Late Palaeozoic evolution of the North Atlantic margin of Pangea

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Abstract

Eleven palaeogeographic maps, spanning the earliest Carboniferous (Tournaisian) to Late Permian (Kazanian), have been constructed for the northern North Atlantic, based on available onshore and offshore data. Each palaeogeographic map corresponds to an epoch (i.e., 4–17 Ma); there are no reconstructions of the Serpukhovian and Tatarian, and the Kungurian–Ufimian are treated as one. The palaeogeographic reconstructions outline a change in the overall depositional environment of the Barents Sea–North Greenland area from huge humid flood plains in the Early Carboniferous, over shallow warm seas in the mid-Carboniferous to mid-Permian, to cooler and possibly deeper marine environments in the Late Permian. In East Greenland, non-marine conditions occurred during the entire Carboniferous, and following a prolonged, early Permian hiatus, warm-water carbonates were deposited during the Late Permian. The changes reflect large-scale shifts in palaeoclimatic and subsidence patterns related to the northward drift of the area and ongoing rifting in the region. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

The well-exposed Upper Palaeozoic sedimentary successions along the eastern and northern margins of Greenland and on Spitsbergen and Bjørnøya allow detailed examination of the sedimentary response to changes in palaeoclimate and basin-forming processes in the northern North Atlantic following the Caledonian and Franklinian orogenies. The overall palaeogeography of the North Atlantic margin of Pangea changed during Carboniferous and Permian times as the results of northward drift of the Pangaea supercontinent and ongoing rifting in the region. The Barents Sea region thus moved, as part of the European plate, from a late Carboniferous position of approximately 25 to 50°N in the late Permian (Scottese and McKerrow, 1990). This latitudinal shift in position clearly affected the depositional conditions and is well expressed in an abrupt regional shift from Carboniferous and earliest Permian warm-water carbonate sedimentation to Artinskian and younger Permian cool-water carbonate deposition in North Greenland and the western Barents Sea (Stemmerik, 1997). As a result of petroleum exploration in the Barents Sea and new mapping of the Wandel Sea Basin in eastern North Greenland, considerable new biostratigraphical and sedimentological data were extracted from these areas over the last 10 years. These data form the basis of a more detailed understanding of this vast depositional area through time (Stemmerik and Worsley, 1989, 1995; Gerard and Buhrig, 1990; Nakrem, 1991; Stemmerik and Håkansson, 1991; Stemmerik et al., 1990b, 1994, 1995; Johannesen and Steel, 1992; Cecchi, 1993; Nilsson, 1993, 1994; Mangerud, 1994; Stemmerik and Elvebakk, 1994; Bugge et al., 1995; Håkansson and Stemmerik, 1995; Lønøy, 1995; Stemmerik, 1995, 1996a,b, 1997; Pickard et al., 1996;
Ehrenberg et al., 1998; Gudlaugsson et al., 1998; Vigran et al., 1999; Worsley et al., 2000).

The Carboniferous and Permian palaeogeography of the North Atlantic margin of Pangea is reconstructed here, based on published and unpublished data from Spitsbergen, Bjørnøya, North and East Greenland and with additional information from IKU Shallow Cores on the Finnmark Platform, deep exploration wells, and seismic data (Piasecki, 1984; Steel and Worsley, 1984; Nilsson, 1988, 1993, 1994; Simonsen, 1988; Rasmussen et al., 1998; Mangerud and Konieczny, 1991; Nakrem, 1991; Nilsson et al., 1991; Stemmerik and Håkansson, 1991; Stemmerik et al., 1991b, 1993, 1995, 1996; Nakrem et al., 1992; Mangerud and Konieczny, 1993; Mangerud, 1994; Vigran, 1994; Stemmerik, 1995; Bugge et al., 1995; Håkansson and Stemmerik, 1995; Stemmerik and Worsley, 1995; Utting and Piasecki, 1995; Vigran et al., 1999). The reconstructions are presented in 11 palaeogeographic maps, each corresponding to an epoch (i.e., 4–17 Ma); there are no reconstructions of the Serpukhovian and Tatarian, and the Kungurian–Ufimian are treated as one. The biostratigraphic resolution of the outcrops in Greenland, Spitsbergen and Bjørnøya and in the IKU Shallow Cores allows for reconstruction on an even finer scale than that presented here, whereas the stratigraphy of the deeply buried offshore areas is less certain with a resolution roughly corresponding to that of the maps. The palaeogeographic reconstructions outline a change in the overall depositional environment of the Barents Sea from huge humid flood plains in the early Carboniferous, over shallow warm seas in the mid-Carboniferous to mid-Permian, to cooler and possibly deeper marine environments in the late Permian. These changes reflect large-scale shifts in the palaeoclimate and subsidence patterns related to the northward drift of the area and ongoing rifting in the region (Stemmerik and Worsley, 1995).

The palaeogeographic reconstructions provide the first step towards a better understanding of the climatic control on Late Palaeozoic sedimentation. Superimposed on the long-term depositional patterns are semi-regional and local changes related to tectonically controlled shifts in circulation patterns and drainage area. Firm correlation of these events is often possible within the present biostratigraphic resolution. Even higher frequency shifts in deposition are related to sea-level fluctuations triggered by glaciations on the southern hemisphere. They are particularly well documented in the mid-Carboniferous to mid-Permian succession, but are of a duration below biostratigraphic resolution and can only be correlated in general terms (Stemmerik and Worsley, 1995).

The application of sedimentary facies analysis, to understand past climate, is best documented by the Kazanian (Late Permian) palaeogeographic map that shows marked regional changes in depositional facies, from cool-water carbonates in the North Greenland area to warm-water carbonates in East Greenland (Stemmerik, 1997).

2. Regional geology

The North Greenland–Barents Sea region formed a complex, rift-related system of rapidly subsiding basins and more stable platforms during the late Palaeozoic (Fig. 1; Stemmerik et al., 1991b; Stemmerik, 1995; Worsley and Stemmerik, 1995). The limits of this depositional area are well defined in Greenland where the Harder Fjord, Trolle Land and East Greenland fault zones separated the depositional areas from the stable Greenland shield, whereas it is less well defined along the Norwegian coastline (Fig. 1; Håkansson and Stemmerik, 1989; Stemmerik and Håkansson, 1991; Stemmerik et al., 1996). The initiation of the Atlantic rift system between Greenland and Norway extending eastwards through the Nordkapp basin in the Barents Sea, and the Arctic rift systems that extended westwards between North Greenland and Spitsbergen to the Sverdrup Basin, took place during the latest Devonian and earliest Carboniferous (Stemmerik et al., 1991b). Important late Palaeozoic rift phases occurred during the mid-Carboniferous (Bashkirian) and mid-to late Permian (Artinskian–Kazanian) (Stemmerik et al., 1991b; Stemmerik, 1995; Stemmerik and Worsley, 1995). This latest Devonian to Early Carboniferous (Tournaisian–Visean) rift pulse is characterized by non-marine
Late Palaeozoic Tectonic Framework

Fig. 1. Pre-drift reconstruction of the northern margin of Pangea. Modified from Stemmerik (1997).
sedimentation in narrow, isolated half-grabens. It is well documented in East Greenland, Spitsbergen and Bjørnøya where sedimentation started during the latest Devonian and in eastern North Greenland where sedimentation began during the Visean (Håkansson and Stemmerik, 1984; Steel and Worsley, 1984; Stemmerik et al., 1991b; Vigran et al., 1999).

Serpukhovian to mid-Bashkirian deposits are missing in Greenland and in most other areas in the northern north Atlantic and western Barents Sea. On the Finnmark Platform, floodplain sedimentation continued into the earliest Serpukhovian (Bugge et al., 1995). Also, palynomorphs of earliest Serpukhovian age have been reworked into younger Carboniferous deposits in East Greenland (Stemmerik et al., 1991b). This suggests that basin subsidence and sedimentation stopped during the earliest Serpukhovian and that uplift and erosion took place during the mid-Serpukhovian to mid-Bashkirian. The extent of the mid-Carboniferous hiatus implies that it was caused by a regional uplift involving the East Greenland margin as well as Spitsbergen, Bjørnøya and the western Barents Sea. In eastern North Greenland, this event was associated with faulting of the Visean succession, possibly in a transpressional tectonic regime (Håkansson et al., 1981).

The mid-Serpukhovian to mid-Bashkirian regional uplift was followed by renewed rifting and basin subsidence during the mid- to late Bashkirian. The Late Carboniferous rift pulse is widely recognized throughout the northern North Atlantic and western Barents Sea where it involved both rejuvenation of older basins and formation of new half-graben systems (Steel and Worsley, 1984; Stemmerik et al., 1991b). Main rifting took place during the late Bashkirian and early Moscovian, where locally, up to 3000 m of sediments were deposited. This was followed by regional subsidence and decreasing rates of sedimentation during the late Moscovian to Gzelian. During the Late Carboniferous rift pulse, the sedimentary basins in North Greenland, on the northern part of the East Greenland shelf and in the Barents Sea area became connected with the ocean, and most basins are filled with marginal marine to shallow shelf deposits. Only in the central parts of the rift systems does subsidence outpace sedimentation; deep mainly halite-filled basins formed. The sedimentary basins of East Greenland remained non-marine also during the Late Carboniferous.

The East Greenland and North Greenland margins and structural highs like the Lopphøya and the Steinen High in the western Barents Sea were uplifted during the early Permian, and Lower Permian sediments are missing or very condensed. A new episode of rifting and basin subsidence started in the Artinskian. This late Early Permian tectonic event is well documented only in the offshore areas of the Barents Sea. It is followed by a widely recognized mid- to late Permian event in the northern North Atlantic and western Barents Sea. This tectonic event is in most areas recognized as a rejuvenation of older lineaments. It connected the sedimentary basins in central East Greenland with the boreal ocean of the present day Arctic, and, for the first time since the Silurian, marine deposition took place in East Greenland and offshore mid-Norway. The mid-Permian rifting eventually connected the Zechstein basin of northern Europe with the boreal ocean (Stemmerik, 1995).

The Carboniferous–Permian succession in the western Barents Sea and the onshore areas of North Greenland, Spitsbergen and Bjørnøya consists of four, low-order depositional sequences (Fig. 2). Three of these sequences are also present in the East Greenland basin further to the south. The second-order sequences have a duration of 8–50 Ma. Their boundaries record regional changes in relative sea-level, palaeohydrographic conditions and palaeoclimate, and they are most likely linked to the most important of the tectonic events in the North Atlantic and Arctic rift systems, described above (Stemmerik and Worsley, 1995).

Non-marine deposits dominate the uppermost Devonian–lowermost Serpukhovian sequence. Marine sediments are limited to the Finnmark Platform where shallow marine deposition took place during a brief interval in the Visean. The lower sequence boundary is a first-order tectonic unconformity that separates the sediments from Caledonian and Ellesmerian affected rocks. Sedimentation took place in isolated half-grabens,
and this depositional sequence exhibits great lateral facies variations.

The mid-Carboniferous to mid-Permian sequence was deposited in a warm and arid climate during a period with high-frequency and high-amplitude glacioeustatic sea-level fluctuations (Stemmerik and Worsley, 1989; Stemmerik et al., 1995, 1996; Stemmerik, 1996). Sedimentation was dominated by deposition of warm-water carbonates, evaporites and locally siliciclastic deposits (Håkansson and Stemmerik, 1984; Steel and Worsley, 1984). The lower sequence boundary is an erosional and, in some cases, tectonic unconformity that separates Visean and older rocks from upper Bashkirian and younger sediments. The boundary is of tectonic origin and records an episode of regional uplift and erosion in the northern North Atlantic and Barents Sea during the mid-Carboniferous. Likewise, in the northern part of the region, there is a marked climatic shift across the boundary from generally humid to more arid climatic conditions. Initial deposition took place in isolated half-grabens. Later, as the sea gradually transgressed the region, sediments onlapped structural highs and the marginal parts of the basin. The Bashkirian to Moscovian (Kasimovian) part of the sequence thus displays great lateral variations in thickness. Structural highs and platform areas were sites of shallow marine carbonate sedimentation with abundant phylloid algae—Palaeoaplysina—and bryozoan build-ups. The main grain producers are forami-
fers and calcareous algae, and the carbonate mud was most likely composed of aragonite. Evaporites are widespread both in the deeper basinal areas and in peritidal settings. The upper sequence boundary is an erosional unconformity along the basin margins and on structural highs. Elsewhere, it is a conform, slightly erosive surface that coincides with a pronounced shift in depositional facies reflecting a climatic shift towards more temperate and possibly humid climatic conditions.

The Artinskian–early Kungurian sequence is only present in the North Greenland–Barents Sea area, where it is separated from the underlying sequence by an erosional unconformity with evidence of subaerial exposure in most areas. The hiatus separating the two sequences spans much of the Early Permian time interval in the onshore areas of North Greenland and Svalbard, whereas it is of very short duration in more basinal settings (Fig. 2). The boundary coincides with a shift from warm tropical carbonates to cool-water carbonates and from high-frequency, high-amplitude sea-level fluctuations to low-frequency, low-amplitude fluctuations. Deposition of the Artinskian–early Kungurian sequence took place during an overall rise in relative sea-level that gradually led to flooding of the margins of the basins. Thick aggradational to slightly retrogradational successions of bryozoan-dominated cementstones and crinoid-dominated packstones and grainstones dominate the lower part of this sequence in the offshore areas. The upper part is composed of brachiopod- and bryozoan-dominated shelf facies in North Greenland and on Bjørnøya, and of shales and chert in more basinal settings on Spitsbergen.

In the northern part of the region, the latest Kungurian–Kazanian sequence is separated from the underlying sediments by a subaerial exposure surface in the platform areas (Stemmerik et al., 1996; Ehrenberg et al., 1998). Development of the exposure surface was followed by a very rapid rise in relative sea-level that outpaced sedimentation, and in most areas, deep-water spiculites and shales rest directly on the sequence boundary. The sea-level rise was most likely caused by a combination of increased rates of tectonic subsidence and eustatic rise in sea-level. In North Greenland, this sequence is divided into two distinctive, 80–100 m thick transgressive-regressive units, each composed of a transgressive succession of black shales and spiculites and a thick regressive succession of bryozoan-dominated rudstone or biogenic floatstone. A similar twofold division is seen in the deep water, shales and spiculite dominated successions in the offshore areas. In East Greenland, the base of the sequence is a first-order sequence boundary. Sediments belonging to the Foldvik Creek Group unconformably overlie Carboniferous and older rocks. The sequence consists of at least five third-order depositional sequences, the lower four of which are dominated by warm-water carbonates and evaporites along the basin margins. In the deeper parts of the basin, fine-grained siliciclastic sediments dominate.

3. Upper Palaeozoic biostratigraphy

Many fossil groups, including fusulinids, conodonts, small foraminifers, ammonoids and palynomorphs, have been used for dating of the Upper Palaeozoic successions in Greenland, Svalbard, Bjørnøya and the offshore areas of the Barents Sea (Dunbar et al., 1962; Cutbill and Challinor, 1965; Piasecki, 1984; Simonsen, 1988; Mangerud and Konieczny, 1991; Nakrem, 1991, 1993, 1994; Nilsson et al., 1991; Stemmerik and Piasecki, 1991; Stemmerik et al., 1991b, 1996; Nakrem et al., 1992; Nilsson, 1993, 1994; Mangerud, 1994; Vigran, 1994; Utting and Piasecki, 1995; Vigran et al., 1999). Problems arise when zonations based on different fossil groups have to be correlated. In the present case, it is most obviously a problem in the Upper Carboniferous part of the succession, where non-marine sediments of central East Greenland have to be correlated with the marine deposits further to the north. In the post-Artinskian part of the succession, biostratigraphic resolution is generally poor, and dating is based on many different fossil groups.

In this paper, the West European miospore zonation of Clayton et al. (1977) has been used for correlation of the Lower Carboniferous rocks as they are all dated by local palynological assemblages. Palynomorphs have also been used to date the Upper Carboniferous continental deposits in
East Greenland. During latest Devonian and Carboniferous times, climatic zones were wide, and the palynological zones recorded from the region are easy to correlate to the West European miospore zones. Clayton et al. (1977) have divided the Tournaisian-Bashkirian into 18 miospore zones (Fig 3). This means that each zone on average represents a time span of approximately 3 Ma. Correlation to the European standard zonation starts to be more difficult for the mid-Carboniferous as bisaccate pollen apparently developed earlier in the Arctic than it did in Europe. Accordingly, dating and correlation of the continental Upper Carboniferous deposits in East Greenland are less certain (Vigran et al., 1999).

The Russian fusulinid-based standard zonation has been used for correlation of the mid-Carboniferous to Lower Permian successions. Fusulinids have been used to date the mid-Carboniferous to Artinskian successions on the Finnmark Platform, Spitsbergen, Bjørnøya and North Greenland (Dunbar et al., 1962; Cutbill and Challinor, 1965; Nilsson, 1988, 1993, 1994; Simonsen, 1988; Nilsson et al., 1991; Stemmerik et al., 1995, 1996). Fusulinids are benthic foraminifers, mainly found in the shallow carbonate platform areas, and therefore have some limits as zonal fossils. The mid-Carboniferous to Early Permian fusulinids recorded in the Arctic region were parts of a distinctive northern faunal province that was widely dispersed throughout the shelf areas from the Sverdrup Basin in the west across North Greenland and the Barents Sea to the Timan-Pechora Basin and the Russian Platform. The Russian standard zonation divides the Bashkirian-Artinskian time interval into 25 fusulinid zones. The best stratigraphic resolution is obtained in the Upper Carboniferous where individual zones are in the range of 1-3 Ma (average 2 Ma). Fusulinid zones correspond to time intervals between 2 and 4 Ma (average 3 Ma) in the Lower Permian.

Conodonts, small foraminifers and palynomorphs have been used to date Artinskian and younger sediments in Svalbard, North Greenland and East Greenland (Rasmussen et al., 1990; Nakrem, 1991; Stemmerik et al., 1996). In Svalbard and North Greenland, the occurrence of the conodont, Neostreptognathodus pequopensis, is used to define the uppermost Artinskian. This species co-occurs with the fusulinid, Schwarrgmina jenkinsii, on Bjørnøya and confirms a late Artinskian age for this fusulinid zone. The presence of Neogondolella idahoensis in the Kapp Starostin Formation on Spitsbergen is used as an indicator for a late Kungurian to Ufimian age (Nakrem et al., 1992). In East Greenland, the Ravnefjeld Formation contains a conodont fauna dominated by Neogondolella recenkrumci. This species indicates a late Kazanian age, and the fauna is clearly younger than that recorded from Svalbard. The palynologically based stratigraphy has much broader zones than in the Carboniferous miospore zonation due to pronounced Late Permian flora provincialism, and only two assemblages have been identified (Piascecki, 1984; Mangerud and Konieczny, 1991, 1993; Mangerud, 1994; Utting and Piascecki, 1995; Stemmerik et al., 1996).

4. Correlation and palaeogeographic reconstructions

The palaeogeographic reconstructions of the North Atlantic margin of Pangea are based on a correlation of major lithostratigraphic units in the outcrop areas and offshore (Fig 4), using the biostratigraphic framework presented in Fig. 3. The reconstructions are mainly based on sedimentological data from East and North Greenland, Bjørnøya, Spitsbergen and the Finnmark Platform, where there is good biostratigraphic control. The reconstruction of the offshore areas is based on less firmly dated information from deep wells and seismic data.

4.1. Tournaisian (363-350 Ma)

The Tournaisian spans approximately 13 million years (Harland et al., 1990). Sediments of this age are known from East Greenland, Spitsbergen and Bjørnøya. They are non-marine and dated by palynomorphs. The oldest Tournaisian sediments are included in the upper Roedvika Formation on Bjørnøya and the basal Traill Ø Group in East Greenland.
Fig. 5. Palaeogeographic reconstruction of the Tournaisian showing overall depositional environments. For further details, see the text.
Greenland and belong to the LE and LN Miospore Zones (Fig. 4) (Vigran, 1994; Vigran et al., 1999). Upper Tournaisian sediments are more widespread in the region. They include the lower Traill Ø Group in East Greenland, the lower part of the Nordkapp Formation on Bjørnøya and the lower part of the Hoelbreen Member of the Hørbyebreen Formation in Spitsbergen (Vigran, 1994; Vigran et al., 1999). These sediments belong to the VI, BP, PC and CM Miospore Zones (Fig. 4).

Deposition took place in narrow isolated half-grabens (Steel and Worsley, 1984; Stemmerik et al., 1991b), and it is therefore likely that Tournaisian sediments are also present in the deep offshore basins along the central parts of the rift systems (Fig 5). In East Greenland, the Tournaisian succession consists of red braidplain sandstones and red lacustrine siltstones in the basal part. These sediments are overlain by a succession of cyclically interbedded fluvial sandstones and coal-bearing flood plain shales. On Bjørnøya, the succession starts with interbedded fluvial sandstones and coal bearing shales that pass upward into alluvial fan conglomerates and sandstones with minor intercalated coal shales. Similar sediments are recorded from Spitsbergen, where alluvial fan deposits pass laterally into coal bearing sediments in swamps and flood basins (Steel and Worsley, 1984).

The sedimentary record thus indicates that during the Tournaisian time, active sedimentation along the north Atlantic margin of Pangea was limited to isolated half-grabens, where non-marine sediments were deposited in an overall warm and humid climate. This is further supported by the presence of kaolinite-bearing terrestrial sediments in northern Kolguiev further to the east. The sea was located to the east of the study area, and shallow to deep marine carbonates and spiculites were deposited in the Timan-Pechora Basin and on Novaya Zemlya during this time interval.

4.2. Visean (350–333 Ma)

The Visean spans approximately 17 million years (Harland et al., 1990). Sediments of Early Visean age are restricted to East Greenland and Spitsbergen, where fluvial deposits belonging to the Pu Miospore Zone occur in the lower part of the Traill Ø Group and the middle part of the Hoelbreen Member, respectively (Fig. 4). In contrast, Upper Visean sediments are widespread in the area. Fluvial sediments belonging to the TC and NM Miospore Zones occur in East and North Greenland and on Spitsbergen (Traill Ø Group, upper Sortebakker Formation, uppermost Hoelbreen Member and Svenbreen Formation). Fluvial sediments, belonging to the NM-NC Miospore Zones, are present in the upper Nordkapp Formation on Bjørnøya, and fluvial to shallow marine sediments of the TC, NM and VF Miospore Zones have been recorded from IKU Shallow wells from the Finnmark Platform (Fig. 4; Bugge et al., 1995).

In East Greenland, the Visean succession is composed of stacked fining-upward cycles of fluvial sandstones and coal bearing shales, and it is suggested that deposition took place on a wide floodplain (Fig. 6; Surfýk et al., 1986; Vigran et al., 1999). Similar deposits are recorded from the Visean Sortebakker Formation in eastern North Greenland. On Bjørnøya, braided stream sandstones and conglomerates and interbedded coal shales form the Lower Visean part of the Nordkapp Formation (Gjelberg, 1981). Also on Spitsbergen, humid alluvial fan deposits and coal bearing flood-plain deposits accumulated during the Visean (Steel and Worsley, 1984). In the western part of the Finnmark Platform, a thick succession of stacked flood-plain sandstones and coal-bearing shales accumulated during the Late Visean. These deposits pass eastward into shallow marine limestones, shales and sandstones of Late Visean age in IKU Shallow Core 7129/03-U-01 from the eastern Finnmark Platform. Marine Visean deposits also accumulated further to the east on Kolguiev and Novaya Zemlya, and during the Late Visean in the Timan-Pechora basin.

The sedimentary record thus indicates that, during the Early Visean time, active sedimentation along the north Atlantic margin of Pangea was limited to isolated half-grabens where non-marine sediments were deposited in an overall warm and humid climate. The depositional area became much larger during the Late Visean with deposition on extensive flood plains that passed eastwards into a shallow marine sea (Fig. 6).
Fig. 6. Palaeogeographic reconstruction of the Visean showing overall depositional environments. For further details, see the text.
4.3. Serpukhovian (333–323 Ma)

The Serpukhovian spans approximately 10 Ma (Harland et al., 1990); it is regarded as equivalent to the Namurian A in the European zonation, and the correlation between the Russian and the European zonation follows Harland et al. (1990) (Fig. 3). Lower Serpukhovian deposits are missing in Greenland, Svalbard, and Bjornoya. They are recorded from the Finnmark Platform where continental deposits belonging to the NC and TK Miospore Zones occur (Fig. 4). Upper Serpukhovian deposits are missing in Greenland, Bjornoya and Svalbard. On the Finnmark Platform, coastal plain deposits of mottled silty shales with root structures, coaly beds and thin fining-upwards sandstones were deposited (Bugge et al., 1993). These sediments are of oldest Serpukhovian age.

4.4. Bashkirian (323–311 Ma)

The Bashkirian spans approximately 12 Ma (Harland et al., 1990) and correlates to the Namurian B and C and the main part of the Westphalian A in the European zonation according to Harland et al. (1990). Following this correlation, the Namurian B and C correspond to the lower Bashkirian, and the main part of the Westphalian A corresponds to the upper Bashkirian.

Lower Bashkirian deposits are not present in Greenland, Svalbard, and the Finnmark Platform. The lower part of the Landnøringsvika Formation on Bjornoya contains an early Bashkirian palyno-assemblage (Vigran, 1994). Upper Bashkirian deposits are not known from North Greenland and the Finnmark Platform. In East Greenland, thick accumulations of fluvial and alluvial sediments of the upper Trall Ø Group contain a miospore assemblage that can be correlated to the latest Bashkirian RA Miospore Zone (Vigran et al., 1999). Sediments of similar age also occur in the lower part of the Ebbadalen Formation on Svalbard (Fig. 4). The upper part of the Ebbadalen Formation, the upper part of the Landnøringsvika Formation and the lowermost part of the Kapp Køie Formation on Bjornoya contain an upper Bashkirian fusulinid fauna (Cuttill and Challinor, 1965; Simonsen, 1988).

During the late Bashkirian, the sea transgressed localized grabens on Svalbard, Bjornoya and elsewhere on the Barents Sea (Fig. 7). On Svalbard, alluvial fan conglomerates accumulated along the margins of narrow rift basins (Gjelberg and Steel, 1981; Steel and Worsley, 1984; Johannesen and Steel, 1992). These conglomerates pass laterally into sabkha anhydrite and shallow shelf carbonates. Similar alluvial fan, coastal plain and shallow shelf sediments occur in the Landnøringsvika Formation on Bjornoya (Gjelberg, 1981). In both areas, the sedimentary succession records an overall transgression during the Bashkirian, and cyclic shelf siliciclastics and carbonates were deposited over large areas by the end of the Bashkirian.

Further to the south, rift-associated continental sediments were deposited in central East Greenland where alluvial fan conglomerates pass laterally into stacked successions of meandering stream sandstones and coaly flood-plain shales (Fig. 8). Lacustrine deposits are of minor importance (Christiansen et al., 1990; Piasecki et al., 1990; Stemmerik et al., 1991a).

The sedimentary record implies that there was a marked climatic shift from the Visean to the Bashkirian in the northern part of the region. The overall humid subtropical climate that characterized the Visean was replaced by an overall arid climate with widespread deposition of evaporites. Sediments in central East Greenland were more likely deposited in a humid, subtropical climate, implying a marked climatic zonation during the late Bashkirian (Fig. 7).

4.5. Moscovian (311–303 Ma)

The Moscovian spans approximately 8 Ma (Harland et al., 1990) and correlates with the uppermost part of Westphalian A and Westphalian B, C and D following Harland et al. (1990). The Moscovian is subdivided into four fusulinid zones in the Russian zonation. Lower Moscovian strata are missing in East Greenland and on the Finnmark Platform. In North Greenland, the Kap
Fig. 7 Palaeogeographic reconstruction of the Bashkirian showing overall depositional environments. For further details, see the text.

Jungersen Formation is dated as early Moscovian, based on fusulinids (Dunbar et al., 1962). The Efuglvika Member of the Kapp Kåre Formation on Bjørnøya contains a Profusulinella assemblage of early Moscovian age (Simonsen, 1988; Stemmerik et al., 1998), and the lowermost part
of the Nordenskiöldbreen Formation on Spitsbergen contains a *Profusulinella* assemblage also of early Moscovian age (Cutbill and Challinor, 1965; Nilsson, 1988).

Upper Moscovian strata are missing in East Greenland. In North Greenland, the Foldedal Formation is of late Moscovian age, based on fusulinids (Stemmerik and Håkansson, 1989; Nilsson et al., 1991; Nilsson, 1994). The uppermost Kapp Káre and the lower Kapp Hanna Formations on Bjørnøya contain fusulinids belonging to the late Moscovian *Fusulinella, Wedekindellina* and *Fusulina* zones (Simonsen, 1988; Stemmerik et al., 1998). On Spitsbergen, the lower part of the Nordenskiöldbreen Formation contains fusulinids belonging to the upper Moscovian *Wedekindellina* zone (Cutbill and Challinor, 1965; Nilsson, 1988).

During the early Moscovian, the transgression reached part of North Greenland and the Nordfjord High on Spitsbergen, and during the late Moscovian, the Wandel Sea Basin of North Greenland and the Finnmark Platform were transgressed, and the northern margin of Pangea formed a huge shelf area (Fig. 9). The lower Moscovian successions in the western Barents Sea and North Greenland are dominated by interbedded shallow marine siliciclastics and carbonates in the platform areas and by evaporites in the deep basins. In North Greenland, interbedded shallow water carbonates and siliciclastics dominated in most areas. Locally, bryozoan, phylloid algae and *Palaeoaplysina* build-ups formed. Shallow subaqueous evaporites and sabkha type anhydrite are restricted to the mid-Moscovian of Amdrup Land in eastern part of North Greenland (Stemmerik, 1993, 1996). These sediments are most likely a shallow-water equivalent to the thick halite and anhydrite successions that accumulated in the Nordkapp Basin and other deep basins during the Moscovian. The same overall depositional conditions are recorded in the western part of the Barents Sea and on Bjørnøya and Spitsbergen (Lønøy, 1995; Pickard et al., 1996; Stemmerik et al., 1998). During the late Moscovian time, the siliciclastic input gradually diminished in the western Barents Sea and North Greenland, and stacked shallow marine carbonates dominated in the platform areas. On Spitsbergen, alluvial fan conglomerates were deposited along the margins of fault blocks. Elsewhere, normal marine to shallow restricted marine and lagoonal warm-water carbonates accumulated (Pickard et al., 1996). Small bryozoan
Fig. 9. Palaeogeographic reconstruction of the Moscovian showing overall depositional environments. For further details, see the text.
build-ups have been recorded locally on Spitsbergen (Lønøy, 1995; Pickard et al., 1996). On the Finnmark Platform, the condensed Moscovian succession is dominated by siliciclastic sediments. Upward-fining sandstones of fan delta origin were deposited in the southern part of the platform (Bugge et al., 1995). Northwards, they interfinger with shallow shelf carbonates (Ehrenberg et al., 1998). Further to the east, on Kolguyev, shallow marine to supratidal carbonates and evaporites were deposited, and comparable sediments dominate in the Timan–Pechora basin. The sedimentary record thus indicates that deposition was limited to the northern part of the region. Pangea, at this time, was fringed to the north by a huge warm-water shelf dissected by deeper water basins. The sediments were deposited during an interval with high-frequency and high-amplitude sea-level fluctuations, and there are several bodies of evidence in the sedimentary record for widespread subaerial exposure of the inner shelf areas. The halite, in the deeper basins, most likely accumulated during sea-level lowstands, when the basins were partly isolated.

4.6. Kasimovian (363–295 Ma)

The Kasimovian spans approximately 8 Ma, according to Harland et al. (1990). It is divided into three fusulinid zones in the Russian zonation. Biostratigraphic data from North Greenland and the Barents Sea are not good enough to allow such detailed correlation, and the unit will be treated as one. Kasimovian sediments are missing in East Greenland. On the Finnmark Platform, sediments belonging to the upper Kasimovian–lower Gzelian Rugosofusulina prisca zone unconformably overlie older strata. The upper part of the Foldedal Formation in North Greenland is of Kasimovian age, based on fusulinids (Nilsson et al., 1991; Nilsson, 1994). On Spitsbergen, Kasimovian deposits comprise three fusulinid zones and are included in the lower part of the Cadellfjellet and Kapitol Members of the Nordenskiöldbreen Formation (Nilsson, 1993). In North Greenland, subsidence rates decreased near the Moscovian–Kasimovian boundary, and the Kasimovian succession is relatively thin. Shallow-water carbonates with isolated tabular phylloid algal mounds dominate (Fig. 10). They pass basinwards into bioturbated deeper subtidal carbonates, mainly wackestones (Stemmerik et al., 1996). On Spitsbergen, normal marine to partially restricted inner platform carbonates capped the Nordfjorden Block and adjacent areas. On the Finnmark Platform, upper Kasimovian shallow shelf to shoreface silstones and fine-grained sandstones were deposited towards the south (Bugge et al., 1995). They pass northwards into cyclically interbedded outer shelf to shoreface shale and siltstone, occasionally capped by thin phylloid algal buildups (Ehrenberg et al., 1998). In the Timan–Pechora basin, shallow shelf carbonates continued to dominate. The sedimentary record thus indicates an absence of major changes in palaeogeography and palaeclimates from the Moscovian to the Kasimovian. The gradual decrease in siliciclastic supply to the shelf area, which started during the Moscovian, continued into the Kasimovian with Bjørnøya as the exception. Local tectonic uplift of eastern Bjørnøya led to renewed siliciclastic sedimentation (Worsley et al., in press).

4.7. Gzelian (295–290 Ma)

The Gzelian spans approximately 5 Ma, according to Harland et al. (1990). This stage is divided into three or four fusulinid zones depending on where the Gzelian–Asselian boundary is placed. Here, the Sphaeroschwagerina fusiformis–S. vulgaris zone is regarded as representing the lowermost Asselian. Gzelian deposits are missing in East Greenland. The oldest Gzelian is missing on Bjørnøya. The top part of the Foldedal Formation in North Greenland is of Gzelian age, based on the presence of the Rauverites ex. gr. rossicus and Schellwienia arctica zones. The lower part of the Kapitol Members of the Nordenskiöldbreen Formation contain four Gzelian fusulinid zones (Nilsson, 1993). Gzelian sediments are also
Fig. 10. Palaeogeographic reconstruction of the Kasimovian showing overall depositional environments. For further details, see the text.
recorded in the IKU Shallow Cores 7029/03-U-02 and 7030/03-U-01 from the Finnmark Platform. Throughout eastern North Greenland, Spitsbergen and Bjørnøya, condensed sections of shallow shelf carbonates were deposited (Fig. 11). In central North Greenland, outer ramp shallow-upwards cycles of bioturbated carbonate mudstones and phylloid algal/Palaeoaplysina build-ups were deposited on the deeper parts of the shelf, whereas the shallow marine, fusulinid-rich carbonates dominated in the near-shore areas. On Bjørnøya, a NE-SW-trending Palaeoaplysina complex formed during late Gzelian times (Lønøy, 1988; Stemmerik et al., 1994), and on Spitsbergen small isolated Palaeoaplysina build-ups occurred on the Nordfjorden block during latest Gzelian time (Skaug et al., 1982). They overlie a laterally widespread, shallow subtidal to supratidal inner shelf succession of mid-Gzelian age (Pickard et al., 1996). Major changes in depositional environments are seen on the Finnmark Platform where inner shelf to sabkha sediments with small isolated Palaeoaplysina build-ups dominated in the southern part (Stemmerik et al., 1995). Comparable changes are also recorded further offshore where Kasimovian silt-dominated shelf deposits are overlain by shallow to deeper shelf carbonates with abundant phylloid algal buildups (Ehrenberg et al., 1998). Thick subaqueous anhydrite beds also occur in the late Gzelian succession of the Finnmark Platform, and most likely, halite and anhydrite accumulated in the Nordkapp Basin during this time interval. In the Timan-Pechora Basin, deposition of open marine platform carbonates dominated.

The most important change in palaeogeography from the Kasimovian to the Gzelian, is the shift from silicilastic-dominated sedimentation to carbonate deposition on the Finnmark Platform and on Bjørnøya (Fig 11). The depositional record implies that a warm and arid climate continued to dominate the region also during the latest Carboniferous. 

**4.8. Asselian (290–282 Ma)**

The Asselian spans approximately 8 Ma (Harland et al., 1990). This stage is subdivided into three fusulinid zones in the Russian zonation. Asselian strata are missing in East Greenland and most of North Greenland. The upper part of the Kapp Duner Formation on Bjørnøya contains middle to upper Asselian fusulinids, and on Spitsbergen, the middle part of the Tyrrellfjellet Member of the Nordensisildbreen Formation is of Asselian age (Nilsson, 1993). Asselian sediments also occur in IKU Shallow cores 7129/10-U-02 and 7030/03-U-01 from the Finnmark Platform.

In North Greenland, Asselian shallow marine shelf carbonates are limited to the northeastern part of the basin. Elsewhere, the older platforms were subaerially exposed during this time period (Fig. 12). On Spitsbergen and Bjørnøya, shallow shelf carbonates dominated. Palaeoaplysina-phylloid algae build-ups are restricted to the western part of Bjørnøya and the central parts of Spitsbergen (Fig. 12). This facies pattern extended eastward along the southern margin of the Finnmark Platform (Bugge et al., 1995; Stemmerik et al., 1995). Further offshore, in the northern part of the Finnmark Platform, inner shelf carbonates with Palaeoaplysina buildups dominated during the early Asselian. They pass upwards into restricted marine, lagoonal to intertidal sediments and, finally, late Asselian open marine inner shelf deposits (Ehrenberg et al., 1998). Anhydrite and halite were deposited in the deeper basinal areas like the Nordkapp Basin, and occasionally, thick subaqueous anhydrite beds extend into the shallower parts of the platforms.

The most important change in palaeogeography, from the Gzelian to the Asselian, is the uplift and exposure of the Greenland margin of the basin (Fig. 12). The depositional record implies that the warm and arid climate continued to dominate the region also during the latest Carboniferous, and that high-frequency and high-amplitude glacio-eustatic sea-level oscillations still had a strong influence on sedimentation.

**4.9. Sakmarian (282–269 Ma)**

The Sakmarian spans approximately 13 Ma (Harland et al., 1990) and is subdivided into three fusulinid zones in the Russian zonation. Sakmarian strata are missing in East Greenland, most of North Greenland and possibly Bjørnøya.
Fig. 11. Palaeogeographic reconstruction of the Gzelian showing overall depositional environments. For further details, see the text.
Fig. 12. Palaeogeographic reconstruction of the Asselian showing overall depositional environments. For further details, see the text.
On the Finnmark Platform, Sakmarian sediments are recorded in IKU Shallow Core 7129/10-U-02. Lower Sakmarian fusulinids have been recorded from the upper part of the Nordenskiöldbreen Formation (Nilsson, 1993). The overlying Gipsukken Formation is poorly dated as late Early Permian and is regarded here as Sakmarian in age.

In North Greenland, outer shelf limestones accumulated in an isolated subbasin towards the northeast (Nilsson et al., 1991; Stemmerik et al., 1991b). Elsewhere in the Wandel Sea Basin, the older carbonate platforms were subaerially exposed during the Sakmarian. A similar rapid drowning of the Asselian carbonate platforms occurred along the Finnmark Platform, and during the early to middle Sakmarian, this area was a deep siliciclastic shelf (Fig. 13). During the later Sakmarian, carbonate platform deposits started to prograde, and the Finnmark Platform became an open marine carbonate platform. The same transgressive-regressive pattern is seen on Spitsbergen, where restricted marine carbonate deposits of late Asselian age are overlain by open marine deeper water carbonates of early to mid-Sakmarian age (Limestone B of Pickard et al., 1996, for example).

The Gipsukken Formation evaporites and restricted marine, inner-shelf carbonates at Spitsbergen represent deposition on a local, latest Sakmarian high. These sediments are the youngest sediments, indicative of a warm and arid climate in the Barents Sea area.

The most important change in palaeogeography from the Asselian to the Sakmarian is the rapid deepening of the shelf areas and the uplift of Spitsbergen, during the latest Sakmarian times. The depositional record implies that the warm and arid climate continued to dominate the region, although the overall deepening of the shelf areas led to colder conditions and local dominance of bryozoans and crinoids.

**4.10. Artinskian (269–260 Ma)**

The Artinskian spans approximately 9 Ma (Harland et al., 1990) and is subdivided into four substages, of which the lower three contain fusulinids.

Lower Artinskian strata are missing from East Greenland, most of North Greenland, Bjørnøya, Finnmark Platform and Spitsbergen. They are widespread in the offshore areas of the Barents Sea. Upper Artinskian strata are missing from East Greenland. Fusulinids are rare in the later part of the Artinskian in the Arctic, and in most areas, the presence of upper Artinskian deposits is documented by the occurrence of conodonts belonging to the *Neostreptognathodus pequopensis* Zone (Nakrem, 1991; Rasmussen and Håkansson, 1996). The lower part of the Kim Fjelde Formation in North Greenland contains *N. pequopensis* and is regarded here as late Artinskian in age. *N. pequopensis* occurs, associated with the fusulinid *Schwagerina jenkinsi* in the upper part of the Hambergfjellet Formation on Bjørnøya, suggesting a late Artinskian age for this formation. *S. jenkinsi* also occurs in IKU Shallow Cores from the Finnmark Platform (Nilsson, 1993). The Vøringen Member of the Kapp Starostin Formation also contains *N. pequopensis*, and is regarded here as late Artinskian in age.

In the Barents Sea, a new rapid transgression took place during the earliest Artinskian, and the sediments gradually onlapped structural highs and the marginal parts of the basin during the Artinskian (Fig. 2). The transgression was associated with a shift in depositional conditions towards cool-water carbonate deposition (Stemmerik, 1997). During the rise in sea-level, large bryozoan-dominated build-ups formed along the northern margin of the Finnmark Platform, on the Loppa High and elsewhere in the Barents Sea (Gerard and Buhrg, 1990; Bruce and Toomey, 1993, Nilsen et al., 1993). The maximum relative sea-level occurred during the mid-Artinskian, and the later part of the Artinskian is dominated by widespread cool-water carbonate platforms throughout the region (Fig. 14). These platforms are dominated by bryozoan-crinoid grainstones in the outer shelf areas of the Finnmark Platform, whereas brachio-pod-dominated packstones were deposited in inner shelf areas of North Greenland, Spitsbergen and Bjørnøya (Stemmerik, 1997). In the Timan-Pechora Basin, depositional pattern changed and deeper water siliciclastic sediments were deposited throughout the basin.

The palaeogeography changed very significantly
Fig. 13. Palaeogeographic reconstruction of the Sakmanian showing overall depositional environments. For further details, see the text.
Fig. 14. Palaeogeographic reconstruction of the Artinskian showing overall depositional environments. For further details, see the text.

from a relatively shallow warm-water platform in the Sakmarian to a much deeper cool-water platform in the Artinskian. In the deep basinal area, evaporite sedimentation was replaced by deep-water resedimented carbonates, shales and chert. The Artinskian transgression reached North
Greenland during late Artinskian times, and over large areas, deposition was resumed for the first time since the latest Carboniferous. The change in climate was associated with a shift in fauna from foraminifer- and algally dominated to brachiopod, bryozoan and locally crinoid-dominated (Stemmerik, 1997).

4.11. Kungurian–Ufimian (260–255 Ma)

The Kungurian spans approximately 4 Ma, and the Ufimian spans 1 Ma (Harland et al., 1990). The two stages correspond to the upper Leonardian in the North American zonation and the uppermost Rotliegendes to lowermost Zechstein in the European zonation. Stratigraphic resolution of this stratigraphic interval is relatively poor.

Kungurian deposits are included in the Kim Fjelde Formation and, possibly, lower Midnatfjeld Formation in North Greenland. In East Greenland, sedimentation possibly started during the Kungurian-Ufimian with deposition of the Huledal Formation (Surlyk et al., 1986). Kungurian-Ufimian deposits are dated on the basis of palynomorphs assigned to the Dyupetalum sp.-Hamiapollenites ballaquorum assemblage in two IKU Shallow Cores from the Finnmark Platform (Mangerud, 1994). The Miseryfjellet Formation on Bjørnøya contains Neogondolella idahoensis and is regarded as Kungurian-Ufimian in age (Nakrem, 1991). The upper part of the Kapp Starostin Formation (above the Voringen Member) contains relatively few fossils of stratigraphic significance. This part of the formation is regarded as Kungurian-Kazanian in age, based on the occurrence of Neogondolella idahoensis in the upper part of the formation.

Kungurian-Ufimian depositional patterns differ significantly from those recorded in the Lower Permian (Fig. 15). Marine sedimentation started in East Greenland during this time interval, and throughout the Barents Sea area, cool-water carbonates, spiculites and shales were deposited. Inner-shelf brachiopod and bryozoan dominated packstones were deposited locally on Spitsbergen, Bjørnøya and along the margins of the Finnmark Platform. Cool-water carbonate platforms formed along the margins of the Wandel Sea Basin. They are seen to pass basinwards into deeper water shales and spiculitic chert (Stemmerik, 1997).

In the Timan-Pechora Basin, shallow marine sandstones and marginal marine sabbkha deposits were deposited during the Kungurian. The area became a vast coastal plain during the Ufimian, and coastal sandstones and coal-bearing shales were deposited.

The most important changes in palaeogeography from the Artinskian to the Kungurian-Ufimian is the establishment of a marine connection southward, along the axis of the Greenland-Norway rift to connect the East Greenland basin with the Barents Sea region. The depositional areas of the Barents Sea region became gradually deeper, and deposition took place in a cooler, temperate climate.

4.12. Kazanian (255–251 Ma)

The Kazanian spans approximately 4 Ma (Harland et al., 1990) and corresponds to the Wordian and lower Capitanian in the North American zonation and the middle to upper Zechstein in Europe. Stratigraphic resolution is poor in this interval.

Kazanian deposits are missing on Bjørnøya. On Spitsbergen, the uppermost part of the Kapp Starostin Formation is of Kazanian age. The Midnatfjeld Formation in North Greenland is of Kazanian age (Stemmerik et al., 1996), and Kazanian sediments are also present in IKU Shallow Cores from the Finnmark Platform, based on the presence of a Scutaspores-Lunatisporites assemblage (Mangerud, 1994). In East Greenland, the Karstryggen, Wegener Halvo and Ravnefjeld Formations are of Kazanian age, based on palynomorphs and conodonts (Piascecki, 1984; Rasmussen et al., 1990).

In East Greenland, restricted marine carbonates were deposited during the early Kazanian. Later in the Kazanian, open marine carbonate platforms with bryozoan build-ups (Fig. 17a) formed along platform margins, and on structural highs, deeper water anoxic shales were deposited in the basinal centre (Fig. 16). Offshore mid-Norway, carbonates of this age have been drilled on a structural high
Fig. 15. Palaeogeographic reconstruction of the Kungurian–Ufimian showing overall depositional environments. For further details, see the text.
Fig. 16. Palaeogeographic reconstruction of the Kazanian showing overall depositional environments. For further details, see the text.
Firmly dated Tatarian deposits are restricted to the Schuchert Dal Formation in East Greenland, which contains a transitional latest Permian to earliest Triassic palynoflora (Piasecki, 1984; Uttingshales were deposited during the Kazanian. Along the margins of North Greenland, cool-water platform bryozoan rudstones, where most bryozoans are delicate fenestrate forms (Stemmerik, 1997). The outer ramp sediments pass laterally into a deeper water succession of siliciclastic-dominated shale and spiculitic chert.

Towards the east, the Timan–Pechora Basin was a huge fluvial plain that passed northwards into coastal plain sandstones and shales of the Pechora Shelf.

The most important change in palaeogeography from the Kungurian–Ufimian to the Kazanian is the deposition of warm-water carbonates in the East Greenland basin. The sea way established along the axis of the Greenland–Norway rift from the Barents Sea and southwards to the East Greenland basin extended further southwards to the Zechstein basin of northern Europe, where thick accumulations of halite are present. The sediments in central East Greenland were more likely deposited in a semi-arid, subtropical climate, implying a marked climatic zonation from the temperate areas in North Greenland and the Barents Sea over East Greenland to the arid areas of northern Europe (Stemmerik, 1995).

4.13. Tatarian (251–245 Ma)

The Tatarian spans approximately 6 Ma (Harland et al., 1990) and corresponds to the upper Capitanian and Ochoan in North America and the Buntsandstein in Europe. The stratigraphic resolution is extremely poor in this interval due to problems in correlating the continental sediments of the stratotype with the marine zonation.

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Fig. 17. Typical Upper Permian sediments. (a) Massive Kazanian bryozoan buildup (WH) passing into well-bedded flank deposits, East Greenland. The exposure is approximately 80 m high. (b) Kungurian–Kazanian bryozoan-rich cool-water carbonates, Kim Fjell Formation, North Greenland. The scale is in centimetres.
located somewhere between 74°45' and 80°15'N in East Greenland. The repeated superposition of mature karstic horizons on shallow marine evaporites in the Upper Permian carbonate platforms of East Greenland led Scholle et al. (1993) to suggest that this zone was forced southwards to at least 70°N several times during the Late Permian.

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