The post-Caledonian development of Svalbard and the western Barents Sea

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Abstract

The Barents Shelf, stretching from the Arctic Ocean to the coasts of northern Norway and Russia, and from the Norwegian–Greenland Sea to Novaya Zemlya, covers two major geological provinces. This review concentrates on the western province, with its complex mosaic of basins and platforms. A growing net of coverage by seismic data, almost 70 deep hydrocarbon exploration wells and a series of shallow coring programmes, have contributed greatly to our understanding of this province, supplementing information from neighbouring land areas. The late Paleozoic to present-day development of the region can be described in terms of five major depositional phases. These partly reflect the continuing northwards movement of this segment of the Eurasian plate from the equatorial zone in the mid-Devonian–early Carboniferous up to its present-day High Arctic latitudes, resulting in significant climatic changes through time. Important controls on sedimentation have involved varying tectonic processes along the eastern, northern and western margins of the shelf, whereas short- and long-term local and regional sea-level variations have further determined the depositional history of the province.

The position of the Barents Shelf on the north-western corner of the Eurasian plate makes it a testing ground for a better understanding of the geological development of Europe, and of the entire Arctic Ocean. The shelf, covering an area of approximately 1.3 million km^2, is surrounded by onland exposures with widely varying geology. Only a synthesis of these, together with available knowledge of the subsurface of the shelf itself, can help us understand the geological development of this vast province, with its prognosed enormous—but as yet little explored and developed—petroleum potential (Fig. 1).

The Svalbard Archipelago, forming the subaerially exposed north-western margins of the shelf, covers a land area of only 63 000 km^2, which is less than 5% of the total area of the Barents Sea, but which displays a comprehensive overview of the geology of the entire region (Steel & Worsley 1984; Worsley et al. 1986; Harland 1997). Svalbard's position immediately south of the polar Euramerican Basin, and east of the Norwegian–Greenland Sea, puts it in a critical position to allow us to recognize many of the main features controlling the development of the western Barents Shelf. The general platform aspect of the archipelago makes it not entirely representative of areas further south, but many characteristic features are highly relevant for understanding the entire subsurface of the south-western shelf (Nøttvedt et al. 1993). Northern Norway, with its basement and Lower Paleozoic outcrops, represents the northernmost part of the Baltic Shield, with rocks affected by late Precambrian and Caledonide orogenies (Ramberg et al. 2008). This cratonic area was only occasionally onlapped during the late Paleozoic and Mesozoic, but its erosional products were important contributors to clastic Upper Paleozoic and Mesozoic hydrocarbon reservoirs on the south-western shelf.

Timan–Pechora to the south-east, with its foredeeps and inversion zones immediately adjacent to the developing Uralides in the late Paleozoic, shows a varied geology with many features of great relevance for eastern shelf areas (Ulmishek 1985). Novaya Zemlya is dominated by Permo-Carboniferous exposures in a complex facies array, perhaps reflecting the development of the archipelago as a component of the Ural–Taimyr orogeny, prior to Triassic westwards-directed thrusting and emplacement into its present position (Otto & Bailey 1995; Sobolev & Nakrem 1996). Franz Josef Land, with its exposures of Mesozoic sediments and volcanics, shows a development similar to that of the north-eastern Svalbard Platform (Solheim

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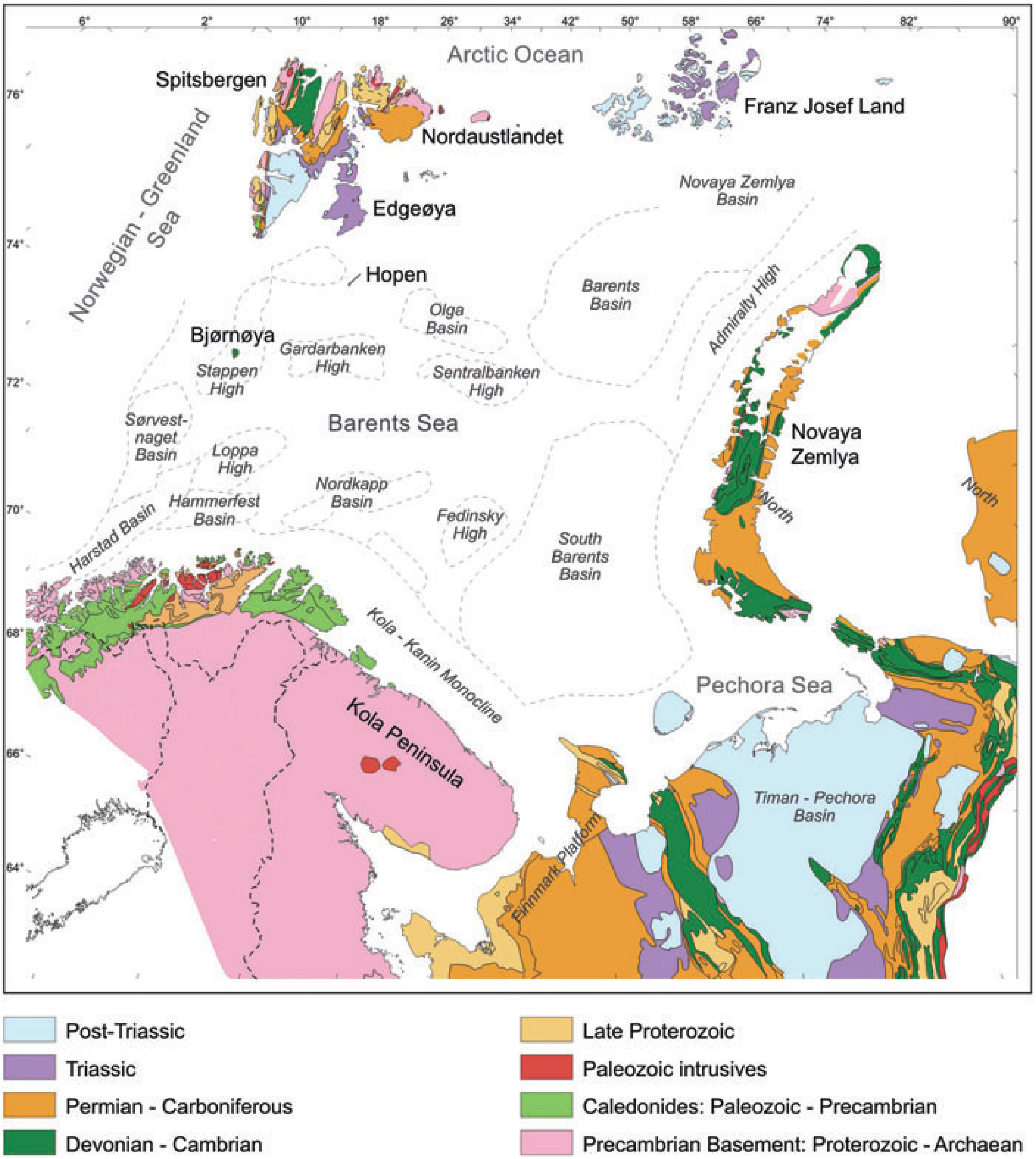

Fig. 1 Land areas surrounding the Barents Sea have widely varying geologies (Mørk 1999). Map compiled by M.B.E. Mørk (see references in Mørk 1999).

et al. 1998), with the volcanism in both areas being closely connected with the opening of the polar Euramerican Basin during the Mesozoic.

The offshore Barents Shelf itself comprises two major and highly disparate provinces (Fig. 2), with a north–south trending, generally monoclinal structure separating eastern from western regions: this transition corresponds roughly with the politically disputed area between Norway and Russia. The eastern region, with its massive South and North Barents basins, shows a development closely linked to that of the Uralides, Timan–Pechora and Novaya Zemlya. The western province, the focus of this review, shows a much more complex tectonic development (Faleide et al. 1984; Gabrielsen et al. 1990; Gudlaugsson et al. 1998). The mosaic of basins, platforms and structural highs in this area reflect the interplay through time between major tectonic processes along the western and north-western margins of the Eurasian plate.

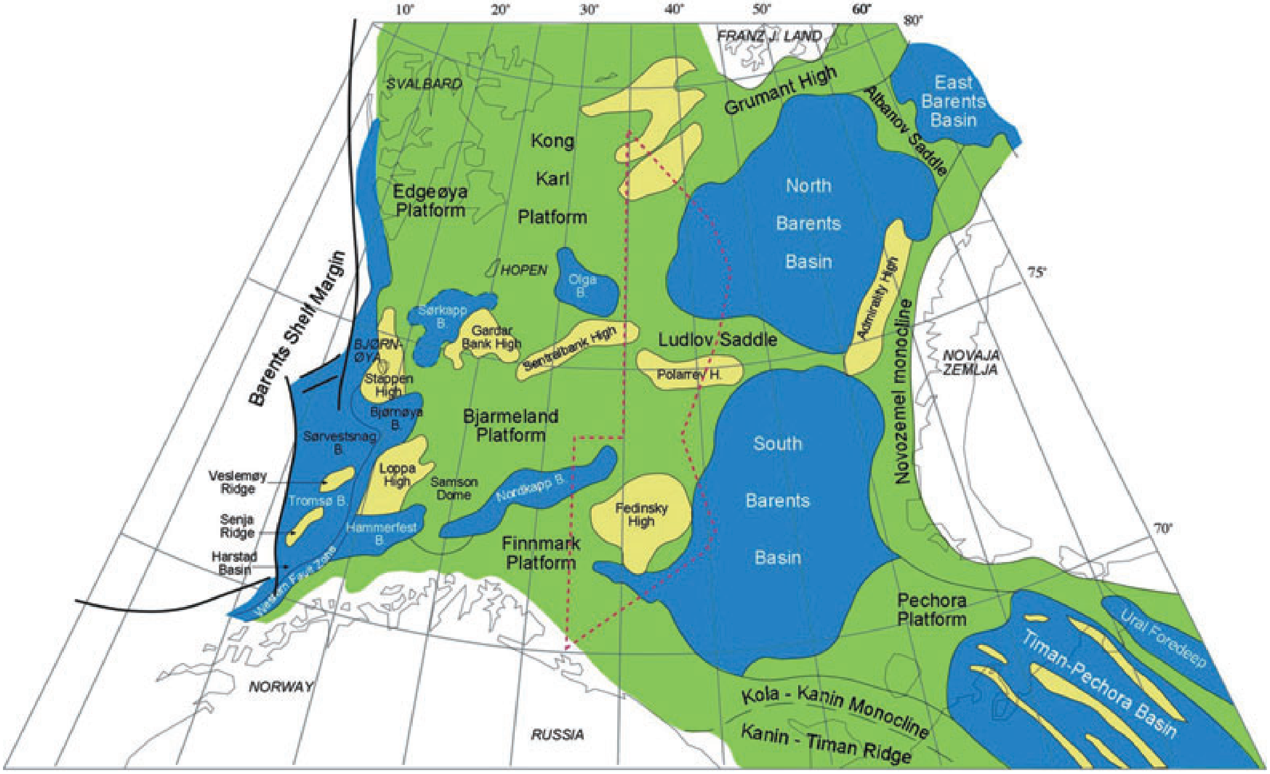

Fig. 2 Major structural elements of the Barents Sea.

Changing tectonic and climatic controls on sedimentation: basement

Precambrian–Lower Paleozoic basement rocks of Svalbard consist of sediments, metasediments and igneous rocks, ranging in age from the Riphean (1275 Mya) to the Silurian. The entire succession has a maximum aggregate thickness of around 20 km, and has been assigned to 20 different lithostratigraphical groups, collectively referred to as "Hecla Hoek". This complexity in part reflects the many nations and stratigraphical philosophies involved in the research, but also the geological reality that there are a wide variety of rocks and successions exposed, grouped generally into three terranes. The north-eastern terrane comprises Precambrian igneous and predominantly sedimentary rocks, including late Precambrian glacial clastics and carbonates, and also Lower Paleozoic sediments: all with clear affinities to exposures in north-east Greenland. The north-western province is characterized by deep crustal metamorphics, including gneiss, migmatite and eclogite, whereas the south-western terrane is a complex mix of metasediments, typical of subduction-zone environments.

Although the relationship between Svalbard and northern Norway during the main phase of Caledonian movements in the Silurian is still uncertain, many workers now believe the hypothesis first suggested by the late Brian Harland, and his Cambridge Arctic Shelf Programme (CASP) co-workers (e.g., Harland & Wright 1979; Harland 1997), that Svalbard's basement comprises three structural provinces that were brought together by large-scale lateral movements during this main orogenic phase. A several-kilometre-thick succession of post-orogenic "Old Red" facies sediments of late Silurian to early Devonian age is essentially confined to a major graben on northern Spitsbergen, and such sediments have not been identified elsewhere in the subsurface of the western shelf. The shift from red to grey sediments around the early to mid-Devonian transition is noteworthy, and indicates the transition from the southern arid zone to the equatorial tropics. Spitsbergen itself then saw a final phase of Caledonian deformation in the late Devonian—the so-called Svalbardian movements, which are correlative with the Ellesmerian orogeny of Arctic Canada. CASP workers (e.g., Friend & Moody Stuart 1972) originally suggested that this phase also involved extensive lateral movements on the scale of 200 km, finally bringing together the elements of the present archipelago into their present position. However, this is now regarded as an essentially compressive tectonic event, with little or no significant lateral movement.

Post-Svalbardian succession

The post-Svalbardian evolution of the archipelago—and of the southwestern Barents Sea—is summarized here in terms of five main depositional phases, extending from the late Devonian to the Neogene, each demonstrated herein by palaeogeographical summary maps displaying essential features of the varying sedimentational regimes. The stratigraphical nomenclature used herein is based on that of Worsley et al. (1988), Dallmann (1999) and Larssen et al. (2005) for Svalbard and the south-western Barents Shelf.

These depositional phases partly reflect the continuing northwards movement of this segment of the Eurasian plate: Svalbard has moved from the equatorial zone in the middle Devonian–early Carboniferous up to its present-day High Arctic latitudes, resulting in significant climatic changes through time. Important tectonic controls on sedimentation have been imposed by the ongoing interplay of varying processes along the shelf margins—first between the compressive Uralide development to the east and proto-Atlantic rifting in the west, and then by the opening of the polar Euramerican Basin to the north, and finally by transpression, transtension and the final opening of the Norwegian–Greenland Sea along the western margins of the shelf. Both short- and long-term local and regional sea-level variations have further defined the sequence development within this general framework.

The late Devonian to mid-Permian was characterized first by widespread intracratonic rifting, following the late Caledonian Svalbardian compressive movements, and then by the development of an immense post-rift carbonate platform, stretching westwards to present-day Alaska. Several large-scale basins—including the Nordkapp Basin of the south-western Barents Shelf and the Sverdrup Basin of Arctic Canada—developed along deep-seated sutures, and were the depositional sites of several-kilometre-thick evaporitic sequences, whereas thinner sabkha deposits and warm-water carbonates formed on the intervening platform areas. A series of western highs, including the Stappen, Loppa and Sørkapp–Hornsund highs, were tectonically active, and show a complex development. The mid-Permian saw a cessation of evaporitic deposition, a shift first to cool-water carbonates and then to clastic and organoclastic deposition, and an accompanying general decrease in tectonic activity along the western margins. The entire Barents Shelf was then marked by a regional and deep-seated response to the Uralide orogeny—reflected by greatly increased subsidence rates, especially in the eastern Barents basins. Subsidence rates waned throughout the Triassic, and following major deltaic progradations from several provenance areas, the late Triassic to mid-Jurassic saw a stabilization of the entire area, with consequently rapidly decreasing sedimentation rates, as extensional tectonism in the mid–late Jurassic established the major platform and basin pattern that we see today. The Jurassic–Cretaceous regional development, mostly dominated by fine clastic deposition, otherwise largely reflects the development of the polar Euramerican Basin on the northern margins of the shelf. Widespread magmatism along the northern shelf margin was accompanied by a general northerly uplift, prior to break-up and oceanic development—although there is still considerable controversy as to how the Euramerican Basin actually developed. The area had steadily moved northwards through temperate latitudes during the Mesozoic, approaching 60°N in the early Cretaceous. The latest Cretaceous and Paleogene were dominated by changing transpressive and transtensional regimes along the western plate suture, before the Eocene/Oligocene break-up and opening of the Norwegian–Greenland Sea. This was followed by the Neogene deposition of thick clastic wedges shed from the newly formed western shelf margins, as a response to large-scale depression and uplift of the hinterland, related to repeated phases of glaciation and deglaciation of the shelf itself from the ?Miocene onwards.

These five late Paleozoic–Neogene sedimentational regimes will now be described in some more detail, each demonstrated by palaeogeographical sketch maps displaying the essential features of the development of the area.

Late Devonian–mid-Permian: evolution of a carbonate platform

The south-western Barents Shelf formed a central part of the northern Pangean margin from the latest Devonian onwards. The definition of three lithostratigraphic groups (Fig. 3) reflects periods with distinct depositional regimes, punctuated by abrupt changes in tectonic and climatic conditions, and in relative sea level, with the latter resulting both from Gondwanan glaciation and deglaciation, and from changing subsidence rates related to the development of the Uralide orogen (Stemmerik & Worsley 1995, 2005). Deposition of the predominantly non-marine tropical humid clastics of the Billefjorden Group started in the late Famennian to Viséan, continuing to the Serpukhovian. Regional uplift, and the subsequent rifting in a series of local half-grabens, was accompanied by a climatic shift to arid conditions, followed by an ongoing regional sea-level rise. The resulting sediments of the Gipsdalen Group were first dominated

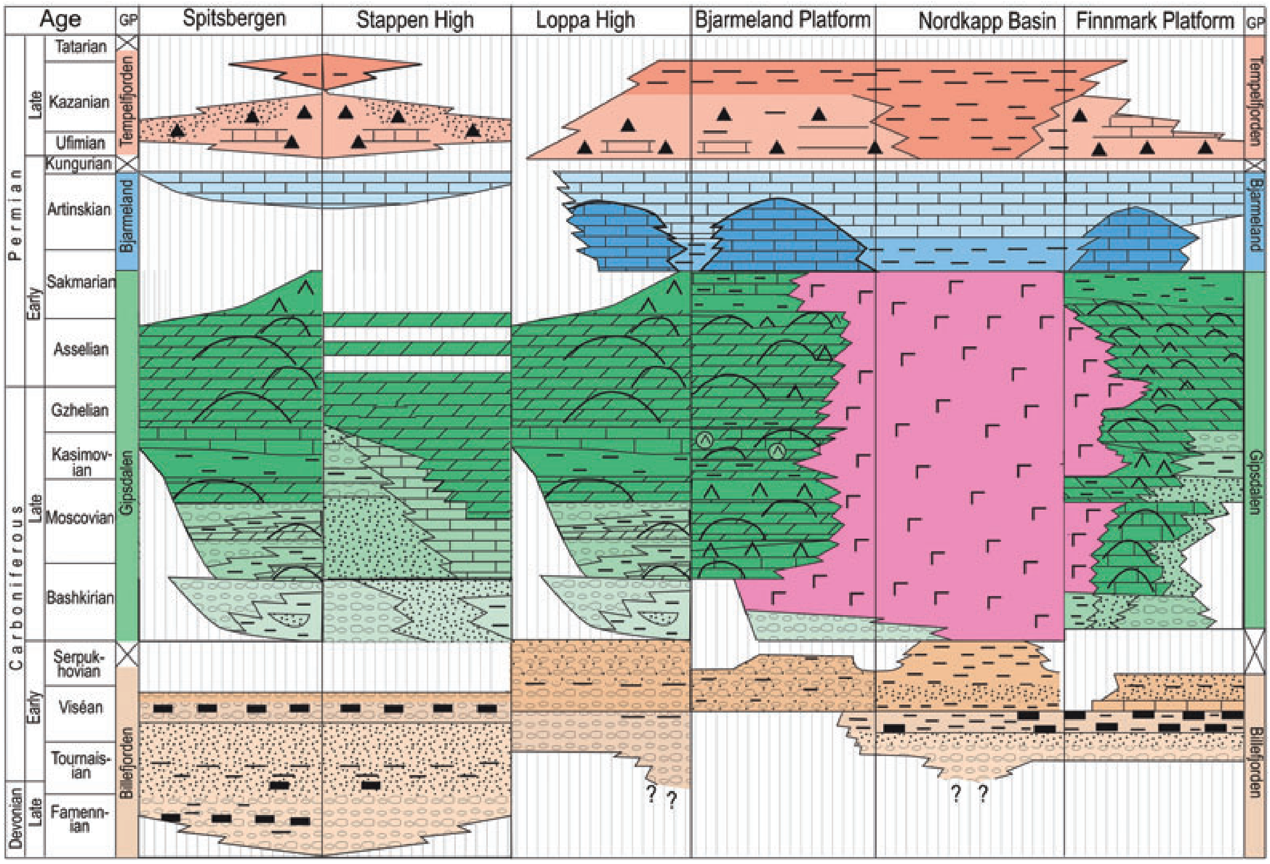

Fig. 3 Upper Paleozoic sequences of the Norwegian Barents Shelf (modified from Larssen et al. 2005).

by clastics shed from faulted graben margins. Increasing tectonic quiescence and ongoing sea-level rises through the late Carboniferous then led to most of the shelf becoming a warm-water carbonate platform, with abundant organic build-ups and the intermittent deposition of sabkha evaporites at times of lowstand. The deep evaporitic Nordkapp Basin developed at this time, and may have formed an immense isolated salina during such lowstand periods (as is also thought to be the case in the even larger Canadian Sverdrup Basin). A radical change in water temperature and depth seems to have occurred around the mid-Sakmarian, resulting in the deposition of the cool-water carbonates of the Bjarmeland Group, especially in and around the subsiding margins of the Nordkapp Basin. The late Permian was characterized by even cooler water conditions, with deposition of siliceous shales.

Latest Devonian–Early Carboniferous: the Billefjorden Group

The Famennian to lower Serpukhovian Billefjorden Group consists mostly of fluvial and lacustrine sediments deposited in humid and warm terrestrial environments over the western Barents Shelf (Fig. 4). Marine influence is only seen uppermost in the group on the south-eastern Finnmark Platform, probably reflecting the existence of a seaway through the Nordkapp Basin that connected to the more open marine environments known to prevail on the eastern Barents Shelf at the time. The oldest deposits are only known from isolated half-grabens on Bjørnøya and Spitsbergen: more widespread deposition started in the Viséan, with the development of a large, humid hinterland that passed eastwards into shallow marine environments. Half-graben development continued to characterize the western shelf margins. The sediment fill of these grabens shows a generally coarsening-upwards trend, from meandering river sandstones and floodplain fines, into braided stream and alluvial fan sandstones, and conglomerates. The Finnmark Platform also shows an eastwards transition from continental to deltaic and shallow marine deposits (Bugge et al. 1995), passing into the fully marine environments of the eastern shelf, as displayed in Timan–Pechora and Novaya Zemlya.

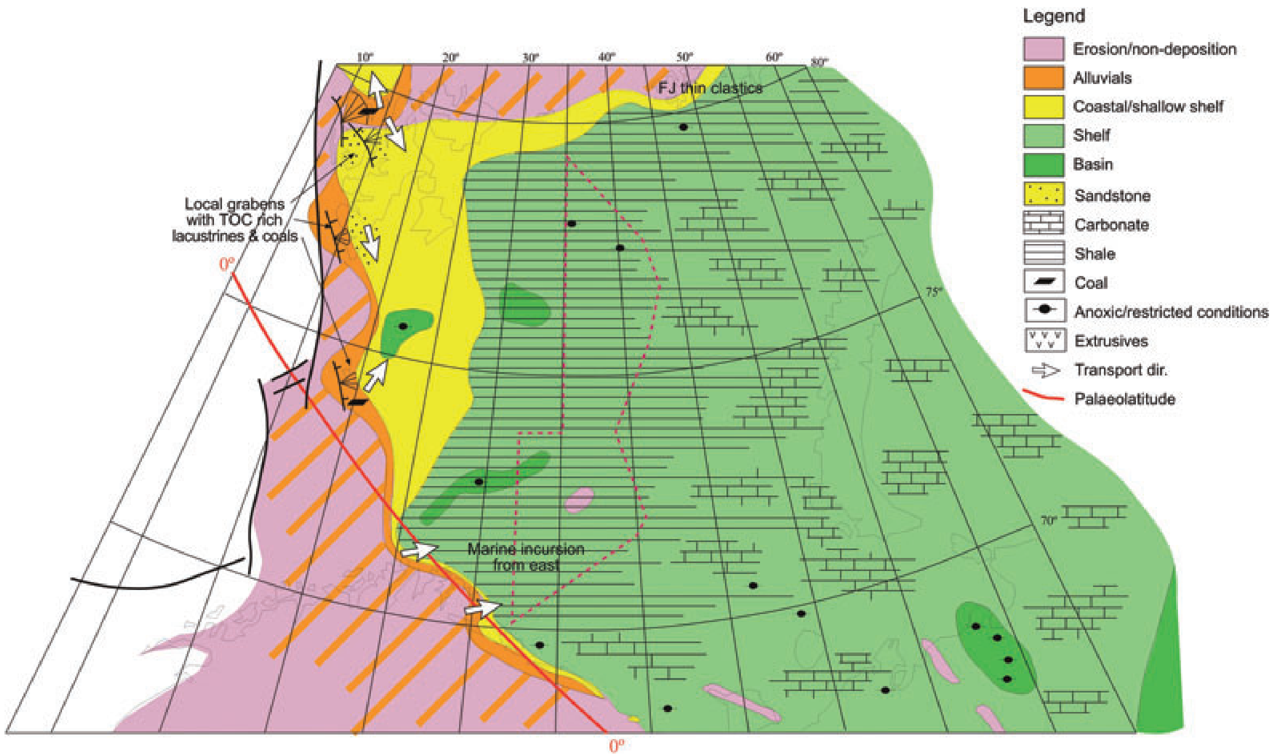

Fig. 4 Palaeogeographic sketch map showing Late Devonian–Early Carboniferous depositional environments.

Thicknesses of around 400–600 m on the Finnmark Platform contrast with cumulative thicknesses of up to 2500 m in the type area of the Billefjorden Trough, in central Spitsbergen, whereas a composite thickness of 600 m is preserved in the half-graben covering Bjørnøya on the Stappen High, midway between northern Norway and Spitsbergen (Worsley et al. 2001): the fluvial deposits on Bjørnøya were clearly transported north-eastwards along the graben axis, probably towards a depocentre under the present-day Sørkapp Basin.

Mid-Carboniferous–mid-Permian: the Gipsdalen and Bjarmeland Groups

The mid-Carboniferous–lower Permian Gipsdalen Group is dominated by shallow marine carbonates, sabkha evaporites and local siliciclastics on the extensive platform areas of the shelf, whereas isolated deep and large basins were the sites of halite deposition during most of this phase. The sediments of the group were deposited in a warm and arid climate, during a period characterized by frequent sea-level fluctuations, reflecting the varying phases of the contemporaneous Gondwanan glaciation.

Deposition of non-marine red beds commenced around the Serpukhovian/Bashkirian transition in locally reactivated half-grabens following regional mid-Serpukhovian uplift (Gjelberg & Steel 1981, 1983; Johannessen & Steel 1992; Worsley et al. 2001). The red beds passed up into marine carbonates in the mid-Bashkirian, and ongoing transgression led to the submersion of the surrounding platforms and local highs, during the Moscovian and Gzhelian, although the Loppa, Stappen and Sørkapp–Hornsund highs in particular were to continue to be tectonically active until the mid-Permian. The unconformable contact between the Billefjorden and Gipsdalen groups reflects major regional uplift, accompanied by a relatively abrupt climatic shift from humid to warm but arid regimes (Fig. 5). This uplift was followed by renewed rifting in pre-existing half-grabens, and also by the development and subsidence of the much larger Nordkapp and Tromsø basins. The ensuing late Carboniferous regional sea-level rise occurred in a global ice-house situation, and the Moscovian–Asselian platform was characterized by shallow-water carbonate deposition at times of high glacioeustatic sea levels, whereas sabkhas and even subaerially formed karsts and fossil soils developed at times of lowstand (Fig. 6). Only limited quantities of siliciclastics were deposited locally immediately adjacent to isolated highs, which themselves gradually became tectonically quiescent. The resultant rhythmic parasequences reflect these high-frequency and -amplitude sea-level variations: outer shelf areas are characterized by

Fig. 5 Lower Carboniferous clastics of the Billefjorden Group are sharply overlain by red beds, which pass gradually up into marine carbonates, Landnørdingsvika, Bjørnøya. (Photo by David Worsley.)

algal-, fusulinid- and sometimes crinoid-rich wackestones and packstones, between subaerial exposure surfaces, whereas more grainstones occur updip, interbedded with palaeoaplysinid/phylloid algal build-ups and associated lagoonal deposits. Frequent exposure led to extensive dolomitization and karstification, with accompanying karst collapse and breccia formation, whereas freshwater flushing led to the early formation of secondary porosity. The entire group shows significant preserved thickness variations from 0 to 600 m on platforms and highs, and up to 1800 m in the Billefjorden Trough of central Spitsbergen; only small (<10-m-thick) organic build-ups are observed onland, draping the graben margins. Offshore, this sequence can be up to 1500 m thick, and build-ups that developed on ramps adjacent to highs can reach a composite thickness of several hundred metres.

The base of the mid-Sakmarian–upper Artinskian Bjarmeland Group is marked by a major flooding event, which coincided with a significant shift from shallow warm waters to the more temperate conditions that determined the cool water biotic composition of the carbonates of this group. This transgressive event marks the end of the high-frequency rhythms of the Gipsdalen Group, and the transgression itself was probably related to the final waning and disappearance of the Gondwanan ice cap. The abrupt change in depositional regimes was probably also related to changes in circulation in the Boreal Ocean as a result of the closing of the seaway to Tethys, along the developing Uralide suture zone. The group is best developed along major basinal margins, and ongoing transgression flooded most areas by the Artinskian: large *Tubiphytes*/bryozoan build-ups developed, all with pervasive early diagenetic marine calcite cement. The group is much thinner or absent over inner platforms and structural highs (e.g., Spitsbergen and the southern Finnmark Platform). In these areas there was renewed uplift during the Sakmarian/Artinskian, again leading to karstification and freshwater flushing of the underlying carbonates. The deep basinal development of the Bjarmeland Group is still uncertain.

Late Permian–middle Triassic: from carbonates to clastics

The Kungurian saw a shift to the deposition of cold- and deep-water fine clastics and silica-rich spiculites, influenced by the development of the Uralides and the opening of intracratonic seaways along the western shelf margins. The early Triassic was dominated by the deposition of non-siliceous shales and mudstones that contrast strongly with the underlying siliceous units. Although the upper Permian Tempelfjorden Group and the lower to mid-Triassic Sassendalen Group show strikingly different lithologies and faunas, both contain shales that are locally rich in organic matter: the Botneheia/Kobbe formations of western areas deposited during the Anisian/Ladinian are particularly organic-rich, and constitute important hydrocarbon source rocks.

Latest Permian: the Tempelfjorden Group

The middle–upper Permian (Kungurian–Capitanian/?Wuchiapingian) Tempelfjorden Group overlies a significant subaerial exposure surface on platform areas (Fig. 7), where there was significant renewed flooding, whereas basins and basin margins show abrupt deepening, with a significant shift to cool- and deep-water spiculitic shale deposition. Interbedded minor units of sandstone and limestone are associated with local highs and platform margins (Fig. 8). The limestones show distinctive and spectacular assemblages of bryozoans, together with spiriferid and productid brachiopods. This dramatic depositional change, from the carbonate environments that had prevailed for almost 40 million years, reflects the development of the Urals and the closure of seaway connections to the warm waters of Tethys. Major plate reorganization resulted in greatly increased subsidence rates in the region, whereas intracratonic seaways developed along the western shelf margins, connecting the Boreal Realm to the central European Zechstein Basin.

The distinctive spiculites of the group, rich in biogenic silica, are found throughout the northern Pangean shelf margins. In the Sverdrup Basin they have been ascribed to the development of extremely cold water conditions, much colder than would normally be expected from the relevant palaeolatitudes of around 35°N. This may perhaps be related to the development of northern winter

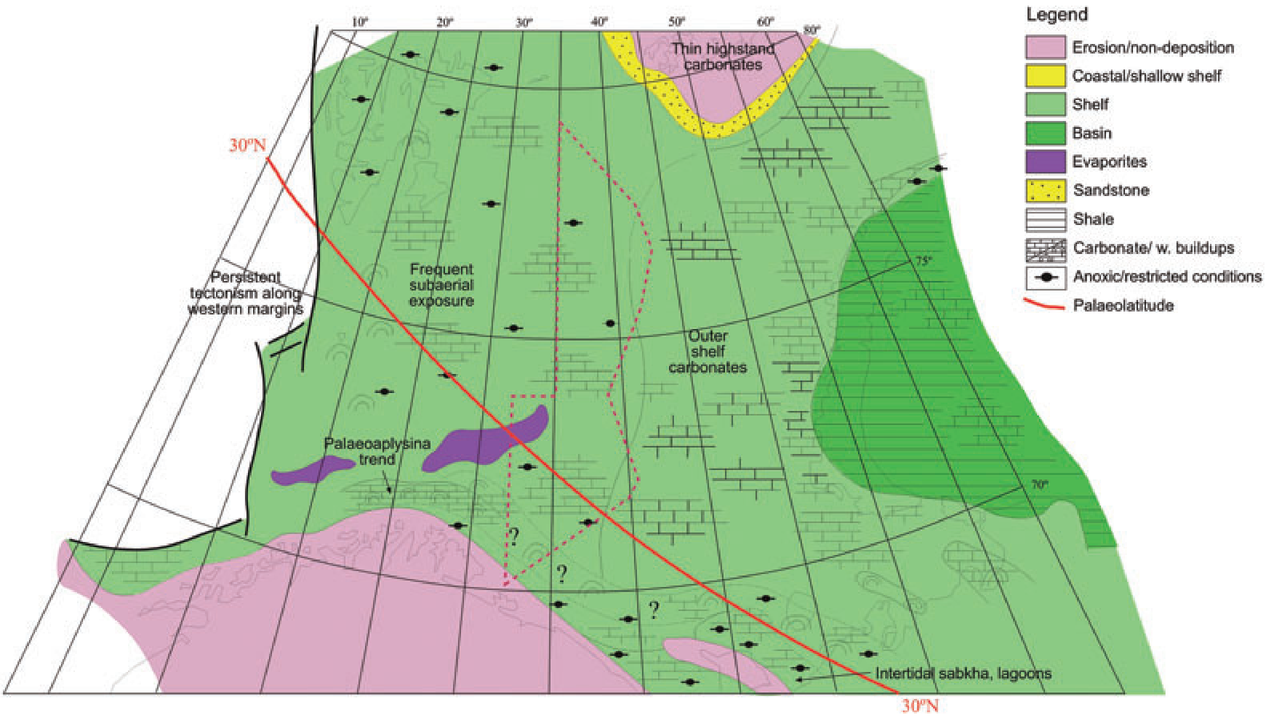

Fig. 6 Late Carboniferous regional palaeogeography.

Fig. 7 The mid–late Permian saw a regional transgression that onlapped and overstepped all of the older units: on Bjørnøya, Lower Carboniferous tectonized sandstones are directly overlain by Upper Permian deposits. (Photo by David Worsley.)

sea ice as a result of cold-water oceanic upwelling, accompanied by a landward surge of the thermocline (Beauchamp & Desrochers 1997): established as a result of major plate reorganization, and of changed oceanic circulation patterns accompanying the Uralide orogeny. A contemporaneous increase in subsidence and sedimentation rates has also been related to the Uralides, but not as a result of the development of the western Barents shelf as a foreland basin—the area affected is much too large for that—but perhaps instead reflects the depression of the 660-km mantle discontinuity, caused by subduction along the Uralide suture. Whatever the triggering mechanism, the group shows thickness variations from zero or near zero, on local highs and inner platforms, up to 900 m in the southern Hammerfest Basin, with the thickest successions on Spitsbergen being 360 and 480 m in the St. Jonsfjorden and Billefjorden troughs, respectively.

The Permian/Triassic transition is still poorly understood throughout the region, but it appears that there was a significant hiatus in the latest Permian (Lopingian), particularly on highs and platforms. Freshwater leaching of the underlying spiculites seems to have locally given rise to secondary reservoir porosity, with implications for hydrocarbon accumulation. The abrupt change from highly cemented spiculitic shales to the overlying non-siliceous shales of the Sassendalen Group is dramatic, both in the outcrop and on seismic data. The so-called "Permian Chert Event" was now at an end, and oceanic waters warmed significantly. Perhaps, as suggested by many authors, this warming was a contributory factor leading to the late Permian major marine extinction. The soft, poorly fossiliferous basal shales of the overlying group apparently contain a Lopingian (Tatarian) palynoflora on outer platforms, and in basinal situations, although their sparse macrofaunas have a Mesozoic aspect.

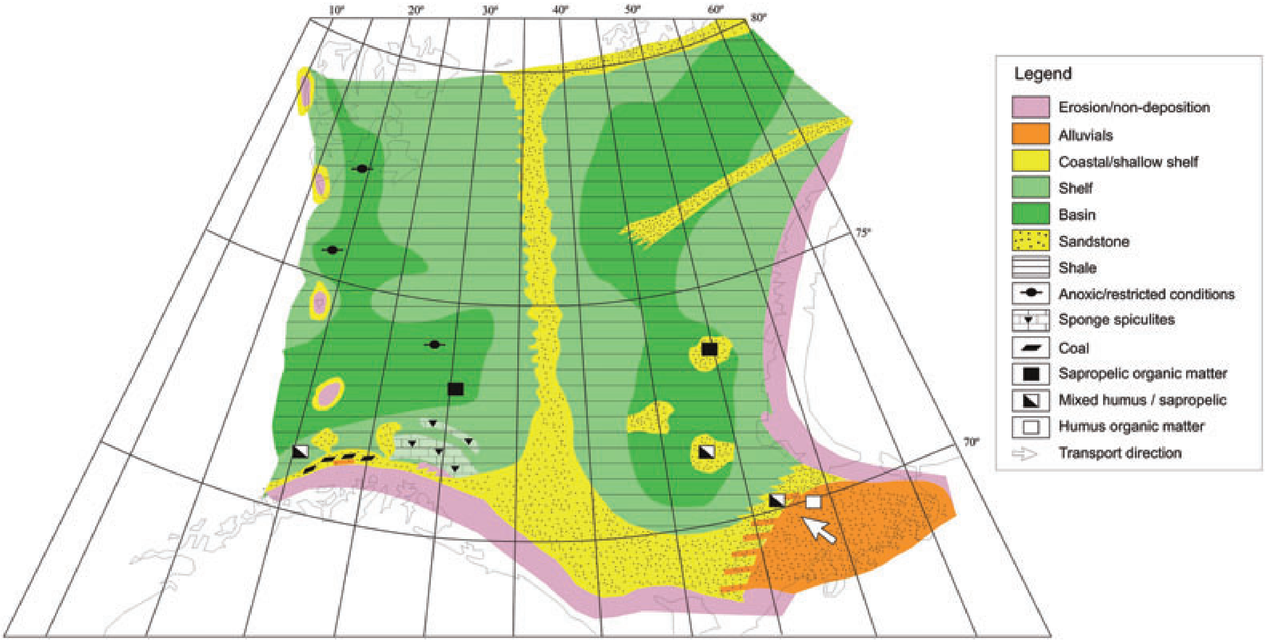

Fig. 8 Late Permian regional palaeogeography.

Early–middle Triassic: the Sassendalen Group

As noted above, the basal shales of the Sassendalen Group may be of latest Permian age, at least where they have been penetrated by exploration wells and shallow stratigraphic coreholes on the margins of the Nordkapp Basin. In more positive platform areas, including Svalbard, an Induan age is suggested. A generally transgressive trend, punctuated by repeated coastal progradations, throughout the early Triassic led to the onlap and submergence of positive features, such as the Sørkapp–Hornsund and Stappen highs by the Olenekian (Fig. 9). The Loppa High only became the site of marine sedimentation in the Anisian/Ladinian.

The entire group is dominated by non-siliceous fine clastics—indeed this time span has been referred to as representing the "Early Triassic silica gap". The south-western Barents Sea was now isolated from central European basins, as the late Permian Zechstein seaway was closed by the uplift of the mid-Norwegian and eastern Greenland shelves (Doré 1991). High subsidence and sedimentation rates continued across the entire Barents Shelf during this depositional phase, a feature most marked in the southern and northern Barents basins of the Russian sector. Thicknesses range from 60–150 m on pre-existing structural highs to 700 m in western Spitsbergen, and are over 1500 m on the south-western shelf and several kilometres in the eastern basins. Sediment transport to these deep basins in the east seems to have been from the central Urals, along the axis of the Timan-Pechora depression, and not from Novaya Zemlya itself. Indeed, limited seismic data suggest a pattern of thinning in the Triassic section towards Novaya Zemlya, leading some workers to suggest that the archipelago originally formed in the late Paleozoic as part of a continuous Ural–Taimyr chain, and was then thrust westwards into its present position during the early to mid-Triassic, subsequent to the main development of the Urals (Otto & Bailey 1995).

Significant sandstone intervals on Spitsbergen are apparently related to repeated coastal progradation from Greenland to the west, and several barrier bar–deltaic sandstone units are exposed along the western coast (Mørk et al. 1982). Through much of the early to mid-Triassic, most of the south-western shelf was distal to an oscillating, but generally north-westerly prograding, coastline, with sand provenance being first from the Baltic Shield and then increasingly from the Urals. By the mid-Anisian, a NNE-trending system of clinoforms, extending over the Hammerfest Basin and on to the Bjarmeland Platform, may have been situated close to the palaeocoast, with the possibility for sand deposition in delta-front/shoreface environments (Fig. 10). The newly discovered hydrocarbon-bearing sandstones in the Kobbe Formation of the StatoilHydro Obesum find belong to this trend. The Obesum hydrocarbon source rocks are not yet in the public domain, but they are likely to be organic-rich shales, which are time-equivalents of the Botneheia

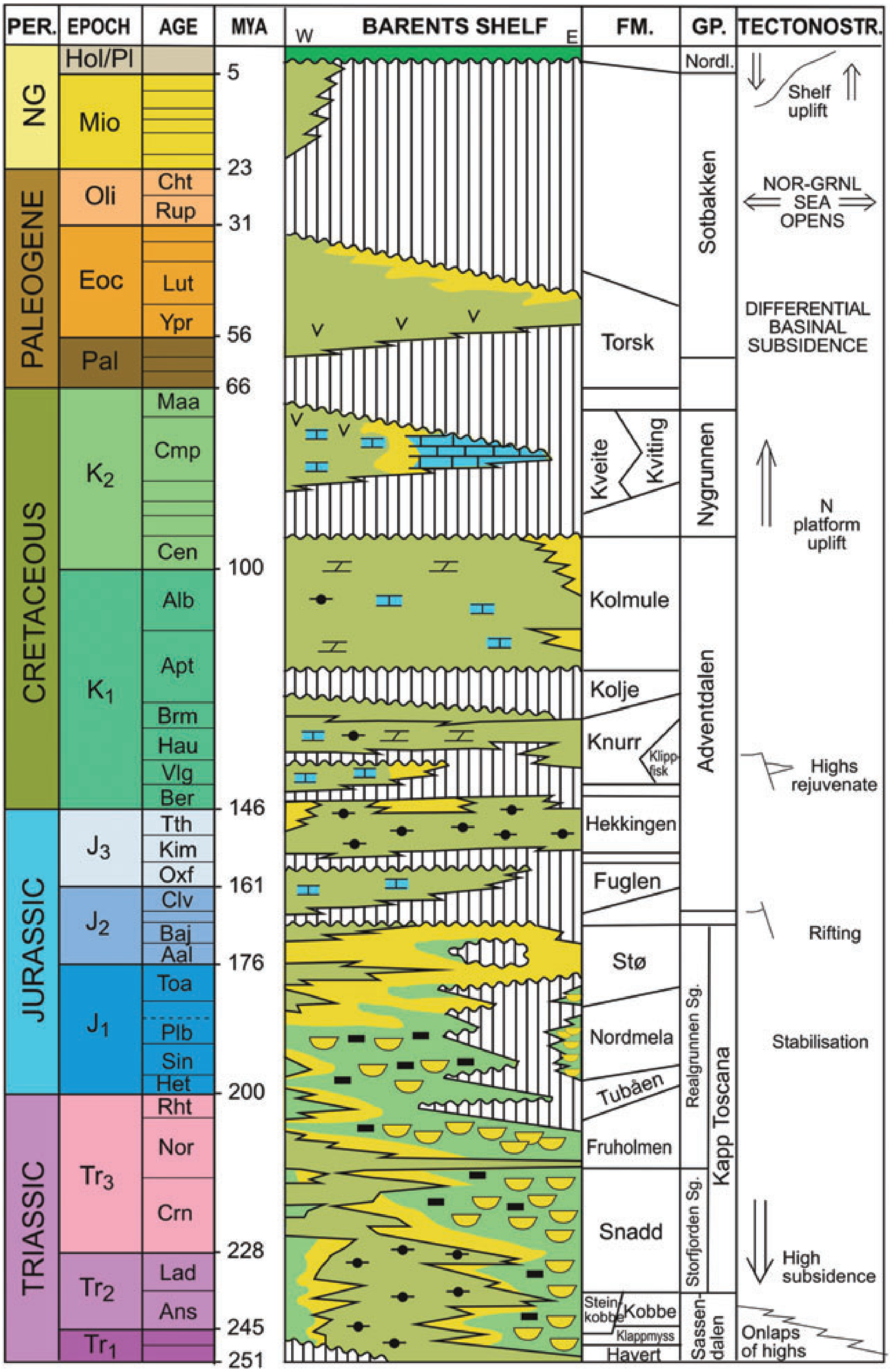

Fig. 9 The Mesozoic and Cenozoic development of the south-western Barents Sea, modified from Nøttvedt et al. (1993), with the geological time scale based on Gradstein et al. (2004).

Fig. 10 The nunatak of Austjøkeltinden (foreground) on the margins of the Sørkapp–Hornsund High shows a complete Triassic succession, younging from the saddle to the left through a condensed Sassendalen Group (terminating in black Anisian/Ladinian shales), and then through a thick Storfjorden Subgroup deltaic sequence, ending (nearest camera) in highly condensed (<10-m-thick) representatives of the Wilhelmøya Subgroup. (Photo by David Worsley.)

Formation of central and eastern Svalbard, and which contain up to 10% of organic carbon. Early workers in the area called this unit the "Oil Shale" because of the presence of free oil in septarian concretions.

Late Triassic–Late Cretaceous: development of the polar Euramerican Basin

This depositional phase contains several sandstone units with significant hydrocarbon reservoir potential, especially in the lower part of the section, which then becomes more shale-dominated upwards. The Ladinian–Bathonian Kapp Toscana Group is locally rich in sandstones of varying origins. The lower Storfjorden Subgroup (Ladinian/Carnian) has a deltaic character, with sandstone provenance from widely differing areas (Fig. 11). Units assigned to the overlying Norian–Bajocian Storfjorden and Norian–Bathonian Wilhelmøya subgroups display a wide variety of coastal/shallow marine settings, often with mineralogically and texturally mature sandstone units. Regional transgression in the Bathonian/Callovian led to deposition of the shale-dominated Adventdalen Group, which has significant organic carbon content, especially in the upper Jurassic units. Sandstones were now largely confined to the margins of the temporarily emergent highs and platforms around the Jurassic/Cretaceous transition, and to northern shelf areas in the Barremian. The latter are clearly related to the uplift of northern shelf margins, which, together with extensive volcanism in the same areas, clearly presaged and accompanied the opening of the present polar Euramerican Basin. The Jurassic/Cretaceous transition also saw the cataclysmic meteoric impact that formed the Mjølnir crater in the central Barents Sea, an impact that may have had long-term implications for the regional depositional environment. Ongoing uplift resulted in a major hiatus from the Albian/Cenomanian to the basal Paleogene over much of the north-western shelf. The clay-dominated sequences of the Upper Cretaceous Nygrunnen Group are restricted to south-western basinal areas.

Late Triassic: the Storfjorden Subgroup

Deposition of organic-rich shales continued throughout the Ladinian on the Svalbard Platform, with most of the south-western Barents Shelf already dominated by the development of prodelta shales in front of the north-westerly prograding systems noted above. Deltaic and floodplain environments were rapidly established over much of the province, with still high, but decreasing, subsidence and sedimentation rates, and a complex palaeogeographic pattern developed. Deltas still prograded from the west, affecting the westernmost parts of Spitsbergen (and Bjørnøya), but these waned markedly throughout the Carnian. New seismic evidence (Riis et al. 2008 [this issue]) suggests that major sediment input from the Urals continued, leading to the establishment of delta-plain environments over much of the northern shelf, and extending to the north-eastern parts of the Svalbard Archipelago (Figs. 12, 13). The existence of a northern volcanic provenance area to the north-east (presumably north of present-day shelf margins) is now in doubt, although fieldwork in Svalbard in 2008 will hopefully clarify this question. The resultant Carnian sandstones, although prolific, are usually texturally and mineralogically immature, with high primary contents of feldspathic, volcanic and lithic fragments, making them susceptible to extensive diagenetic alteration, and often rendering them essentially impermeable, especially if subjected to appreciable burial. Areas further to the south in the Norwegian sector may have been affected by continued progradation from the Baltic Shield: Carnian sandstones recently encountered in the Nordkapp Basin and on the Finnmark Platform apparently show better reservoir properties than their northern equivalents. These channel and coastal sands were derived from mature provenance areas on the Baltic Shield, and their primary reservoir quality was probably enhanced by marine reworking at times of highstand, especially in near-coastal environments. Subsidence rates were still high throughout the entire area, and earlier Paleozoic highs were now inverted: exploration wells on the Loppa High, for example, show an Upper Triassic succession that, although incomplete because of subsequent erosion,

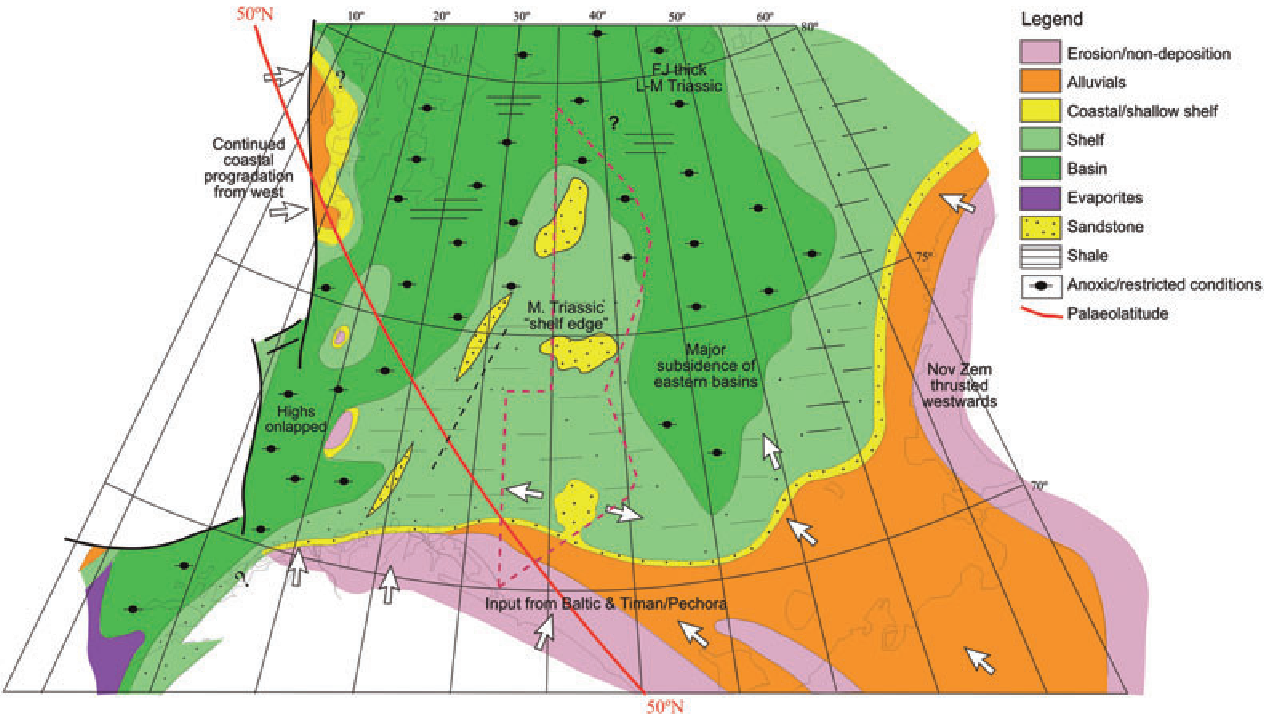

Fig. 11 Mid-Triassic regional palaeogeography.

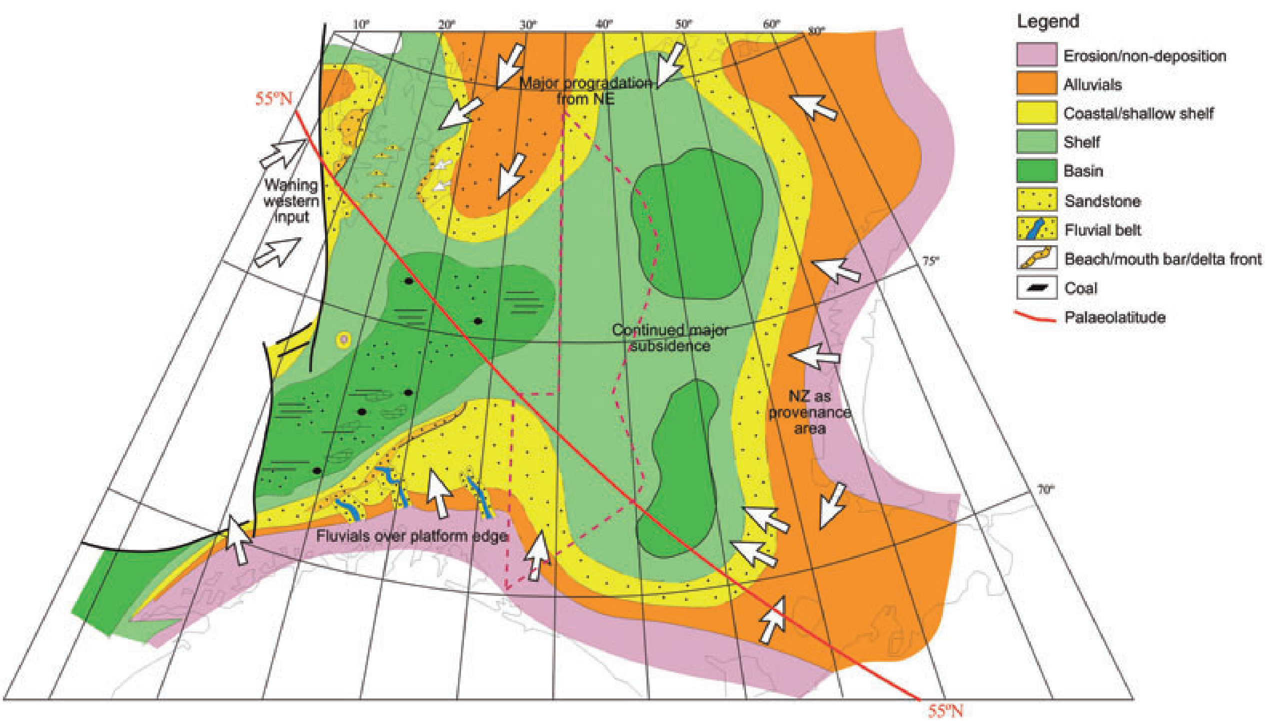

Fig. 12 Late Triassic regional palaeogeography.

Fig. 13 Storfjorden Subgroup deltaics on Hopen: a fluvial channel cutting into delta-plain overbank deposits. (Photo by David Worsley.)

is almost as thick (about 1300 m) as the complete equivalent sequence in the Hammerfest Basin, to the south of the high (1410 m). The basins in the eastern sector continued to subside, but now also with the newly emplaced Novaya Zemlya as a significant provenance area. It is interesting that sandstones throughout the region show a convergence of lithologies upwards in this sequence, perhaps reflecting increasing marine reworking and mixing of the components from the different provenance areas (Mørk 1999; Riis et al. 2008). Increasing local tectonic activity also led to a breakdown of the geographically synchronous transgressive/regressive sequences that had hitherto characterized Triassic deposition in the region (Mørk et al. 1989; Egorov & Mørk 2000; Mørk & Smelror 2001). Indeed, in the Storfjorden Group, the base of the progradational sequences stretches from the Ladinian base Snadd Formation in south-eastern areas to the Carnian prodeltaic shales of the Tschermakfjellet Formation on Spitsbergen.

Latest Triassic–Middle Jurassic: the Realgrunnen and Wilhelmøya subgroups

A supra-regional relative sea-level rise in the early Norian—the so-called "Rhaetian" transgression of central Europe—established marine connections between the Tethyan and Boreal oceans along the proto-Atlantic seaway. This was accompanied by a major shift in structural regimes and depositional systems throughout the entire circum-Arctic province. The Barents Shelf saw greatly decreased subsidence and sedimentational rates (only 5% of those of the earlier Triassic regimes). The Uralian-sourced progradational systems were no longer dominant, and shallow marine and coastal environments were established throughout the province. Although still with multiple provenance areas, the resultant sandstones reflect extensive reworking, and are texturally and mineralogically mature (Bergan & Knarud 1993), with excellent primary reservoir properties, such as those in and around the Snøhvit Field in the southern Hammerfest Basin. However, in areas subjected to greater maximum burial (e.g., western Spitsbergen and the western Hammerfest Basin), the same units show extensive quartz overgrowth, resulting in well-cemented quartzites. This entire sequence shows a rhythmic development of migrating barrier-bar and coastal environments. The individual units are patchily preserved over platform areas, reflecting intermittent primary deposition as migrating bars or banks, at times of relative highstand, and subsequent erosion following the initiation of differential block movements in the mid-Jurassic. Highly condensed remanié deposits are also common on these platforms, for example in central Spitsbergen. Local and unpredictable thicker developments may represent sand infill of incised valleys that probably formed along platform margins during lowstand, and/or as a result of these movements.

Basinal areas were the sites of more continuous sedimentation, although uppermost sandstones in the group contain numerous remanié horizons, reflecting the onset of mid-Jurassic movements. These further defined present-day structural features, and also accentuated the pre-existing differentiation between platform and basinal areas: for example, the entire sequence thins from 500 m in the Hammerfest Basin to less than 50 m on the central Bjarmeland Platform. An extreme example of this variation can be seen onshore in Svalbard, with dramatic variations in thickness and development over the Billefjorden Lineament. Western platform areas show only a few metres of a highly condensed and incomplete Norian–Bajocian sequence, which thickens rapidly eastwards across the lineament to over 200 m on Kong Karls Land. Phosphatic conglomerates are common at several horizons, the most noteworthy being the well known "Lias Conglomerate" (Brentskardhaugen Bed) uppermost in the sequence, which contains phosphatic nodules with remanié fossils of Toarcian–?Bajocian age (Bäckström & Nagy 1985).

Mid-Jurassic–mid-Cretaceous: the Adventdalen Group

Renewed regional transgression in the Bathonian cut off the supply of coarse clastics, and marine calcareous mudstones gave way to the anoxic black shales of the Hekkingen and Aghardjellet formations during the Callovian/Oxfordian (Fig. 14). All earlier highs and platforms were now submerged, but thickness variations—from almost 400 m in the south-western Hammerfest Basin to less than 100 m over central highs on the basinal

Fig. 14 Helvetiafjellet, central Spitsbergen: Upper Jurassic organic-rich black shales pass up, at the break of the slope, into much leaner Lower Cretaceous black shale. A major difference from the southern shelf areas is the development of Barremian deltaic sandstones prograding southwards, but with a delta front over south-eastern Spitsbergen. These are overlain by transgressive Aptian shales with thin storm-deposited sandstones. (Photo by Atle Mørk.)

axis—reflect earlier and ongoing Jurassic tectonism. Similar thickness variations are seen onshore in Svalbard (Dypvik et al. 1991). The Upper Jurassic black shales are excellent source rocks for petroleum in western parts of the Barents Shelf, with marine-dominated kerogens and organic contents of up to 20%. The subsequent burial history of the region indicates that significant oil generation has only occurred in the deeper western basinal areas, and perhaps locally in deeper parts of the Nordkapp Basin.

A major change in depositional environments around the Jurassic/Cretaceous boundary seems to be related to a lowering of sea level, and the general development of more open marine environments with better bottom circulation, except in locally restricted basinal areas. The Mjølnir meteor impact on the north-eastern Bjarmeland Platform may have had short-term catastrophic consequences over a large area (Dypvik et al. 1996; Smelror et al. 2001; Dypvik et al. 2004), as well as heralding this general environmental shift. Local sandstone fans were also built out from platform margins into the adjacent basins at this time.

The early Cretaceous was otherwise dominated by the deposition of fine clastics over much of the province, with up to 700-m-thick basinal shales that have some organically enriched intervals. Platform areas have much thinner and more carbonate-dominated sequences. Most marked features of this sequence are seen in northern shelf areas, where a Barremian southerly directed deltaic progradation overlies an unconformity, heralding the onset of northern margin uplift, and this was accompanied by extensive extrusive magmatism along the same northern margins, reflecting the break-up prior to the opening of the polar Euramerican Basin (Fig. 15). Delta-plain environments characterize the development of the sandstones of the Helvetiafjellet Formation in northern and central Spitsbergen (Gjelberg & Steel 1995), but spectacular synsedimentational collapse features around Kvalvågen in south-east Spitsbergen (Nemec et al. 1988) mark the southernmost extent of fluvial sandstones, with exposures further south passing into marine sandstones and thicker more shale-rich sequences. Large-scale southwards-directed clinoforms seen on seismic lines from the Bjørnøya Basin may represent distal equivalents of this sequence. An Aptian regional sea-level rise significantly cut off coarse-clastic supply, even in the north. Northern uplift continued, however, so that a 190-m-thick condensed Aptian/Albian shale-dominated wedge in central Spitsbergen thickens to over 1000 m in southernmost land exposures, and then thickens further to 1400 m and extends through to the Cenomanian in the south-western Barents margin.

Late Cretaceous: the Nygrunnen Group

The uplift and erosion of northern shelf areas continued throughout the late Cretaceous, so that basement, Devonian and Upper Paleozoic rocks dominate exposures there, with only an occasional thin veneer of younger sediments. From Longyearbyen and southwards on Spitsbergen, Paleogene basal conglomerates rest directly on lower Cretaceous units of varying Aptian–Albian ages (Fig. 16). The only areas with significant deposition were the western marginal basins, where exploration wells in the Tromsø Basin have encountered up to 1200 m of claystones with thin limestone interbeds. The entire sequence thins eastwards to 50–250 m in the Hammerfest Basin, where condensed calcareous to sandy units bear witness to intermittent deposition, only at times of maximum transgression.

Paleogene: transtension, transpression and the opening of the Norwegian–Greenland Sea

The Paleogene development of the region was dominated by tectonic activity along the western shelf margins, prior to the final opening of the Norwegian–Greenland Sea in the Eocene/Oligocene. The opening occurred after the formation of the compressive Tertiary orogenic belt of Spitsbergen and the north-western shelf, which entailed crustal shortening estimated to around 30 km. Meanwhile, southern shelf margins (south of 76°N) showed a generally passive and subsiding character throughout the Paleogene, apart from volcanism and marginal uplift

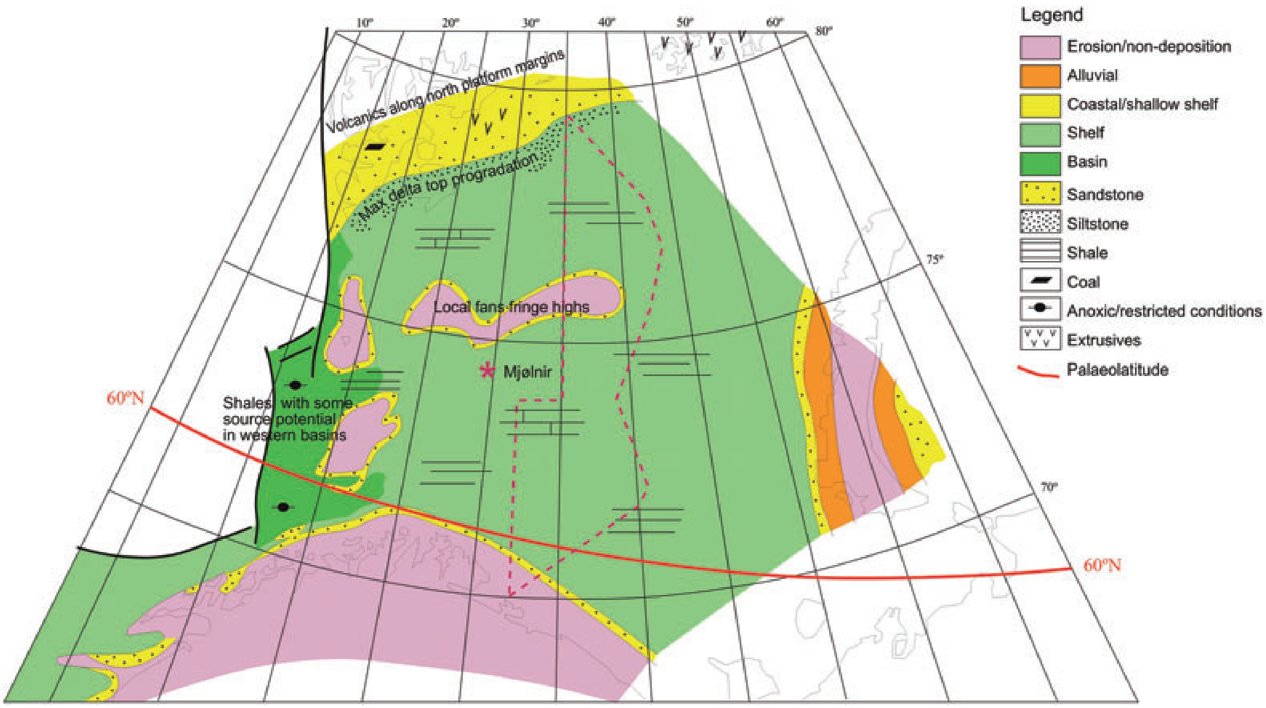

Fig. 15 Earliest Cretaceous–Barremian composite regional palaeogeography.

Fig. 16 Base Paleogene, central Spitsbergen. Upper Cretaceous deposits are totally missing from the northern shelf areas: here, a Paleogene basal conglomerate rests directly on eroded Albian marine shales and storm siltstones. (Photo by Atle Mørk.)

prior to and accompanying the break-up that finally produced oceanic crust to the west.

Paleocene–Oligocene: the Van Mijenfjorden and Sotbakken groups

Paleogene sediments on the north-western shelf are preserved in the Central Basin of Spitsbergen, and in several isolated smaller basins in south-western and north-western parts of the island. With a preserved thickness of 1900 m, the clastic deposits of the Van Mijenfjorden Group in the Central Basin (Fig. 17) reflect alternating transtensional and transpressive regimes along the western shelf margin (Steel et al. 1985). This depositional episode culminated in the progradation of shallow marine to alluvial sands from the west that finally filled the basin in the Eocene. Other Paleogene units in local basins seem to have developed during the main compressive movements that followed the development and filling of the Central Basin (Nøttvedt et al. 1988; Dallmann et al. 1993). A similar development has been identified southwards to about 76°N, where the entire shelf margin changes character from a compressive to passive aspect (Bergh & Grogan 2003). Volcanism in the Vestbakken Province between 75 and 72°N is apparently related to this transition. The south-western shelf is characterized by the claystone-dominated Sotbakken Group, which is largely confined to the western basins and outer shelf margins, although thin units are apparently also preserved throughout the south-western Nordkapp Basin, and sporadically in the north-eastern arm of the Nordkapp Basin. The sequence thickens westwards through the Hammerfest Basin from 180 to 770 m; western basins show even thicker developments, up to 900 m in the Tromsø Basin, 1000 m in the Bjørnøya

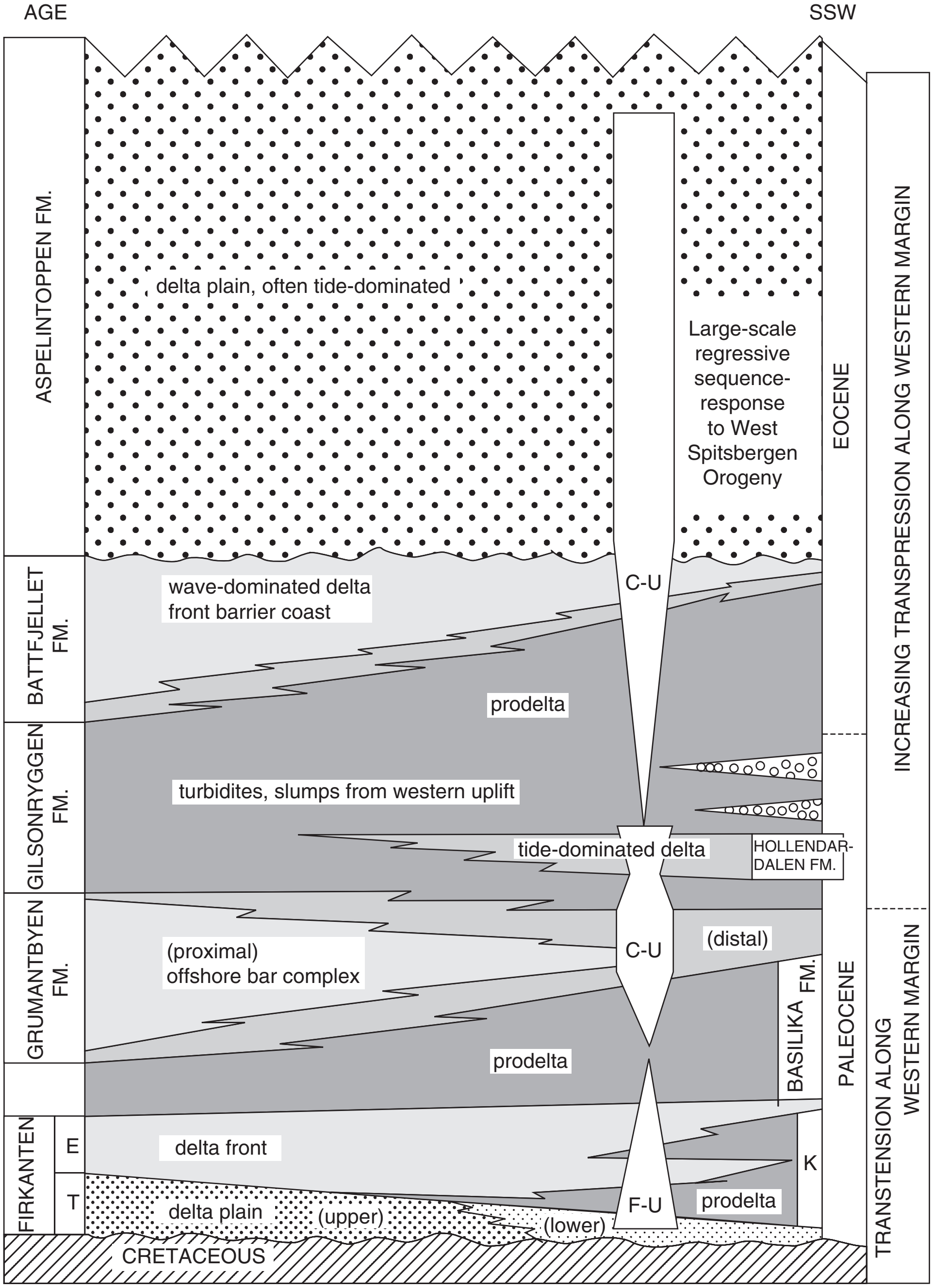

Fig. 17 The Paleogene succession of the Central Basin, Spitsbergen (from Steel et al. 1985).

Basin and over 2800 m in the Sørvestsnaget Basin (Ryseth et al. 2003). Recent studies suggest that there was some uplift of shelf areas associated with the Tertiary orogeny and opening of the Norwegian–Greenland Sea (Fig. 18). The Hammerfest and Nordkapp basins were apparently least affected, but uplift of 1–2 km may have affected the northern platform areas.

Neogene: glaciation and uplift, and renewed volcanism

The Neogene saw the development of a massive wedge deposited over and off of the western shelf margins, fed by clastics derived from large-scale and predominantly glacially related repeated shelf depression and uplift

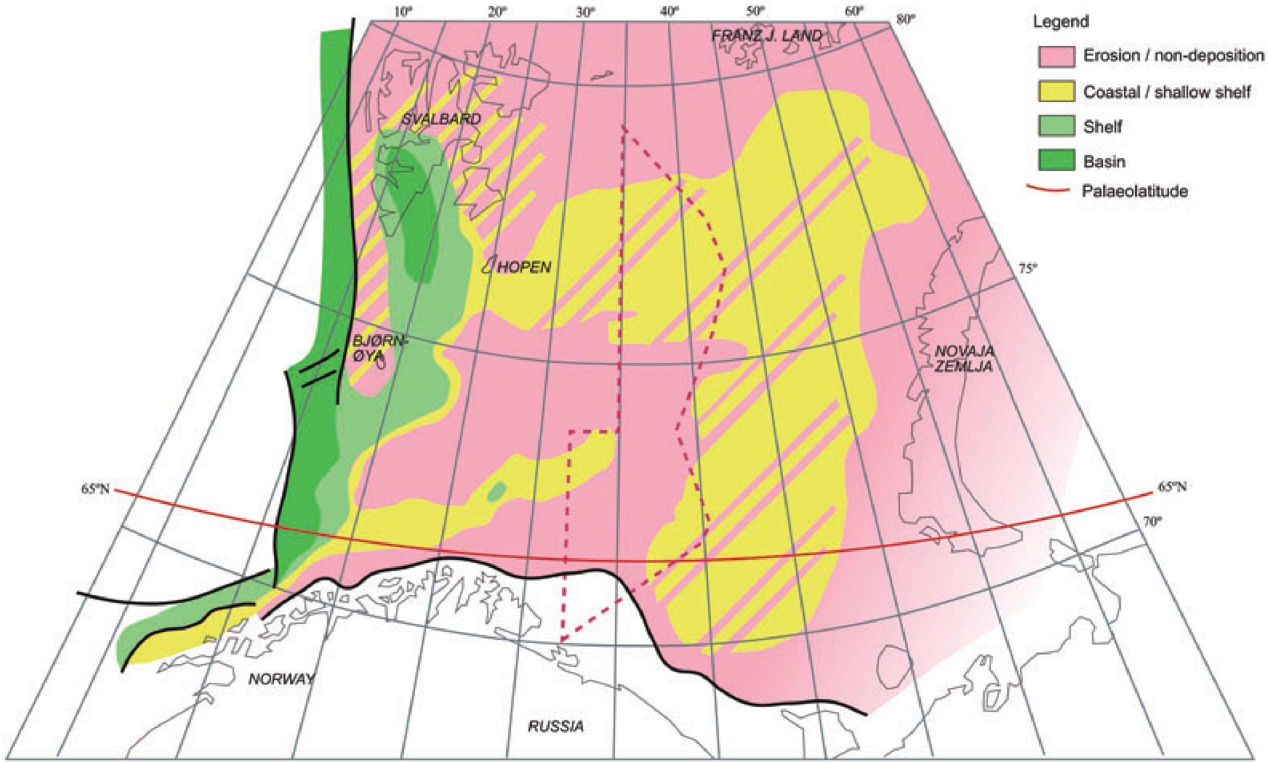

Fig. 18 Late Paleogene regional uplift.

(Faleide et al. 1996; Dimakis et al. 1999). Late Quaternary volcanism in north-western Spitsbergen may be related to the Yermak hot spot to the north-west of the archipelago.

Miocene–Pleistocene: the Nordland Group

The Neogene throughout the entire shelf was characterized by repeated glacially induced subsidence and uplift, with sedimentation restricted to the western shelf margins, and spilling over onto the newly formed oceanic crust (Fig. 19). This is true of marginal areas north and south of 76°N, where up to 5 km of fine-grained deposits of the Nordland Group accumulated along the entire western Barents Shelf margin (Faleide et al. 1996). These erosional products reflect glacial erosion and periodic isostatic uplift caused by erosional unloading during the Pliocene and Pleistocene (Vorren et al. 1991; Mangerud et al. 1996). The Hammerfest Basin and south-western Nordkapp Basin were least affected, with an uplift of less than 2 km, whereas platform areas to the north experienced an uplift and erosion of up to 3 km. These differential movements have had significant effects on pre-existing hydrocarbon accumulations, and are important risk factors now being addressed in current exploration activity (Nyland et al. 1992).

Afterword and acknowledgements

This brief review is based on a series of presentations directed mainly towards the petroleum industry over recent years. It draws on a multitude of sources, in addition to the author's own research and industrial experience since 1970. I have therefore chosen to restrict references to only a few works, without intending any offence to all of the other important contributors to this field of Arctic research over the years.

Thanks are overdue to past students, many of which are now present colleagues, for their boundless enthusiasm for Arctic geology through the years—not least Atle Mørk and Hans Arne Nakrem, who were the main drivers of the Boreal Triassic Conference. Long-term cooperation with Lars Stemmerik, Geological Survey of Denmark and Greenland, has greatly improved my understanding of the Upper Paleozoic carbonate development, and I am grateful to Ashton Embry and his colleagues in Calgary for giving me a better circum-Arctic overview. The maps have evolved in cooperation with collaborators at SAGEX Petroleum, especially with Dirk van der Wel. A special thanks to the ever-patient Turid Oskarsen for her excellent drafting, and to my ever-patient wife and colleague Rosalind Waddams.

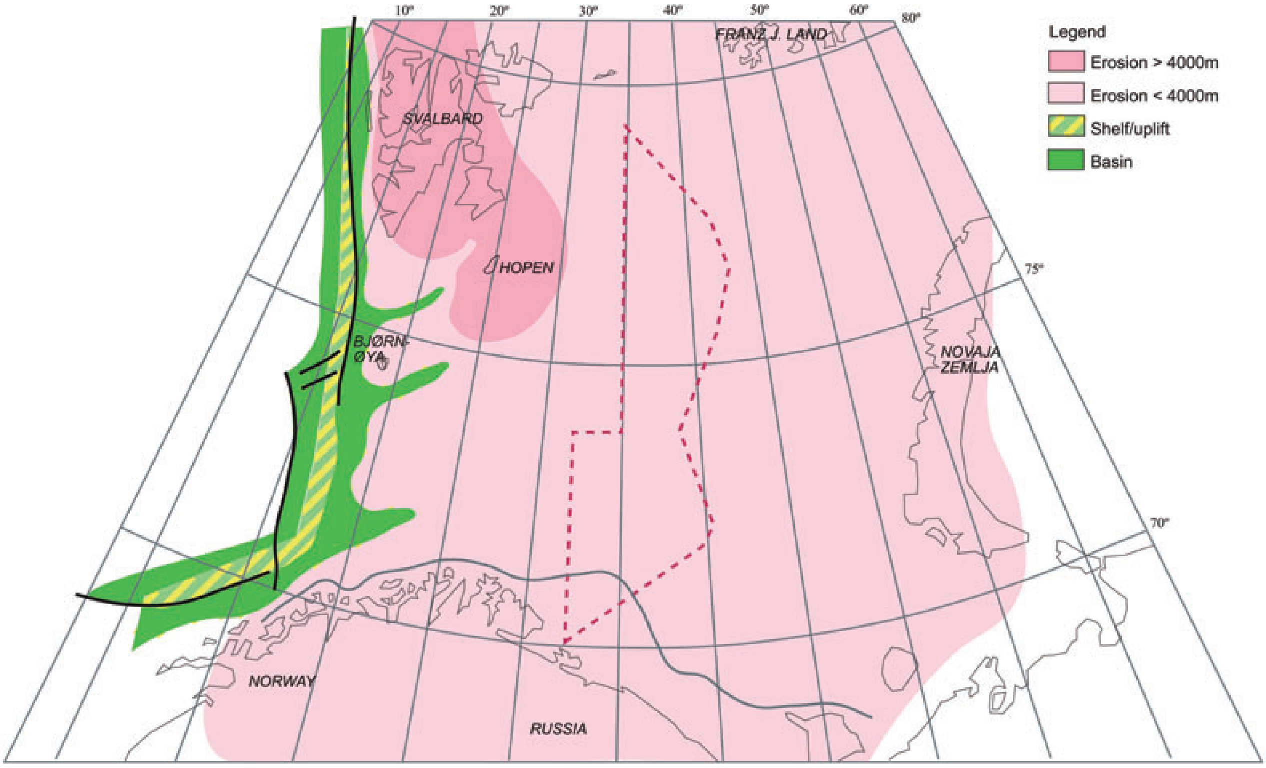

Fig. 19 Neogene regional palaeogeography.

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