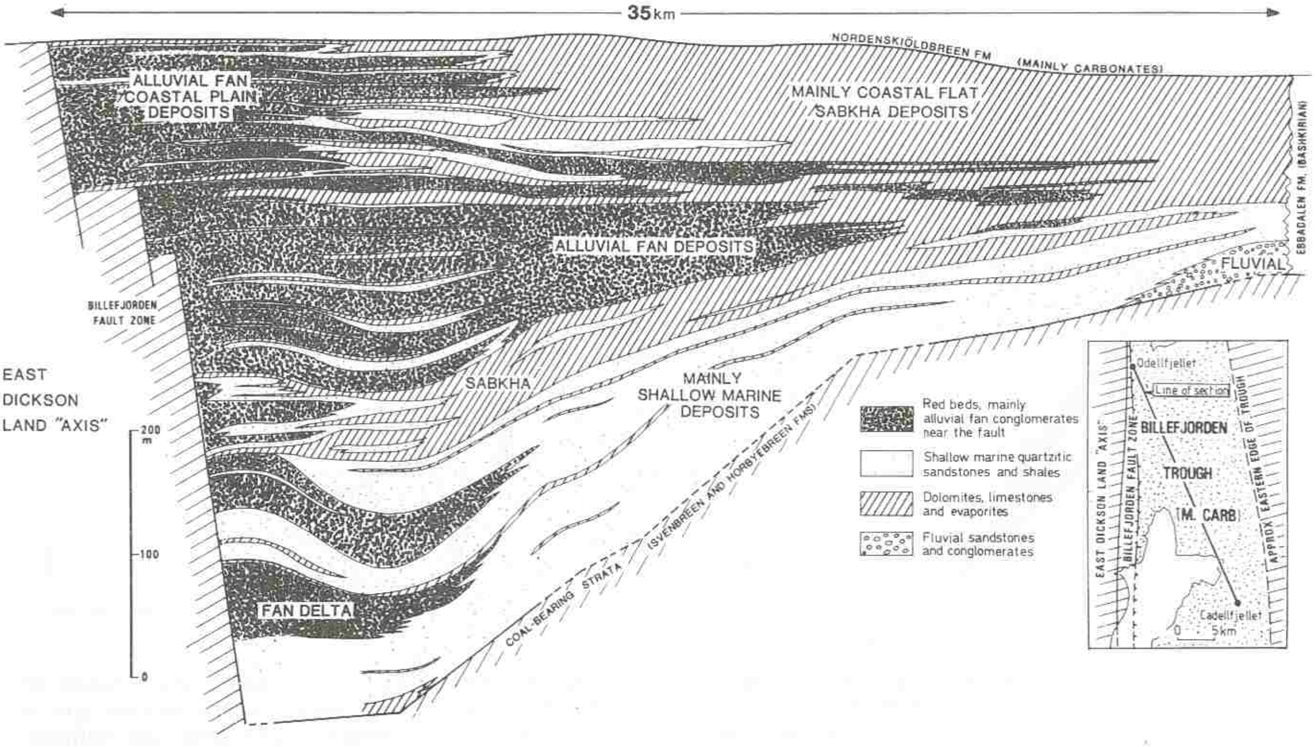

Fig. 9. The Bashkirian development of the Ebbadalen Fm in the Billefjorden Trough.

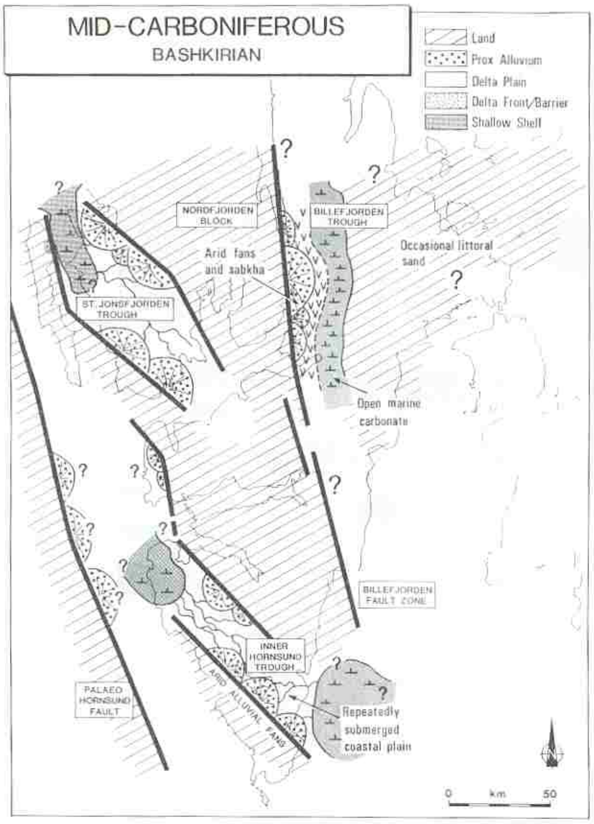

Fig. 10. Bashkirian palaeogeography.

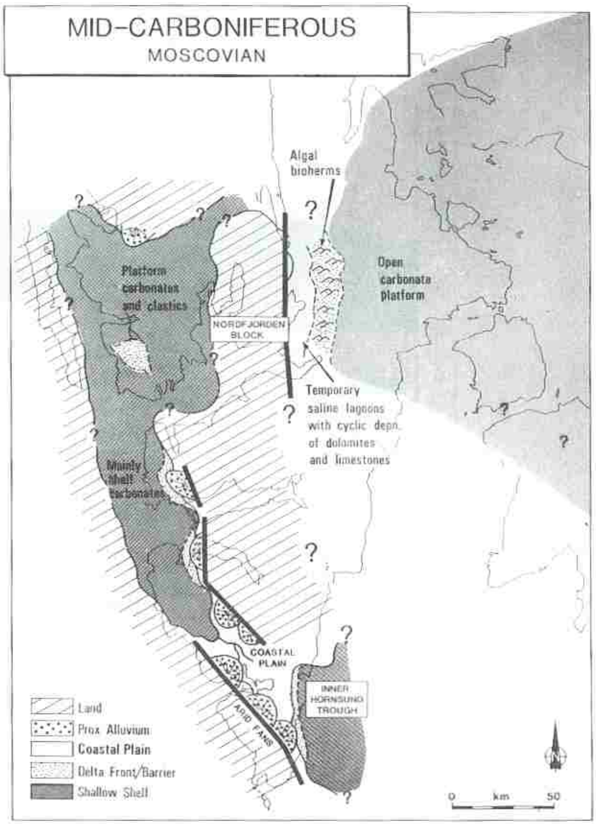

Fig. 11. Moscovian palaeogeography. By latest Carboniferous times much of the Nordfjorden Block and the Inner Hornsund Trough was submergent, though the margins of the latter were still tectonically active.

ern, central and eastern areas, as distinguished from the Inner Hornsund Basin of southern Spitsbergen, and from the Bjørnøya area.

Mid-Carboniferous sedimentation in central and eastern areas of Spirtsbergen was centred on the Billefjorden Trough (Figs. 9 and 10). The varied development of the (<800-m thick) Ebbadalen Fm represents alluvial fans and fan deltas which built out eastwards from the Billefjorden lineament into restricted marine and sabkha environments (Gjelberg and Steel, 1981). Rhythmic intercalations of these, often organized into thin upwards coarsening sequences (Johannessen and Steel, 1981), reveal an intricate interplay of local lineamental activity and regional transgression; the trough developed as an embayment opening to normal marine environments to the north. A general fining-upwards succession reflects ongoing transgression, finally leading to development of the carbonate-dominated Nordenskioldbreen Fm. Platform areas to the east of the trough were submerged in the course of the Moscovian (Fig. 11).

In the St. Jonsfjorden Trough, the mid-Carboniferous clastic sequences of the Brøggertinden, Petrelskardet and Tårnkanten Fms suggest the development of alluvial fans out from fault scarps along both eastern and western basinal margins; sequences appear to become finer northwards through floodplain deposits to open marine environments. The Moscovian saw the establishment of marine carbonate sedimentation also in this area. The late Carboniferous development was characterized by stabilization and the progressive eastwards transgression of the adjacent Nordfjorden Block. This structure was finally transgressed by the close of the Carboniferous, but until then it formed an effective barrier between marine depositional sites to the west and east. Consequently Billefjorden Trough areas adjacent to the block's margins show restricted lagoonal developments behind barrier and shoal systems formed by bioclastic banks and algal bioherms (Fig. 12). There appears to have been minor uplift of the entire area around the Carboniferous/Permian transition, resulting in the development of laterally extensive discontinuity surfaces and intraformational conglomerates. Renewed transgression in the early Permian led to the establishment of open marine environments on both sides of the earlier block. Although there are no significant thickness variations in Lower Permian units at the block's margins, shoals and bioherms still tended to develop along these sites (Fig. 13). A major regressive sequence from the Sakmarian to the Artinskian led to the eastwards progradation of sabkha sequences (Fig. 14) of the (approximately 200 m) Gipshuken Fm (Lauritzen, 1981). The margins of the Nordfjorden Block represent the approximate easternmost extent of sabkhas, although dolomitization is prevalent throughout eastern platform areas and these were evidently the site of restricted marine circulation.

Tertiary tectonism and the present distribution of outcrops along the western margins of the Inner Hornsund Basin make detailed interpretation of this area's evolution difficult. Present data suggest a mid-Carboniferous development of the Sørkapp-Hornsund High (Fig. 6) from which alluvial fans of the Hyrnefjellet Fm built out eastwards. Ongoing transgression produced the fan delta systems and interbedded carbonates of the Treskelodden and

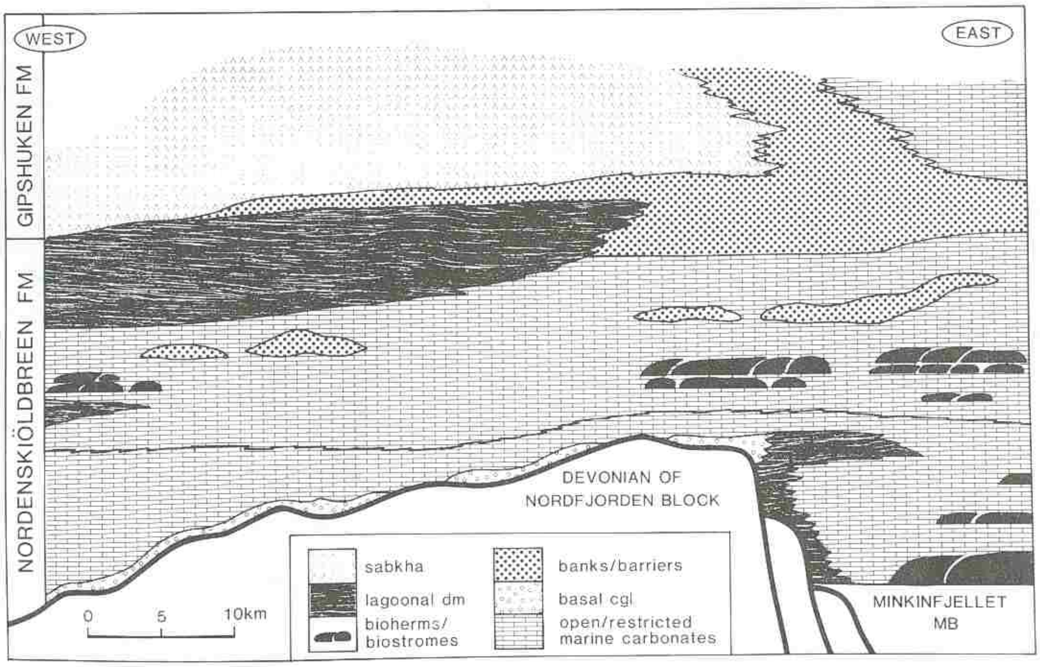

Fig. 12. Late Carboniferous to early Permian facies developments over the eastern and western margins of the Nordfjorden Block.

Reinodden Fms, which may represent progradations from western and eastern margins, respectively. Although datings are uncertain, active fan deltas probably persisted into the early Permian (Kleinspehn *et al.*, 1983). Marginal areas were then uplifted and exposed, but the transition from clastic domination into sabkhas and then open marine carbonates in exposures towards the centre of the basin (Nysæther, 1977) may suggest a transgression which is not detected clearly in the dolomites and sabkhas of the Gipsuken Fm to the north.

Local representatives of the Gipsdalen Gp on Bjørnøya suggest a complex depositional development of this southern sector of the Svalbard Platform in the late Carboniferous and early Permian. Red beds dominate the ?Bashkirian development of the Landnørdingsvika Fm and conglomeratic fans built out eastwards from fault scarps probably forming a southern continuation of the Palaeo-Hornsund Fault Zone (Gjelberg and Steel, 1981, 1983). Lineamental stabilization and rising sea-level led to the transition

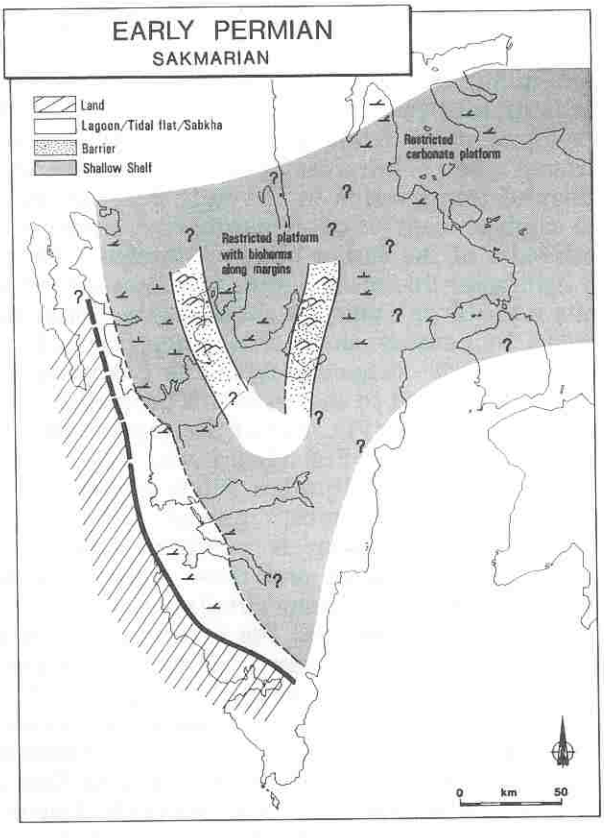

Fig. 13. Sakmarian palaeogeography.

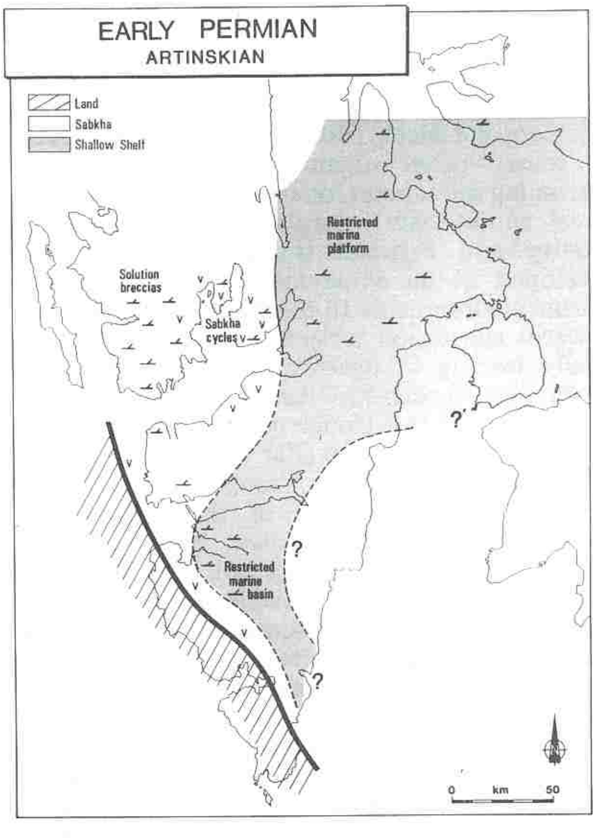

Fig. 14. Artinskian palaeogeography.

to platform carbonate sequences in the middle of the Moscovian Kapp Kåre Fm. So far, depositional patterns had closely paralleled the northern Spitsbergen model, but basinal inversion in the late Moscovian and Gzhelian produced *westerly* prograding alluvial sequences of the clastic-dominated Kapp Hanna Fm from new fault scarps established in the eastern parts of the area. Temporary stabilization around the Carboniferous–Permian boundary, resulting in the carbonate sequences of the Kapp Duner Fm, was followed by extensive faulting, uplift and erosion in the early Permian. The Artinskian transgression noted in the Inner Hornsund Basin may be represented on Bjørnøya by the thin easterly onlapping wedge of the mixed clastic and carbonate Hambergfjellet Fm; however, the horst which had developed in the east of the area in the late Carboniferous does not appear to have been submerged at that time.

LATE PERMIAN TRANSITIONAL REGIMES

The sharp contact between the carbonate-dominated Gipsdalen Gp and the cherty sequences of the Tempelfjorden Gp represents a major facies change which can be traced throughout Svalbard. This change, dated to the late Artinskian–early Kungurian, reflects a large-scale transgression which was either responsible for, or accompanied, a transition from warm arid to temperate humid climatic conditions. Resultant changes in lithofacies from the Gipsdalen to Tempelfjorden Gps include: the cessation of evaporitic mineral formation, even in marginal marine depositional areas; the shift from carbonate to clastic-dominated sediments throughout the area; the replacement of chlorozoan by foramol related biotic associations in the sediments.

The high frequency of cherts and of silica cements in the Tempelfjorden Gps shales, siltstones, sandstones and limestones is striking. Siliceous sponges appear to have been the primary and dominant source of the silica and sponge spicules form an important biogenic component in all lithofacies.

The tectonic setting of the group is also transitional between that of under- and overlying units. Unlike older groups, there is no evidence of major syn-sedimentational faulting in central Spitsbergen or on Bjørnøya. However, preferential downwarping did occur along the lineaments bounding the Nordfjorden Block, and thickest sequences (<490 m) fill the troughs on either side of this structure. Eastern areas show a stable platform development, thinning gradually to 150 m on Nordaustlandet (Fig. 15). An even thinner development (120 m) is seen on Bjørnøya, where basal deposits of the group rest on a peneplaned surface of all older units.

In contrast, the tectonic setting of southwest Spitsbergen was more akin to that of Carboniferous times; the Sørkapp-Hornsund High was clearly a positive structure through the late Permian and sequences thin dramatically against the eastern margins of this structure. A small exposure area around the southwestern tip of Spitsbergen displays a 425-m thick sequence which was probably deposited off the western margins of the high; however, the original position of this sequence is uncertain because of crustal shortening in the Tertiary deformation.

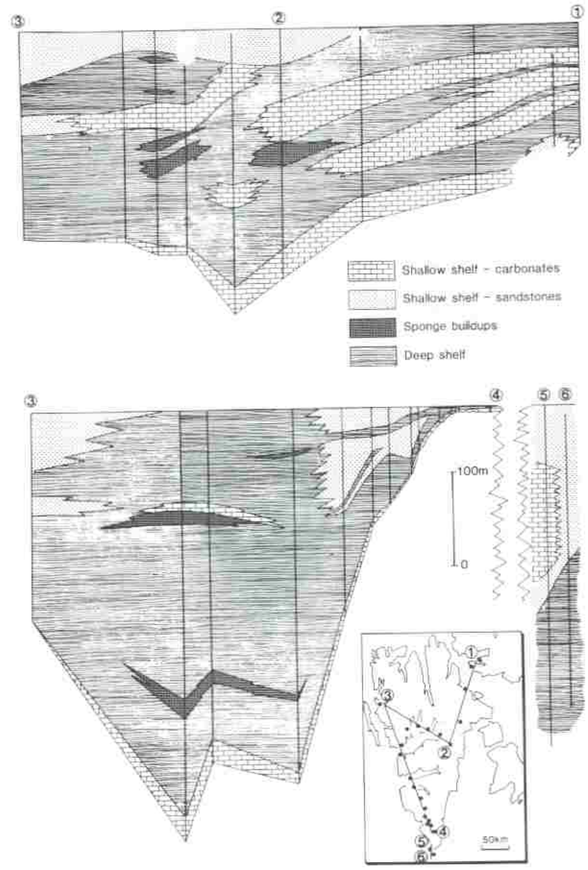

Fig. 15. Cross-sections showing the development of the Tempelfjorden Gp throughout Spitsbergen.

Tempelfjorden Group

The Tempelfjorden Gp comprises three laterally equivalent formations developed in geographically separated areas: the Kapp Starostin Fm of all exposures east and northeast of the Sørkapp-Hornsund High; the Tokrossøya Fm in the area southwest of the high; the Miseryfjellet Fm of Bjørnøya.

The depositional history of the group is best reviewed by discussing the main platform and trough development of central and eastern areas of Spitsbergen separately from the special developments observed along the margins of the Sørkapp-Hornsund High and on Bjørnøya.

Basal beds of the Kapp Starostin Fm commonly consist of bioclastic limestones with a sharp and often erosive contact to the underlying Gipshuken Fm. The limestones are interpreted as shoreface deposits formed by the transgression of barrier sequences over the restricted marine platform and sabkha environments represented by Gipshuken Fm strata (Fig. 16). This basal development grades upwards into the spiculitic shales/siltstones and cherts which form the most abundant lithofacies of the formation, especially in trough areas.

Abundant trace fossils, such as *Zoophycos*, clearly indicate low energy, but oxygenated, bottom environments well below normal wave base. Various interbedded units include bioclastic or sandy shoals and massive chert bodies interpreted

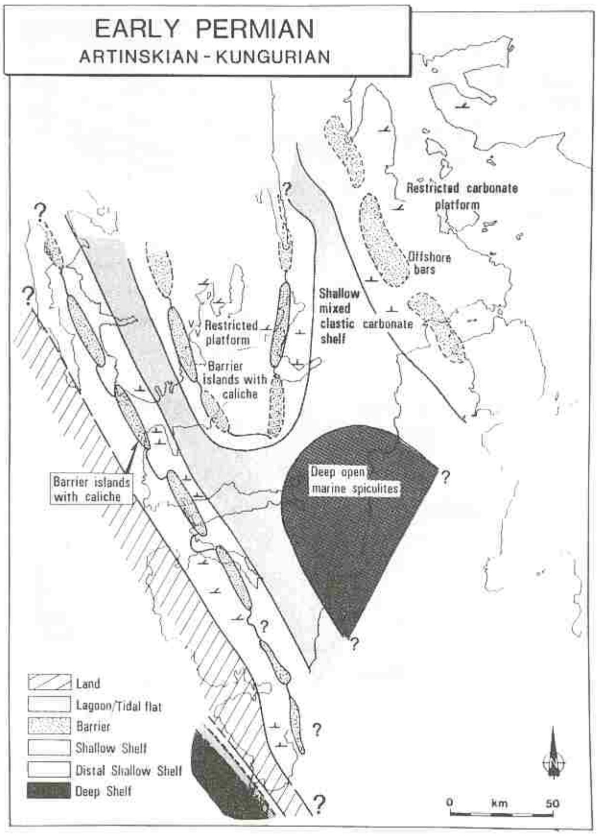

Fig. 16. Artinskian—Kungurian palaeogeography.

as organic (sponge) buildups. Shoals are most common on eastern platform areas (Figs. 15 and 17), whereas organic buildups tend to be concentrated along platform margins. Thin developments of these facies in trough areas may have developed at times of regional low sea-level stand. Sandstones are found only in the uppermost part of the sequence in northwestern exposure areas — these have a high glauconite content (<30%) and are heavily bioturbated; both features suggest relatively low rates of deposition in intermediate water depths.

Southwestern exposure areas of the Kapp Starostin Fm show a major coarsening-upwards sequence wedging onto the margins of the Sørkapp-Hornsund High (Fig. 15). Thinnest sequences immediately adjacent to the high show either fine-grained silty limestones or complex highly condensed sequences with both intra- and extraformational clasts. Both facies types rest on eroded or karstic surfaces of the Gipsdalen Gp and no sequences of the Kapp Starostin Fm have yet been found overlying Lower Carboniferous or earlier units on the high itself. The Tokrossøya Fm to the southwest of the high also shows a large-scale coarsening-upwards sequence, passing from spiculitic siltstones into sandstones interpreted as beach sands (Siedlecka, 1970) or peritidal sand waves (Hellem and Worsley, in press). The total development along both margins of the Sørkapp-Hornsund High suggests that the transgression which initiated the group's deposition may have submerged this structure, but subsequent uplift produced the coarsening-upwards sequences observed on both sides of the high. The sandstones of northwestern exposures may reflect similar lineamental movements rather than a general northern tilting of the entire depositional platform: note that youngest units in northeastern areas show a deep shelf spiculitic facies (Fig. 18).

The Miseryfjellet Fm of Bjørnøya consists of sandy limestones and well-sorted sandstones deposited in shallow well-agitated environments. The newly submerged structure which had de-

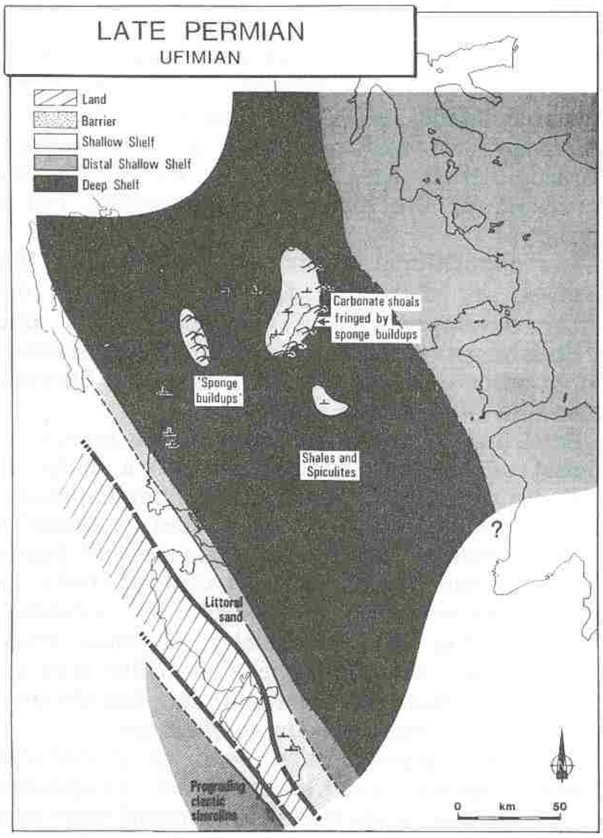

Fig. 17. Ufimian palaeogeography.

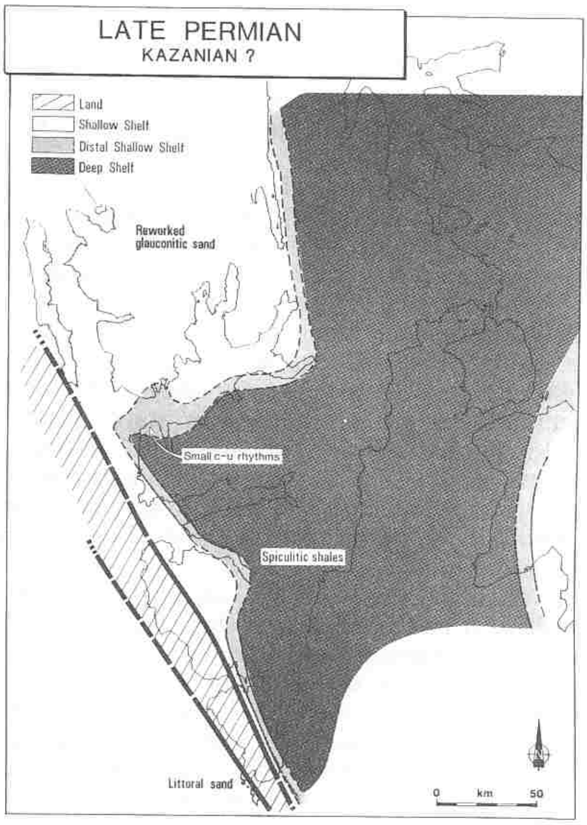

Fig. 18. (?)Kazanian palaeogeography.

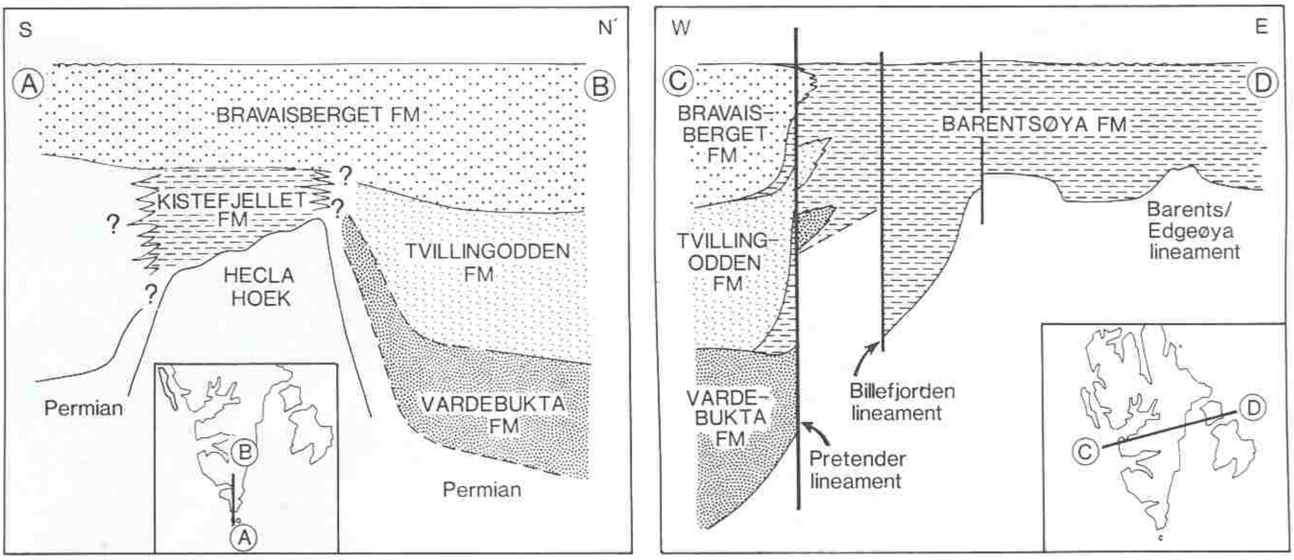

Fig. 19. Schematic cross-sections showing the development of the Sassendalen Gp.

veloped after the cessation of faulting activity in this area was evidently still a positive feature.

Although datings are uncertain and conflicting, the uppermost beds of the group throughout Svalbard are probably not younger than the Kazanian; the duration, cause and nature of the hiatus between Permian and Triassic deposits is, as in many other areas, poorly understood.

THE MESOZOIC DEPOSITIONAL PLATFORM

The Mesozoic development of Svalbard is characterized by genererally stable platform environments throughout the archipelago. There is little evidence of active faulting, except around the Jurassic—Cretaceous boundary — a period also marked by intrusive and volcanic activity. Major breaks in deposition are characteristic of the early Jurassic of western areas and of the late Cretaceous of the entire region. The clastic sequences of this depositional phase are dominated by marine shales; several major sandstone sequences occur, however, reflecting coastal and deltaic progradations from both the Palaeo-Hornsund Fault Zone and from northern and eastern uplifted areas.

Sassendalen Group

The group consists of marine shales, with subordinate siltstones and sandstones, ranging in age from Griesbachian to Ladinian. Appreciable thickness variations are closely related to downwarping over the sites of earlier active lineaments and a maximum thickness of 700 m is seen in the St. Jonsfjorden trough between the Sørkapp-Hornsund High to the southwest and the Nordfjorden Block to the east (Fig. 19). Western areas of Spitsbergen display a clear three-fold division, passing eastwards into the laterally correlative but finer grained Barentsøya Fm and southwestwards into an attenuated sequence on the Sørkapp-Hornsund High.

Basal shales and siltstones with Griesbachian faunas disconformably overlie siliceous siltstones and sandstones of the Tempelfjorden Gp, but an erosive contact is only rarely demonstrable. Basal conglomerates are only developed on the Sørkapp-Hornsund High; these overlie various Hecla Hoek and early Carboniferous units and mark the Dienerian submergence of this structure.

The three coarsening-upward sequences of the western exposure belt suggest a regionally transgressive regime interrupted by repeated coastal progradations caused by ongoing uplift, perhaps along the Palaeo-Hornsund Lineament. Sandstones in the (late Griesbachian) upper parts of the Vardebukta Fm around Isfjorden are interpreted as barrier systems with tidal inlets and are associated with lagoonal back-barrier units (Fig. 20). Less prominent sandstone units in southern localities suggest more open marine environments, while the Sørkapp-Hornsund High was either the site of very shallow shoals or was intermittently emergent throughout the Griesbachian. Transgression in the early Dienerian submerged the high completely and led to the development of finely-laminated dark shales in the lower parts of the Tvillingoden Fm in basinal areas. This formation's marked coarsening-upward sequences in southern areas terminate in delta-front sandstones. A major transgression in the Lower Anisian is marked by the black phosphatic shales of the lower parts of the Bravaisberget Fm. These again coarsen up through delta-front deposits to tidally influenced channels developed on a delta plain located on the Sørkapp-Hornsund High (Fig. 21).

Central and eastern areas of Svalbard show a more homogeneous shale development now assigned to the Barentsøya Fm. This formation has its thickest development (420 m) in the Billefjorden Trough, thinning gradually to about 200 m in eastern Edgeøya. Its three component members are general time equivalents to the formations of western areas; the two lowest members show varying contents of interbedded thin silts in the shales. The uppermost Botneheia Mbr shows a weak coarsening-upward trend from soft, organic-rich, shales to somewhat more silty beds. This uppermost member is rich in organic carbon (mean 5—7%) composed mainly of marine kerogens, and has an interesting source rock potential. Although there is no suggestion of large-scale sediment

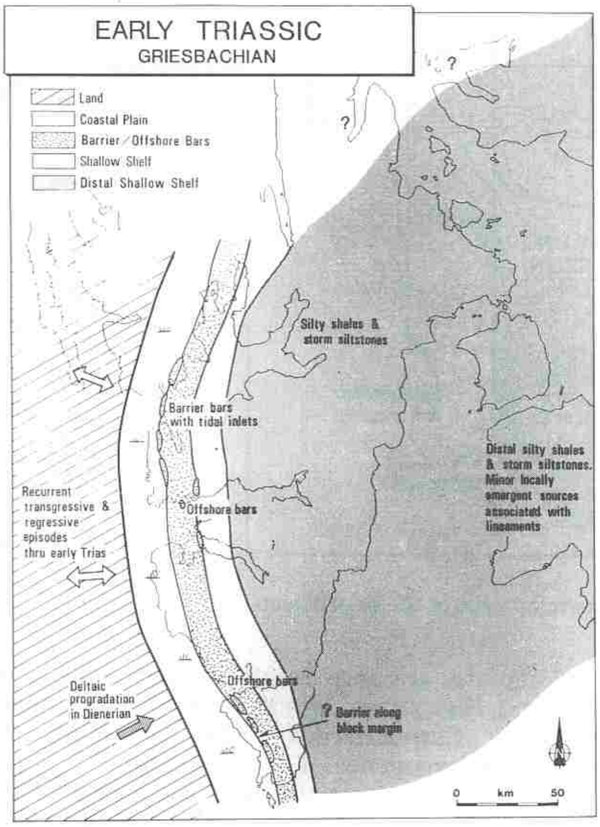

Fig. 20. Griesbachian palaeogeography.

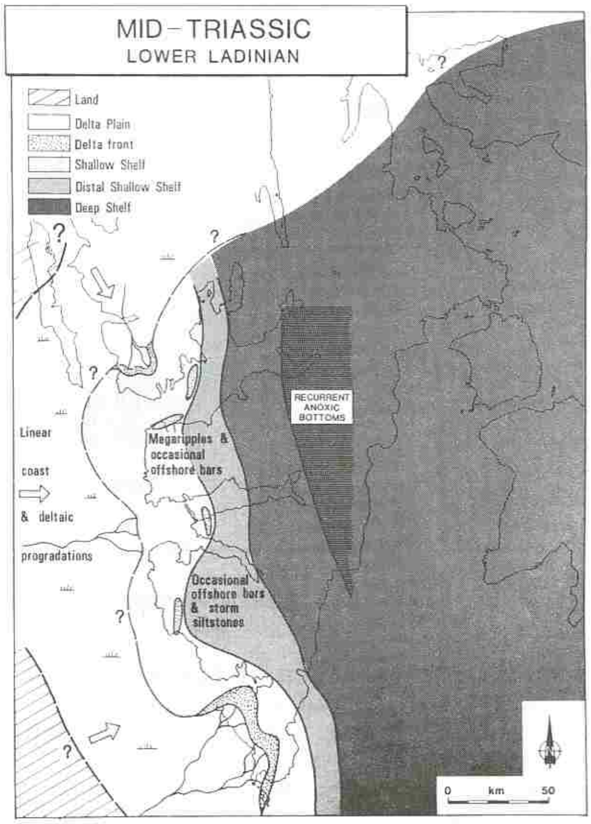

Fig. 21. Lower Ladinian palaeogeography.

transport from the east or northeast we note that organic geochemical studies show no simple W—E reduction in land-derived organic matter, as might be expected if the only source area was to the west.

Kapp Toscana Group

The junction between the Sassendalen and Kapp Toscana Gps may reflect a mid-Ladinian hiatus in many localities; present evidence suggests a period with low sedimentation rates which produced marked horizons with condensed faunal assemblages.

The deposits of the Kapp Toscana Gp represent two broadly regressive sequences; sedimentational patterns reflect an important change in depositional and tectonic regimes around the Norian/Rhaetian transition.

The Ladinian to Norian sequence of the combined (<550-m thick) Tschermakfjellet and De Geerdalen Fms forms an eastwards-thickening wedge, with significant local increases over the margins of the Sørkapp-Hornsund High and the Nordfjorden Block (Fig. 22). We note that although the De Geerdalen Fm's strata have earlier been

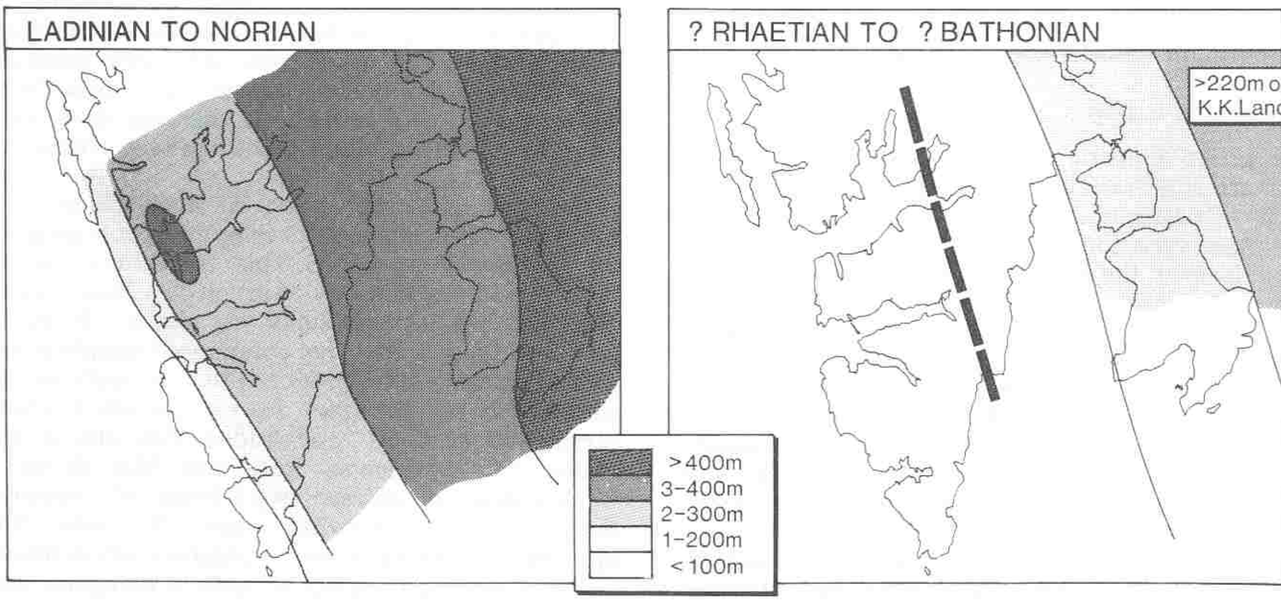

Fig. 22. Isopach maps of the two main depositional sequences in the Kapp Toscana Gp.

referred to as 'continental' or 'fresh-water' in origin, delta plain environments have only been detected in restricted parts of some northeastern and southwestern exposures. Deltaic influx clearly influenced late Triassic depositional regimes in many other areas, but most exposures demonstrate wave and storm reworking of deltaically introduced sediments in marine environments (Fig. 23).

The late Triassic sequences of western areas appear to represent a natural continuation of the coastal progradations seen in the underlying Sassendalen Gp. Fluvial dominated channels low in the sequence around Hornsund show that delta plains now extended further east and north than earlier. Channel sequences have not yet been found in northwestern exposures; repeated, small (5–15 m), coarsening-upward rhythms there suggest deposition in marine environments adjacent to major delta lobes. Present data suggest decreasing deltaic influence and more extensive marine reworking upwards in the west as eastern deltaic systems become dominant; maximal basin subsidence also shifted eastwards to Barentsøya, Edgeøya and Hopen during this depositional phase. Sequences in these eastern exposure areas show a progradation from prodelta shales into delta front deposits with wave-reworked mouth bar and barrier sands. Delta plain environments, with occasional thin coals in interdistributary areas, advanced westwards and southwestwards through the Carnian and Norian and at their maximum extent were developed over large areas of Barentsøya and Edgeøya (Lock *et al.*, 1978). Synsedimentary deformation, interpreted as growth faults in delta-front areas by Edwards (1976a), is now known from several localities on these islands. Eastern and central areas of Spitsbergen also show coarsening-upward sequences, but sandstone units there represent offshore bars reworked by wave and storm processes on a marine platform. Some of these sand bodies had temporarily emergent tops and the rhythmicity developed clearly reflects deltaic processes to the east; however, the entire development in these areas shows the overriding imprint of marine distribution and deposition of sediments introduced onto the platform. A major question, not yet resolved, is whether these sequences formed in a marine embayment closed to the north. On balance, present evidence suggests an open seaway between western and eastern source areas; this contrasts with the situation which developed in the Cretaceous and Tertiary, with uplifted northern land areas.

The uppermost part of the Kapp Toscana Gp in western Spitsbergen is represented by thin sequences which represent intermittent deposition between the Norian/Rhaetian and the mid-Jurassic. Thicker developments in eastern areas led Worsley (1973) to define the Wilhelmøya Fm, comprising a coarsening-upward unit developed east of the Billefjorden lineament (Fig. 24; see also Pcelina, 1980).

This interval has now been recognized in all exposure areas west of the Billefjorden lineament; thin (5–45 m) developments of sandstone and shale in central and northwestern areas represent widespread transgression in the Norian/Rhaetian and again in the Toarcian/Bajocian, with an intervening long period of non-deposition (although

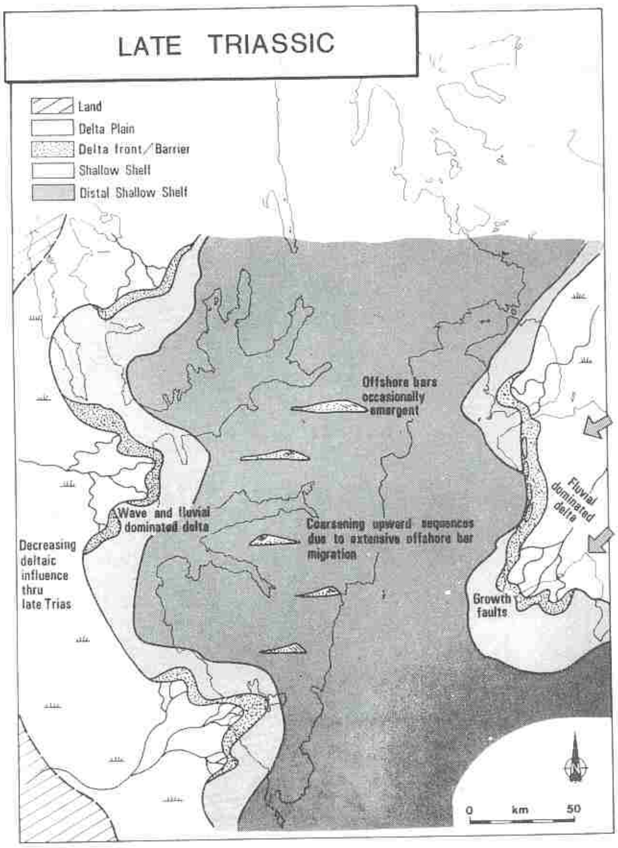

Fig. 23. Late Triassic palaeogeography, composited for the Carnian–Norian.

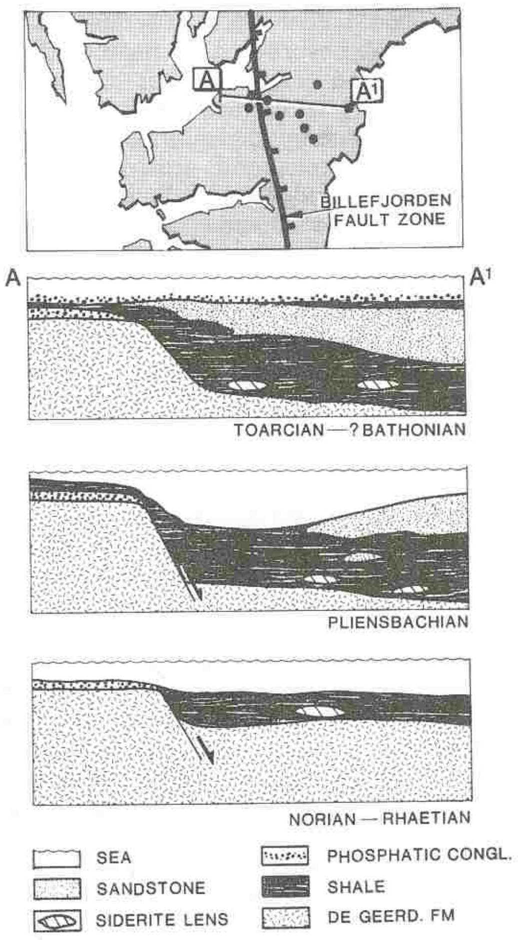

Fig. 24. Schematic cross-section showing the development of the Wilhelmøya Fm over the Billefjorden Lineament.

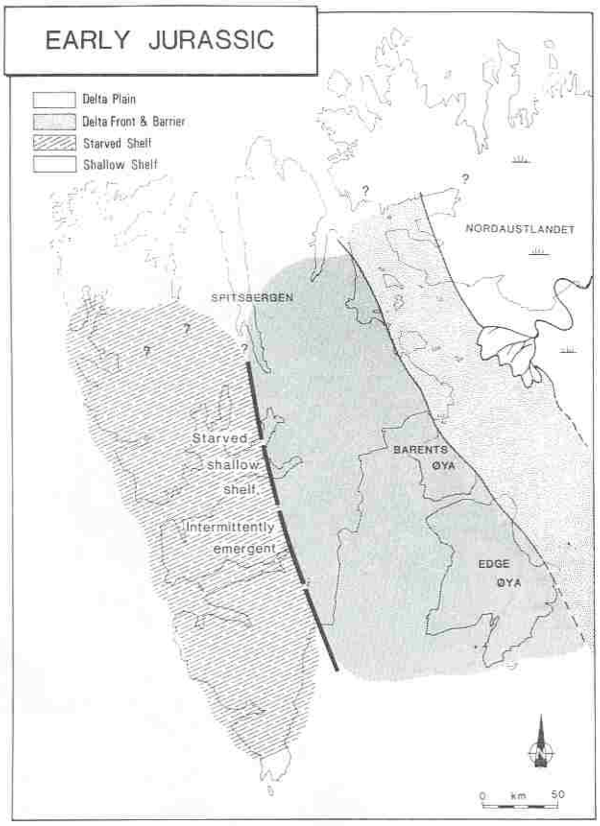

Fig. 25. Early Jurassic palaeogeography, composited Hettangian—Pliensbachian.

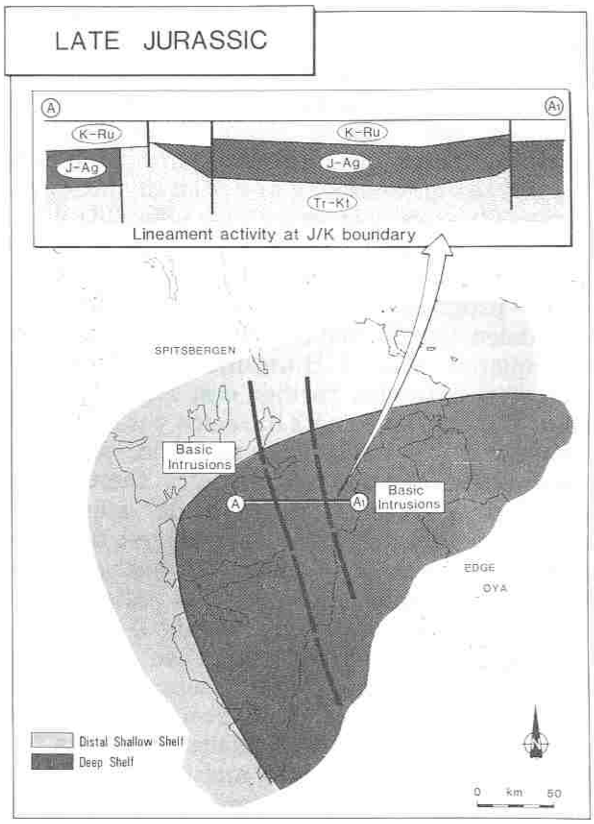

Fig. 26. Late Jurassic palaeogeography, composited for Callovian—Kimmeridgian. Abbreviations: Jurassic (J), Cretaceous (K), Triassic (Tr), Kapp Toscana (Kt), Agardhfjellet (Ag), Rurikfjellet (Ru).

highly condensed Pliensbachian sequences are also seen locally). Exposures on or near to the earlier Sørkapp-Hornsund High consist of well-sorted quartz sandstones with trace fossils and structures suggesting high energy depositional environments; frequent lag horizons and erosive surfaces also indicate highly condensed sedimentation in this area. In contrast to all older units, this sequence tends to thicken slightly on to the earlier horst structure. The top of the group is clearly marked in all areas by the phosphatic and quartzitic conglomerates of the Brentskardhaugen Bed. Phosphatic nodules contain remanié faunas of Toarcian/?Bajocian age, but the conglomerate itself was probably deposited in the late Bajocian or Bathonian. It clearly represents the beginning of a regional transgression leading to deposition of the overlying black shales of the Janusfjellet Fm.

Equivalent sequences east of the Billefjorden lineament thicken to 120 m on Wilhelmøya, and to >220 m on Kong Karls Land. Such young deposits are not preserved on Edgeøya and Barentsøya, but the lower parts of a similar unit on Hopen are 135-m thick. When traced eastwards the succession thickens, contains fewer breaks and takes on a more proximal character. The section on Wilhelmøya coarsens upwards from marine shales to mouth-bar or coastal sands while Kong Karls Land shows a development from marine shales through barrier sands into back-barrier lagoons (Worsley and Heintz, 1977; Løfaldli and Nagy, 1980). Thus, while western areas of Spitsbergen developed as a positive block only intermittently transgressed at times of high sea-level, eastern areas were the site of more continuous sedimentation with renewed deltaic progradation from the northeast (Fig. 25). There is a marked mineralogical contrast between the immature lithic wackestones of the De Geerdalen Fm and the mature quartz sandstones of the Wilhelmøya Fm. Regional and stratigraphical evidence suggests that this reflects lower rates of deposition and consequent more extensive reworking of the younger unit's sands, rather than palaeoclimatic variation or changing source areas. Although the Brentskardhaugen Bed is also seen in areas east of the Billefjorden lineament, more continuous deposition eastwards led to this unit becoming less well marked and it has not been found on Kong Karls Land.

Adventdalen Group

The group comprises three superimposed, but diachronous, formational units: open marine shales (<800 m) of the Janusfjellet Fm (Callovian to Hauterivian); deltaic sandstones (<150 m) of the Helvetiafjellet Fm (Barremian to ?Aptian); mixed marine sequences (<850 m) of the Carolinefjellet Fm (Aptian to Albian).

Barremian alluvial influx was a response to regional uplift of Spitsbergen, particularly in the north; thickening of alluvium along the west of the basin and local sediment dispersal from the same direction suggest, however, that uplands along the line of the incipient Hornsund Fault Zone were also source areas. Terrigenous input was evidently great, but it was outpaced both by basinal subsidence and by a eustatically rising sea-level, so that the alluvial-deltaic system and its distal equivalents progressively onlapped older strata northwards.

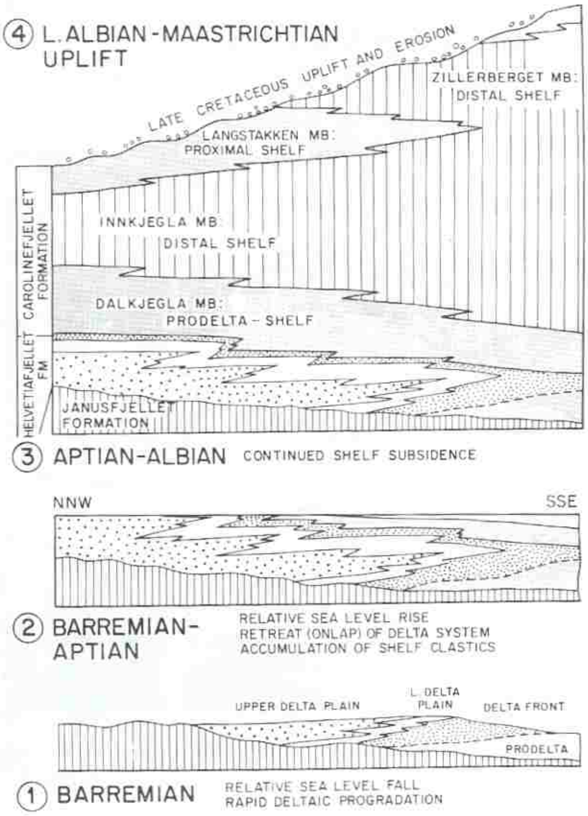

Fig. 27. Schematic cross-sections showing the early Cretaceous development of Spitsbergen on a north to south traverse.

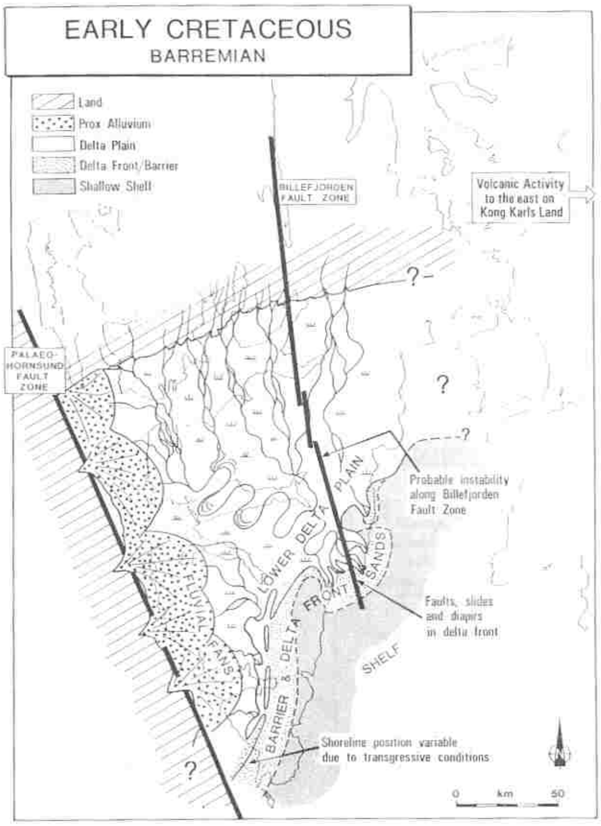

Fig. 28. Barremian palaeogeography.

Apart from these large-scale trends, local tectonic unrest is otherwise indicated by: thickness changes in the Janusfjellet Fm's shales over the Billefjorden and Agardhbukta Fault Zones; synsedimentary faulting and sliding in the Barremian delta front sequences adjacent to the Billefjorden lineament at Kvalvågen; and Barremian to ?Aptian volcanic activity in eastern Svalbard (notably on Kong Karls Land), as well as dolerite sill intrusions in the late Jurassic and early Cretaceous throughout the region.

The Janusfjellet Fm comprises variable thicknesses of dark shales and mudstones; thickest developments (<800 m) are seen along the western basin margins. Thinner sequences in central and eastern areas show marked thickness variations over the Agardhbukta and Billefjorden lineaments. The dark shales of the Agardhfjellet Mbr (Callovian to Volgian) suggest continuing transgression and the development of deep and often anoxic shelf environments. Organic carbon contents achieve maxima of 12% in Callovian paper shales (Dypvik, in press) but otherwise vary between 1% and 4%. Increasing interbeds of bioturbated sandstone to the west and north, especially in the lower parts of the member, prompt the reconstruction of Fig. 26. Differential subsidence along the Billefjorden and Agardhbukta lineaments in the late Jurassic culminated in marked movements in the earliest Cretaceous (Parker, 1966). A contemporaneous minor break in deposition throughout central and eastern Spitsbergen was followed by renewed fine clastic sedimentation; the bioturbated mudstones of the Rurikfjellet Mbr (Berriasian to Hauterivian) are enriched in volcanogenic debris and have a higher silt and lower organic carbon content than the underlying shales. The Rurikfjellet Mbr of central areas shows a weak upward coarsening sequence, often not detectable in the field, and prodelta shales may be sharply and directly overlain by deltaic sand (Fig. 27). A different situation is seen in the south, where deposition appears to have been continuous through the late Jurassic to early Cretaceous and gradual transitions from prodelta through delta-front to delta plain sequences are well developed (Edwards, 1976b). This geographic variation is further discussed below.

The non-marine (albeit coastal) nature of much of the Helvatiafjellet Fm has long been known, not least because it is coal-bearing. Analyses of the unit show that it contains fluvial, bay, mouth-bar, wave-dominated shoreline and shelf elements (Fig. 28) and that a deltaic rather than purely alluvial setting is likely (Steel, 1977; Steel *et al.*, 1978). Spectacular examples of rotational block faults, slides, and mudflows are seen in the distributary channel and delta front deposits of the unit on coastal cliffs north of Kvalvågen.

Evidence that the Helvetiafjellet Fm sandstone belt is diachronous, younging northwards includes: the lack of significant lateral facies changes southeastwards towards the palaeocoast, over a distance of more than 200 km; alluvium is no finer distally (Kvalvågen—Agardhbukta) than it is some 150 km to the northwest in exposures near to source areas; marine sandstones are more common in northwestern than southeastern exposures.

These anomalies can be best accounted for by postulating a diachronous sandbody complex, where alluvial facies always pass southeastwards, along time lines, into marine facies within less than 100 km. A gradual northwestwards retreat of both alluvial and coastal tracts, onlapping the Janusfellet

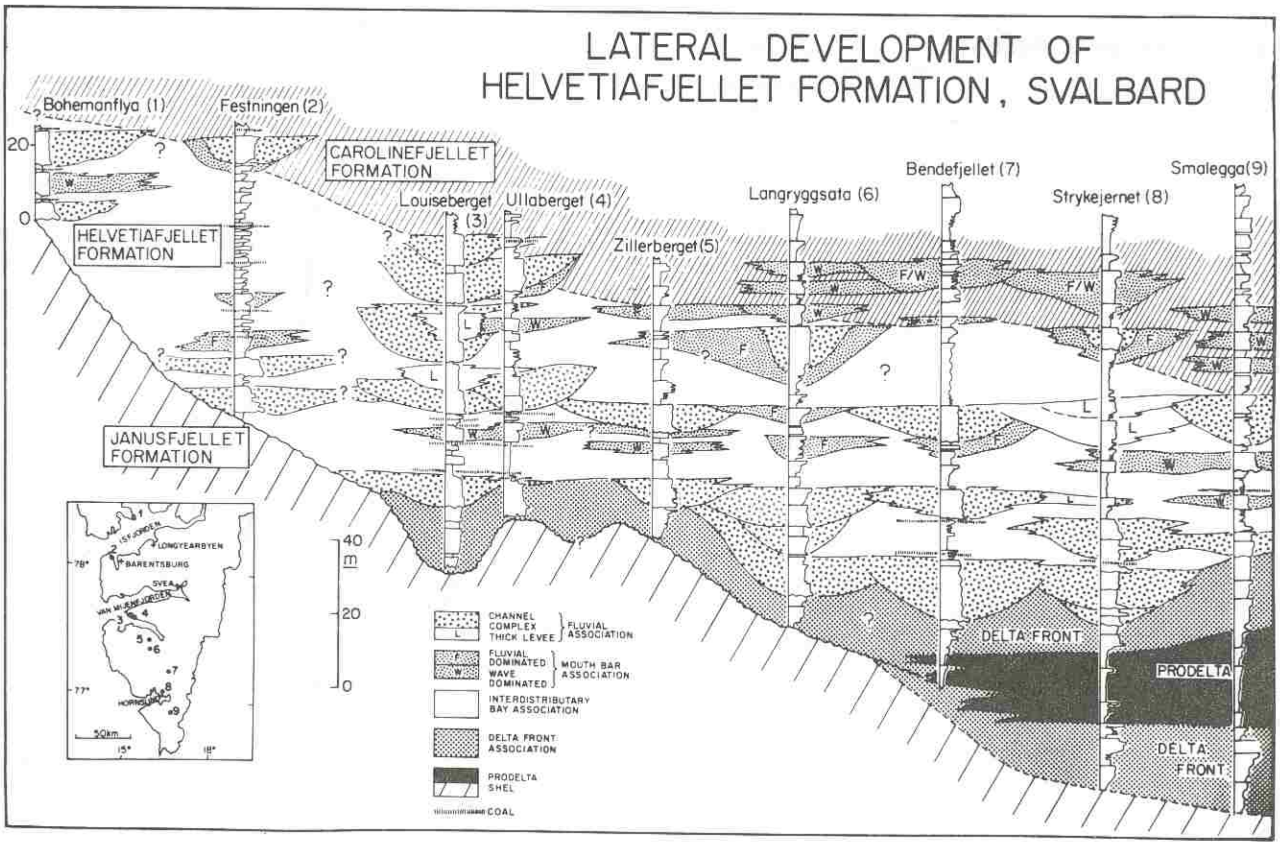

Fig. 29. Lateral development of the Helvetiafjellet Fm, suggesting the northwards-younging diachronous model presented herein.

Fm surface possibly through both Barremian and Aptian time, caused the present great lateral extent of the sandbody. Independent evidence of an important eustatic sea-level rise in early Cretaceous times (Vail *et al.*, 1977) is consistent with the proposed transgressive nature of the succession on Spitsbergen, though we believe that most of the relative sea-level rise may be accounted for by subsidence.

We have already noted the important contrasts in early Cretaceous development in the region north of Van Keulenfjorden as compared with that in the south. In the north, fluvial sediments commonly overlie the Janusfjellet Fm shelf deposits abruptly, whereas in the south there is a transition through thick marine sandstones (delta front/barrier) and lagoonal shales (Fig. 29). This contrast may reflect a general downcutting of the fluvial systems on the delta plain as well as the erosive and diachronous nature of the sandstone in the north. Alternatively, it may simply be due to a northwestwards change in the coastal configuration, from a wave-dominated regime in the south to a more strongly fluvial-dominated deltaic regime in the north.

Up to 850 m of alternating sandstones, siltstones and shales of the Carolinefjellet Fm overlie (and are probably partly laterally equivalent to) the coalbearing deltaic sequence. The overall environmental interpretation is of shelf sedimentation, although three sandier levels in the succession suggest lower delta front facies. The latter are commonly organized into upward coarsening sequences (<15-m thick) representing delta lobe progradation (Steel, 1977), although abandonment (carbonate-rich) and transgressive (upward fining) sequences have also been identified (H. Ramberg-Moe, personal communication, 1980). Overall wave-domination and the importance of storm waves and storm-induced bottom currents on the shelf is emphasized by the abundance of wave-generated ripple lamination and of hummocky cross-stratification in the Carolinefjellet Fm.

In the speculative palaeogeographic reconstruction of Fig. 30, the coastline, compared with its Barremian position, has receded northwards, and there is evidence for the importance of a northeasterly provenance in addition to some sediment input from the northwest.

Late Cretaceous Uplift

Spitsbergen was uplifted and subject to erosion in late Cretaceous times, preferentially in the north because erosion cuts deeper into Carolinefjellet Fm strata there (Fig. 27). Lower Palaeocene strata thus overlie Albian strata in southeastern areas and Aptian strata in the northwest of the basin (Nagy, 1970). This uplift of the northwestern edge of the Barents Shelf was probably part of a doming related to development of the Arctic Basin to the north, and was also an immediate precursor to large-scale transtensional tectonics along the western margins of Svalbard.

THE TERTIARY RIFT BASINS

The Tertiary basins of Svalbard developed during considerable tectonic upheaval, in contrast to the relative quiet of Mesozoic conditions. Detailed

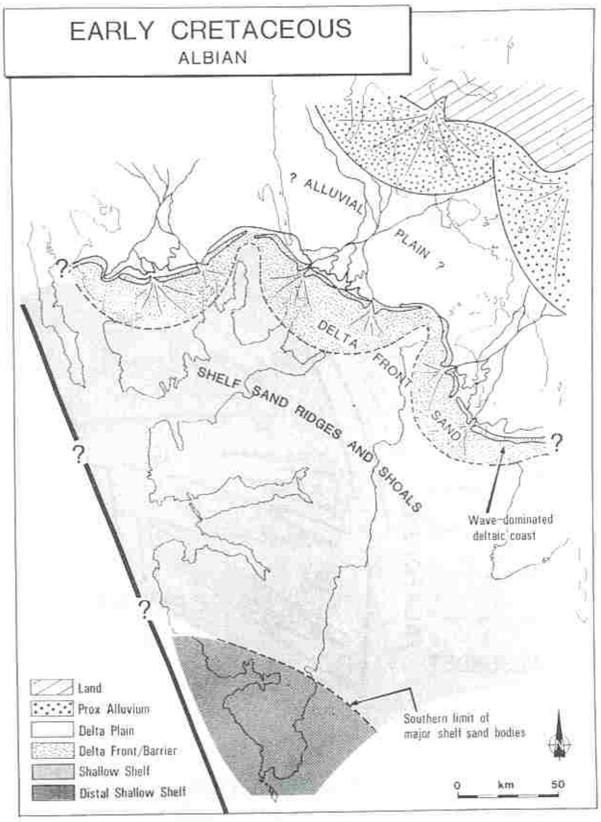

Fig. 30. Albian palaeogeography.

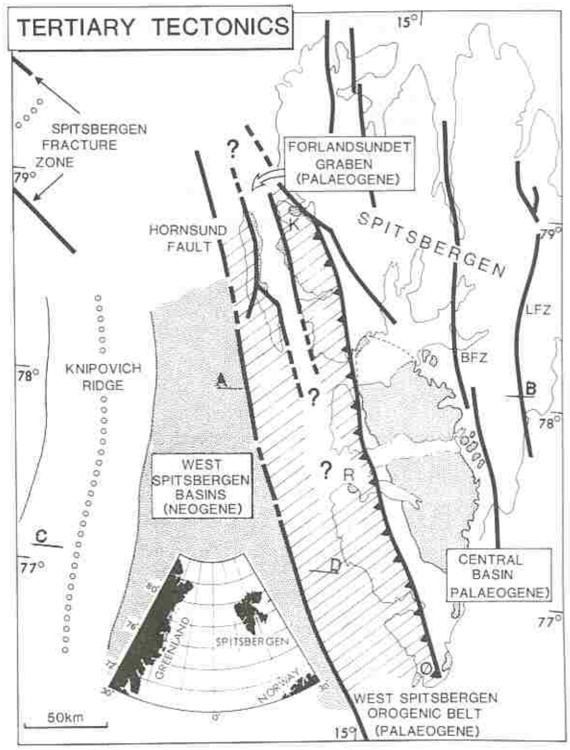

Fig. 31. Tertiary tectonic framework and sedimentary basins. Small Tertiary exposures in Kongsjorden (K), Reinardodden (R) and Øyrlandet (Ø) are indicated. The Billefjorden (BFZ) and Lomfjorden—Agardhbukta (LFZ) Lineaments are also shown. The rift basins west of the Hornsund Fault are mainly of Neogene age, but probably originated in late Palaeogene times.

interpretations of Tertiary sedimentation are critical to an understanding of the development of the oblique-slip mobile belt in West Spitsbergen and of the later continental margin, discussed in many papers (Harland, 1969; Birkenmajer, 1972; Lowell, 1972; Kellogg, 1975; Steel *et al.*, 1981). Figure 31 shows the three main basins of Tertiary sedimentation in relation to the West Spitsbergen Orogenic Belt. The Central Basin (Van Mijenfjorden Gp and probably also the Forlandsundet Graben (Forlandsundet Gp) are of Palaeogene age. The former probably originated somewhat earlier than the latter, but both are a consequence of oblique-slip movement along the orogenic belt. The larger basinal area west of the fold belt is probably mainly Neogene in age and developed after the change from sheared to rifted margins around 36 Ma (Talwani and Eldholm, 1977).

Van Mijenfjorden Group

The Van Mijenfjorden Gp is subdivided schematically as shown in Fig. 32. The succession is generally accepted as being of Palaeocene—Eocene age (Harland, 1969), though Livsic (1965) has suggested that it may, in part, be Oligocene. The latter is now less likely in view of a late Palaeocene dating for the upper regressive sequence (Manum and Throndsen, 1978).

The Central Basin succession thickens from northeast (1.5 km) to southwest (2.5 km), reflecting mainly a Palaeocene basin asymmetry towards the sheared margin (Fig. 32). The original thickness of the Palaeogene pile was <1.5 km greater, as judged by vitrinite reflectance data (Manum and Throndsen, 1978).

The early Palaeocene development of the Central Basin is shown in Fig. 34. Sedimentation took place in (and possibly, in part, prior to) a tensional tectonic setting on the flank of the shear zone between Greenland and the Barents Platform. That this early setting was tensional (superimposed on the regional 'shear' regime) is suggested by: the marked thickness asymmetry of the basinfill towards the west; the overall transgressive nature of the succession from coaly sequences up through wave-dominated deltaic sequences to shelf and prodelta sequences; the scarcity of sediment supply from the shear zone into the basin.

The last observation reflects a lack of compression (uplift) along the sheared margin, while the former two probably indicate that rift-floor subsidence outpaced terrigenous influx. The transgressive succession is too thick to be explained merely by eustatic sea-level rise, though this factor may also have been important.

Figure 33 illustrates the main features of early Palaeocene deltaic sedimentation. A basal estuarine system and three overlying regressive deltaic units (Todalen Mbr) are of fluvial/tide-dominated character and have been discussed by Steel *et al.* (1981) and Nøttvedt (1981). It is from those sequences that coal is presently taken by Norwegian and Soviet mines at Svea, Longyearbyen and Barentsburg. The main reason for abundant coal at these lowest levels in the succession is evident from Fig. 33. The early deltas in the north were pro-

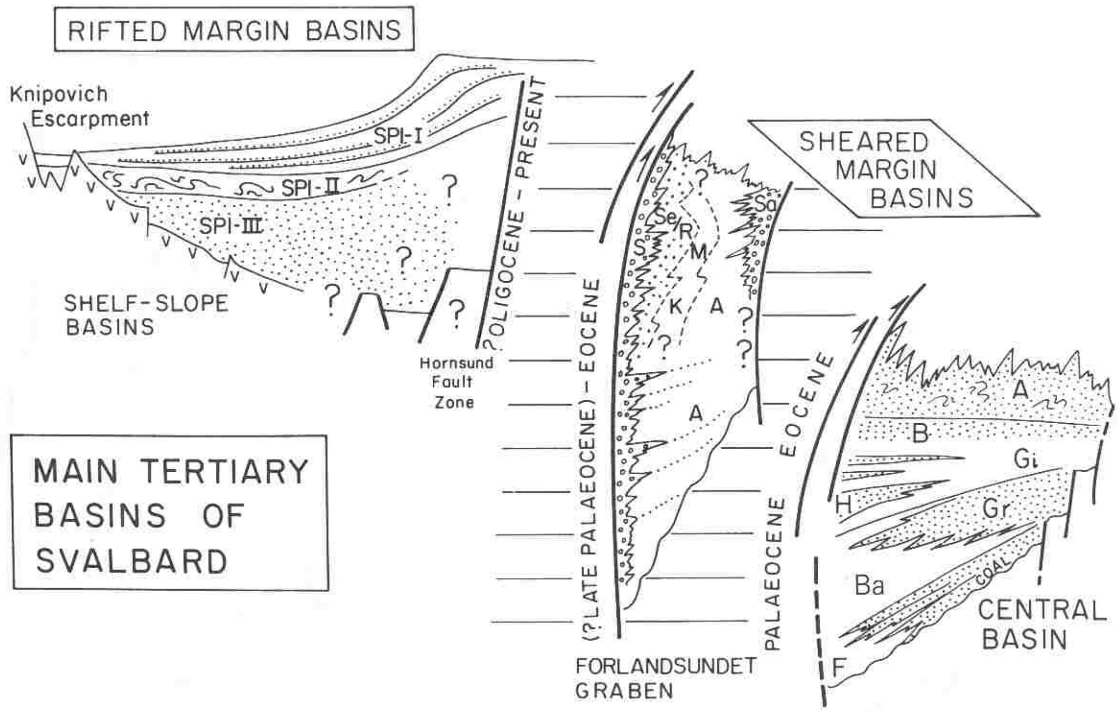

Fig. 32. Schematic cross-sections (not to scale) showing the development of Svalbard Tertiary basins. Central Basin: the Firkanten (F), Basilika (Ba), Grumantbyen (Gr), Hollenderdalen (H), Gilsonryggen (Gi), Battfjellet (B) and Aspelintoppen (A) Fms.

Forlandsundet Graben: the Aberdeenflya (A), Marchaise Lagune (M), Krokodillen (K), Reinhardpynten (R), Sesshøgda (Se), Selvågen (S) and Sarstangen/Sarsbukta (Sa) Fms. Marginal rift basin: sequences SPI–III to SPI–I represent depositional sequences suggested by seismic studies of Schlüter and Hinz (1978).

tected in a semi-enclosed embayment by the high-standing edge of a southern block. Later drowning of this barrier changed the coastal configuration and at least three more sand sequences, now wave-dominated (Endalen–Kalthoffbergen Mbrs), developed. The more open coastal regime was not conducive to coal development as there were no longer extensive delta plains. The early Palaeocene development is concluded by the prodelta-shelf siltstones and sandstones of the Basilika Fm, marking high sea-level stand and the culmination of transgressive (transtensional) conditions in the basin.

Late Palaeocene sedimentation in the Central Basin is less well understood as yet, but was dominated by a major regressive pulse of sedimentation (Kellogg, 1975; Steel *et al.*, 1981). This segment of the basin infill is also markedly asymmetric, thickening from northeast (<200 m) to southwest (>500 m), away from source areas and towards the shear zone. The sediments reflect shallow marine environments in the northwest (Grumantbyen Fm) and give way southwestwards to offshore/shelf siltstones and shales of the Basilika Fm (Fig. 32). During this phase of basin development rift subsidence no longer outpaced sediment influx. However, sediment influx is judged to have been low, as recorded by unusually intense bioturbation throughout this succession. This implies decreased subsidence rates in the basin, probably heralding the latest Palaeocene–Eocene transpressive conditions.

Eocene sedimentation in the Central Basin was dominated by a transpressive tectonic regime along the western margin. Signs of this type of setting are:

(1) the regressive nature of the entire latest Palaeocene–Eocene succession, and an upwards coarsening succession more than 1.5 km thick in places;

(2) influx of sediment from the *west* (already in late Palaeocene times) implying western uplift and a major shift in drainage patterns into the basin;

(3) unusual abundance and intensity of syn-sedimentary deformation in the uppermost 1 km of strata, probably earthquake-induced.

The lower 200–400 m of the succession consist of black shales and occasional siltstones of the Gilsonryggen Fm with a wedge-shaped deltaic sequence at its base (Dalland, 1977; Steel *et al.*, 1981). Intercalations of turbidites, slump sheets and occasional conglomerates formed on a fringe of easterly directed submarine fans (Fig. 35) occur increasingly upwards in the succession. Upwards coarsening is most marked by the incoming of barrier and wave-dominated deltaic sand sheets of the Battfjellet Fm, representing a prograding coastline. The marine sequence is then capped by the very thick succession of coastal and deltaic plain deposits of the Aspelintoppen Fm which show unusually intense signs of liquefaction and soft sediment deformation.

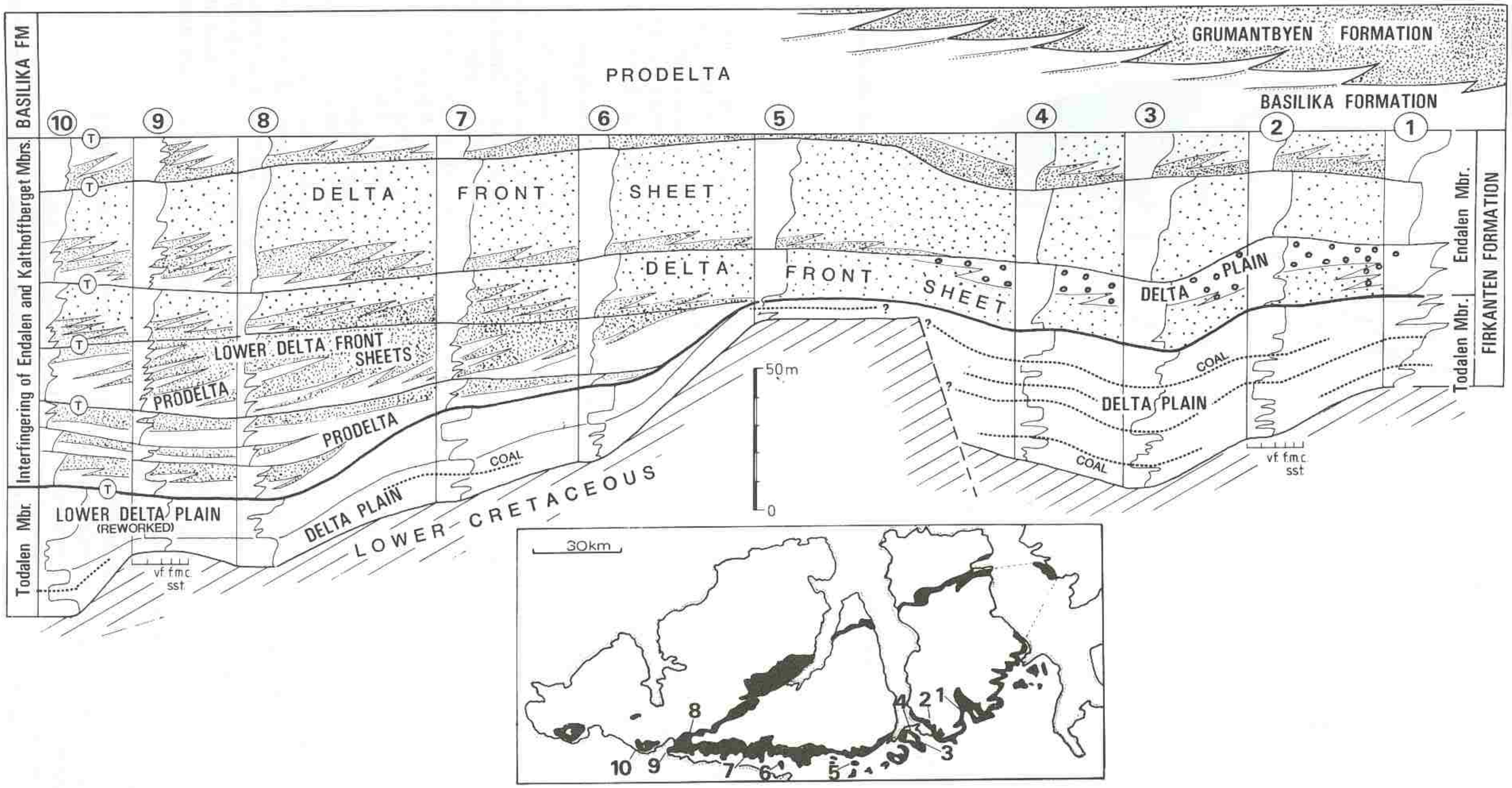

Fig. 33. Cross-section showing the tectonic control on coal development in the lower part of Firkanten Fm, in contrast to the later, more open, wave-dominated conditions (from Steel *et al.*, 1981).

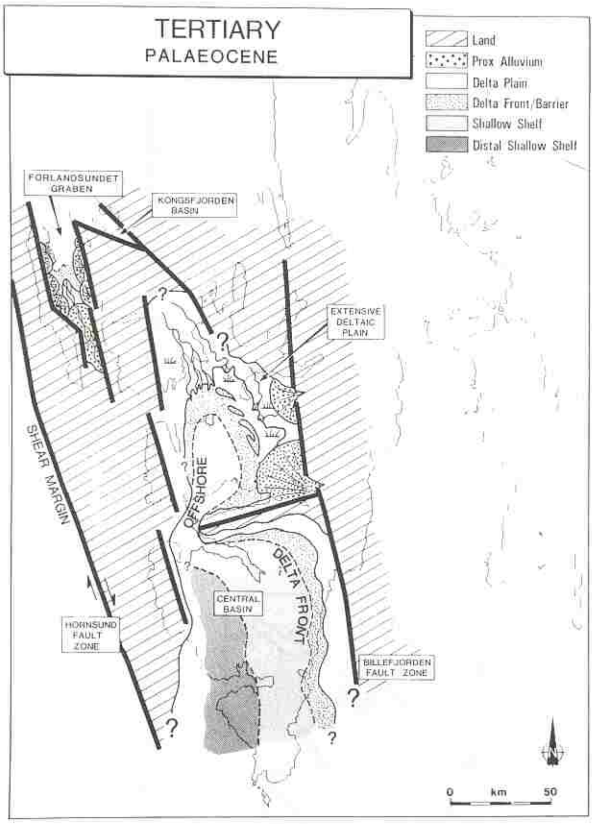

Fig. 34. Palaeocene palaeogeography. Forlandsundet Graben probably developed from latest Palaeocene times. The age of the Kongsfjorden Basin is uncertain.

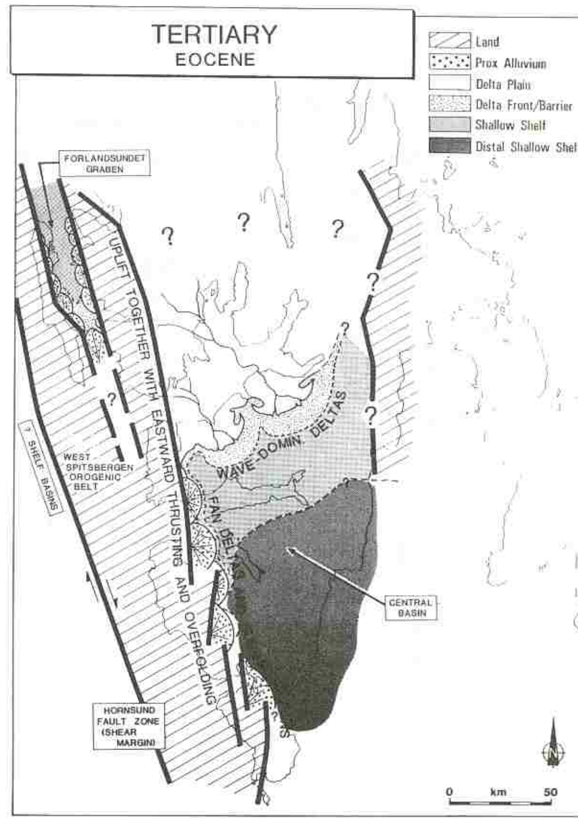

Fig. 35. Eocene palaeogeography.

Forlandsundet Group

Forlandsundet Graben is an elongate (<50 km), but narrow (<20 km) trough which is entrenched in the West Spitsbergen Fold Belt (Fig. 31). It displays a sequence with a stratigraphic thickness of more than 5 km (Rye-Larsen, 1982). Marine geophysical results from southern Forlandsundet suggest a thickness of some 3 km there (Sundvor *et al.*, 1977). Along both sides of the trough there are alluvial fan deposits (Selvågen, Sarsbukta and Sarstangen Fms). These interfinger basinwards with fan delta deposits (Sesshøgda and Reinhardpynten Fms) and other nearshore deposits (Krokodillen and Marchaise Lagune Fms). Much of the axial region of the basin, especially in the north, consists of submarine fan deposits of the Aberdeenflya Fm (Fig. 32).

Sedimentation patterns, trough asymmetry (deep to west), present structural attitude and the apparently great stratigraphic thickness of the succession suggest that the graben migrated southwards during infilling, and that the true vertical thickness at any point is less than 3 km. This evidence from the sediments themselves, together with evidence of NE-trending faults splaying from the western master fault and of deformation of the Tertiary deposits by NW-trending folds (Atkinson, 1962), strongly suggest that the graben developed and was infilled in an oblique-slip tectonic regime. We therefore suggest that Forlandsundet Graben formed somewhat earlier than has been previously assumed (Harland, 1969; Kellogg, 1975) and was probably a feature of the sheared margin rather than of the later rifted margin. Infilling is likely to have begun in the north of the graben in latest Palaeocene times, though development was mainly though the Eocene, as suggested by tentative dating of the youngest strata (Manum, 1962; Livsic, 1965).

Tertiary deposits west of Spitsbergen

A thick wedge of Tertiary deposits (Fig. 32) has been shown to underlie the continental shelf and slope off western Spitsbergen (Malod and Mascle, 1975; Sundvor *et al.*, 1977), while more recent surveys have defined this as a complex basinal area lying largely between the Knipovich Escarpment and the Hornsund Fault (Fig. 31). (Schlüter and Hinz, 1978; Sundvor *et al.*, 1979). Although there is general agreement as to the Plio-Pleistocene age of the uppermost part of this more than 6—7 km thick succession, there continues some debate as to whether the lower parts of the sequence are also largely Neogene (Talwani and Eldholm, 1977) or extend into the Palaeogene (Schlüter and Hinz, 1978). Steel *et al.* (1981) and Myhre *et al.* (1982) discuss this question in more detail.

THE TERTIARY OROGENY

The Tertiary fold belt

The Tertiary fold belt extends along the western coast of Spitsbergen for some 300 km, usually in a belt less than 50 km wide (Fig. 31). The first clear suggestions that this orogenic belt related to a

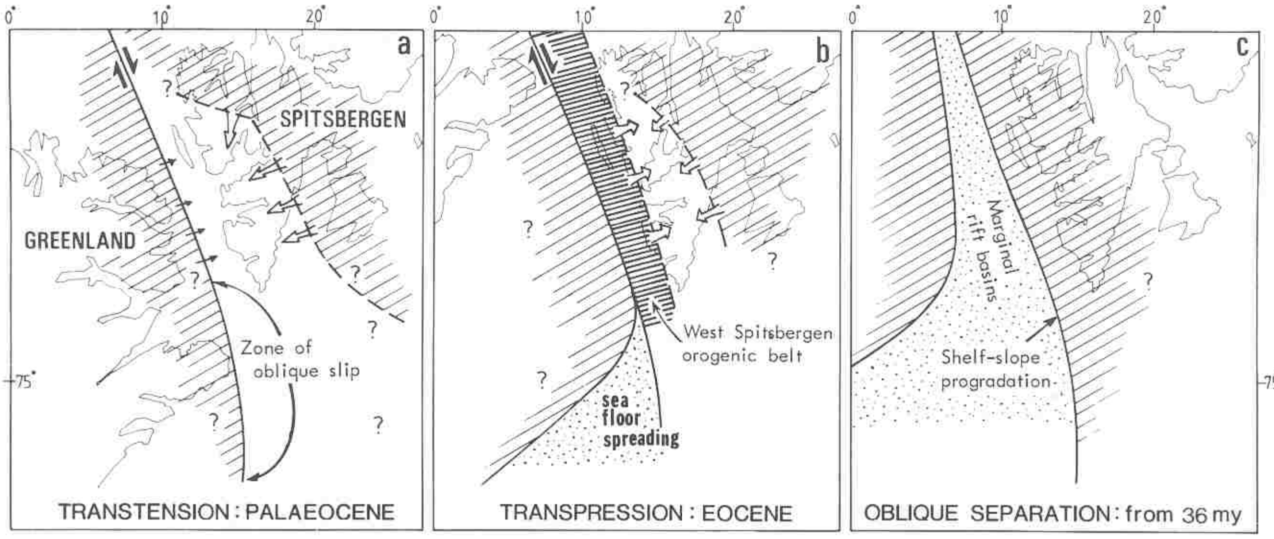

Fig. 36. The Tertiary evolution of the Norwegian-Greenland Sea (from Steel *et al.*, 1981).

major continental transform fault and to the opening of the Norwegian-Greenland Sea were made by Harland (1969), while Lowell (1972) and Kellogg (1975) elaborated upon details of the oblique-slip motion and associated tension and compression. The fold belt occurs along and adjacent to the steep western limb of the broad asymmetric syncline which presently contains Tertiary outcrops. Folds are generally strongly asymmetric and associated with major overthrusts in the southern and northern regions, all symptoms of eastwards directed compression. Signs of uplift and compression die out rapidly eastwards, so that deformation in central and eastern Spitsbergen is gentle, and often restricted to minor folds, faults or local thrusts associated with pre-existing major lineaments.

Sedimentation and tectonics: sequence of events

The following sequence of events summarizes the development of the oblique-slip mobile belt in western Spitsbergen, and its eventual transformation to a passive, rifted margin (Fig. 36).

Early—mid Palaeocene

Regional tension (probably transtension by mid-Palaeocene) and the initial development of a major continental transform fault zone; Central Basin subsidence leading to deltaic sedimentation in an overall transgressive setting; some of the major normal faults (e.g. those preserving Carboniferous strata along the west coast) may have originated at this time.

Late Palaeocene—Eocene

Growing compression (transpression) along the embryonic fold belt, uplift in the west and drainage reversal into the Central Basin, leading to the development of a megasequence of regressive character. Forlandsundet Graben probably originated at this time as an elongate, (southerly migrating) transpressional trough within the mobile belt.

Late Eocene—(?) early Oligocene

Climax of transpression (maximum impingement of Greenland and Svalbard) causing extensive overthrusting in the west; probable continued sedimentation in Central Basin, and minor folding.

Early Oligocene

Major change in tectonic regime; growing tension along western Spitsbergen with thinning of continental crust and location of spreading axis in Greenland Sea; sea-floor spreading and new oceanic crust formed west of Hornsund Fault; initial development of rifted margin and possible deposition of lower parts of sequence SPI—III of Schlüter and Hintz (1978) in grabens west of Hornsund Fault.

Mid Oligocene—Miocene

Increasing uplift of northwestern part of Barents block (Spitsbergen) and terrigenous influx (SPI—III to II, Fig. 32) to the new marginal basin.

Early Pliocene—Present

Eastwards shift of spreading axis in Greenland Sea to just beyond the Svalbard continental slope, 5—6 Ma (Eldholm and Sundvor, 1979), causing damming and overspill of terrigenous input from uplifted Svalbard (SPI—I, Fig. 32).

DISCUSSION

The main aim of this brief review has been to outline the status of present knowledge of the evolving depositional regimes reflected by the post-Caledonian strata of Svalbard. Our maps, figures and explanatory texts make a summary redundant; it is more relevant at this stage to note the limitations and perspectives of our work to date.

In spite of considerable research activity on Svalbard in recent years, much work remains to be done to test our models. The lack of precise biostratigraphical control on many units is a serious limitation to a full palaeogeographical application of many of the sedimentological analyses carried out to date. Reconstructions of the late Palaeozoic and Mesozoic evolution of western exposure areas are also still at an early

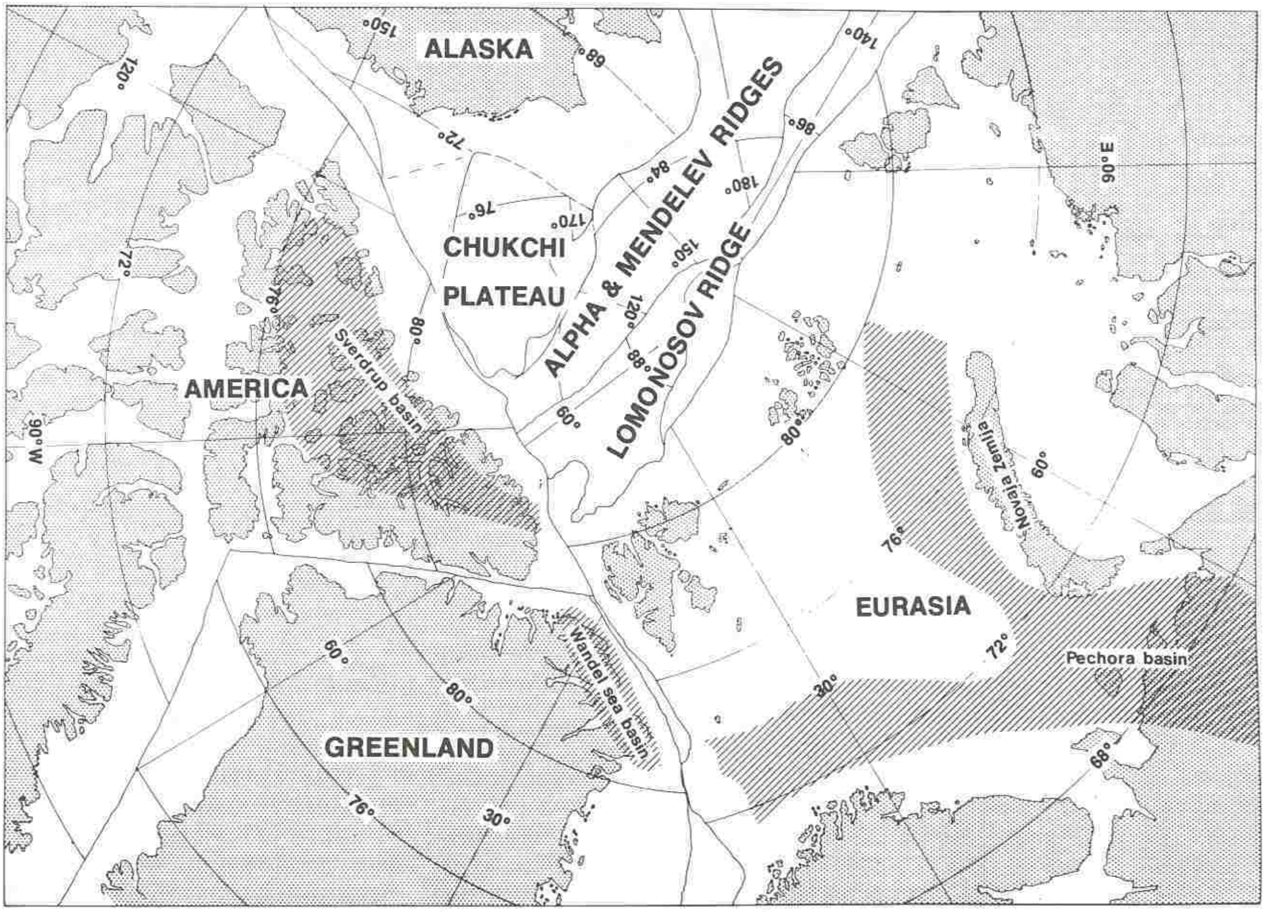

Fig. 37. Probable geographic relationships of the Sverdrup, Wandel Sea and Pechora Basins in relation to the Svalbard Platform during the late Palaeozoic and early Mesozoic.

stage; further work will demand extensive interdisciplinary co-operation in the fields of biostratigraphy, sedimentology and structural geology to establish the primary relations of the clearly parautochthonous sequences there. We hope, at least, that our interpretations will encourage a dynamic approach to continued investigations, not least to enable more meaningful extrapolations on to the Barents Shelf and adjacent northern Norwegian Shelf areas.

The Svalbard Archipelago's critical position near the northwestern margins of the Eurasian Plate is clear. Increased understanding of the dynamic stratigraphy of Svalbard's post-Caledonian strata and relations to the Pechora, Wandel Sea and Sverdrup Basins (Fig. 37) are essential for meaningful reconstructions of the evolution of both the Norwegian-Greenland Sea and the present Arctic Ocean. Comparisons of the sedimentational patterns displayed by these different basins will significantly augment present knowledge of the evolution of Arctic land, shelf and oceanic areas.

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APPENDIX I

Theses on Svalbard

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