30 years on – Arctic Upper Palaeozoic stratigraphy, depositional evolution and hydrocarbon prospectivity

Lars Stemmerik & David Worsley

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The southern Norwegian Barents Sea – Svalbard – North Greenland area formed the central portion of the east–west oriented northern Pangaean shelf during Carboniferous and Permian times. Integration of onshore geological data and offshore, mainly geophysical data, has greatly improved our understanding of the evolution of this part of the shelf during Late Palaeozoic time. The four-fold lithostratigraphic division of the succession reflects long, 15–30 Myr periods of relatively stable depositional conditions separated, at the group boundaries, by abrupt changes which can be linked to ongoing rifting of the area and the northward drift of Pangaea. Deposition of the dominantly non-marine Billefjorden Group started onshore in the Late Famennian (in the offshore areas during the Early Viséan) and continued into the Early Serpukhovian. Following regional uplift, sedimentation resumed diachronously during mid-Serpukhovian – Early Moscovian times. The climate changed from humid to arid during the latest Serpukhovian, and the bulk of the Gipsdalen Group is characterised by warm-water carbonates and evaporites. The Upper Sakmarian – Artinskian (?lowermost Kungurian) Bjarmeland Group reflects deposition on a cool-water carbonate shelf. The mid-Sakmarian shift from warm- to cool-water carbonates seems to predate a comparable transition in the Sverdrup Basin which is dated to have taken place 5–8 Myr later, in the Early Artinskian. During Kungurian and younger Permian time the central Pangaean shelf was dominated by deposition of deeper water spiculites and shale, and sandstones and cold water carbonates were restricted to isolated highs and the southern shelf margin.
Moscovian–Asselian exposure-capped shelf carbonates and *Palaeoaplysina* – phylloid algal buildups of the Gipsdalen Group form the most prospective reservoir rocks in the region. The top of the main reservoir interval is defined by a major, Early Sakmarian, flooding surface which forms a regional seismic mapping horizon. Post-depositional fresh-water modification of the carbonates took place locally due to Artinskian and younger Permian uplift and subaerial exposure. Mapping of Permian karst systems is a major task for better reservoir prediction.

L. Stemmerik, Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 København K, Denmark. ls@geus.dk; D. Worsley, Færgestadveien 11, NO-3475 Sætre, Norway. david.worsley@prw.no

Introduction

During the last 30 years the knowledge of Arctic Upper Palaeozoic stratigraphy and depositional evolution has increased considerably, and our understanding of hydrocarbon prospectivity in the southern Norwegian Barents Sea has improved accordingly. To date, almost 400 000 km of 2D seismic and 10 000 km^2 of 3D seismic have been acquired in the Norwegian sector (Larssen et al. 2002). In addition, 14 wells have drilled Upper Palaeozoic sediments: six of these had the Upper Palaeozoic succession as a target, but so far no commercial discoveries have been made in these rocks.

Hydrocarbon exploration in the southern Norwegian Barents Sea was initiated in the 1970s, and the first seismic data formed the basis for dividing the shelf area into a series of major sub-provinces, each with a complex structural and sedimentological development (Rønnevik et al. 1982; Rønnevik & Jacobsen 1984; Faleide et al. 1984). The acquisition of seismic data was accompanied by a revitalisation of outcrop-based studies of the Upper Palaeozoic succession on Svalbard, and later, North Greenland and Arctic Canada, as summarised in a series of papers from the mid-1970s to early 1990s (e.g. Worsley & Edwards 1976; Skaug et al. 1982; Steel & Worsley 1984; Håkansson & Stemmerik 1984, 1989; Worsley et al. 1986; Beauchamp et al. 1989; Davies et al. 1989; Stemmerik & Håkansson 1989; Stemmerik & Worsley 1989; Beauchamp 1993, 1994; Stemmerik & Larssen 1993; Stemmerik et al. 1994). The first three exploration wells to penetrate the Upper Palaeozoic section of the Norwegian Barents Shelf were drilled in the mid-1980s on the Loppa High – a prominent Late Palaeozoic to Early Triassic positive feature in the south-western Barents Shelf (Fig. 1). They were followed by shallow core drilling by IKU Petroleum Research on the Finnmark Platform and, together with improved seismic data quality resulted in the first more detailed understanding of the offshore areas (Gabrielsen et al. 1990; Gerard & Buhrig 1990; Bruce & Toomey 1993; Cecchi 1993; Nilsen et al. 1993; Bugge et al. 1995; Stemmerik & Worsley 1995; Stemmerik et al. 1995).

Drilling in the mid-1990s of well 7128/6-1 on the Finnmark Platform with its almost continuous core of the marine Upper Palaeozoic section marks the next important step forward in the understanding of the offshore succession. The core has been intensively

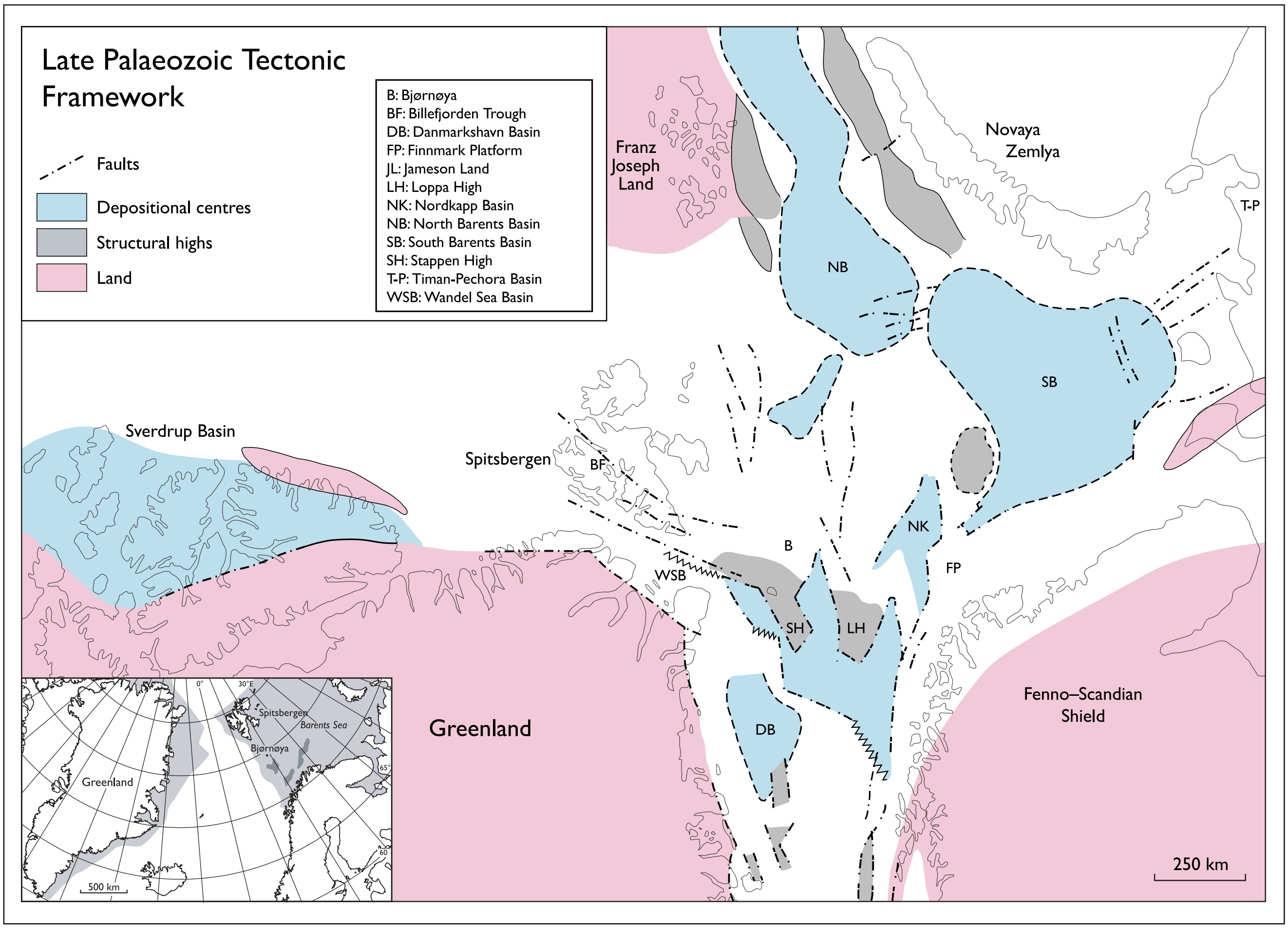

Fig. 1. Pre-drift reconstruction of the northern margin of Pangaea showing major structural elements. Inset map shows the present day position of Greenland and Norway and the adjacent shelf areas.

studied (e.g. Groves & Wahlman 1997; Ehrenberg et al. 1998a, 1998b, 2000, 2001), and the well has been important for dating seismic sequences both in regional 2D and more localised 3D seismic data sets (e.g. Elvebakk et al. 2002; Larssen et al. 2002; Samuelsberg et al. 2003).

This paper gives a stratigraphic and depositional overview of the Upper Palaeozoic succession in the Barents Sea – Svalbard – North Greenland area with focus on aspects important for hydrocarbon prospectivity. The integration of outcrop, seismic and well data gained over the last 30 years has resulted in a much more refined understanding, not only of the stratigraphy and depositional facies variations but also of key aspects of the hydrocarbon system. The reservoir properties of the Upper Palaeozoic carbonate succession in the southern Norwegian Barents Sea are directly linked to primary mineralogy and early diagenetic processes, and differ on a gross scale from group to group. The best properties are generally in Upper Carboniferous to Lower Permian dolomitic carbonates of the Gipsdalen Group (Stemmerik et al. 1999). Access over the last few years to large 3D seismic data sets has further improved our understanding of the three dimensional variations in depositional facies and rock properties in these carbonates (Elvebakk et al. 2002; Rafaelsen et al. 2003; Samuelsberg et al. 2003; Colpaert et al. 2004), and it is becoming increasingly evident that fluid flow related to Permian karst systems is locally important in modifying reservoir properties (Hunt et al. 2003). Karst overprinted, Upper Palaeozoic carbonates have been described from Bjørnøya and more recently from Spitsbergen (Stemmerik & Larssen 1993; Eliassen & Talbot 2003a,b), but their importance for reservoir properties offshore has yet to be tested.

Regional setting

The area from the Sverdrup Basin of Arctic Canada in the west across North Greenland and the Norwegian Barents Sea to Arctic Russia in the east formed part of the same, east–west oriented shelf, defining the northern margin of Pangaea during the Late Palaeozoic (Fig. 1; Golonka & Ford 2000). The shelf drifted northwards with a rate of 2–3 mm per year from approximately

20°N to approximately 45°N palaeolatitude during the Carboniferous and Permian. The gradual shift in palaeolatitudinal position is reflected by a change in climatic conditions from tropical and humid in the Early Carboniferous to temperate in the Late Permian (Beauchamp 1994; Beauchamp & Desrochers 1997; Beauchamp & Baud 2003; Stemmerik 1997, 2000).

The Barents Sea – North Greenland – Svalbard area, central on this northern shelf was characterised by the development of two linked rift arms during the Late Palaeozoic, and deposition took place in a complex of rapidly subsiding basins and more stable platforms (Stemmerik & Worsley 1989, 1995; Gudlaugsson et al. 1998; Stemmerik 2000). The Atlantic rift arm started to form between Greenland and Norway and extended towards the north-east across the central Barents Sea whereas the Arctic rift arm extended westwards between Greenland and Spitsbergen and eventually linked with the Sverdrup Basin rift in the far west (Fig. 1; Gudlaugsson et al. 1998). Rifting started in the Early Carboniferous, and following regional uplift in the Serpukhovian, rifting was intensified during the mid-Carboniferous (Bashkirian) (Stemmerik et al. 1991; Stemmerik & Worsley 1989, 1995). This led to fault-controlled subsidence and depocentres forming along the rift axis as in the case of the Tromsø, Nordkapp and Danmarkshavn basins and in more local half-grabens, such as the Billefjorden Trough (Fig. 1). Rifting was followed by a marine transgression in the Bashkirian and the rapidly subsiding offshore basins became sites of deeper water deposition during the Late Palaeozoic (Stemmerik 2000). The more slowly subsiding areas such as the Bjarmeland and Finnmark platforms and tectonically active blocks such as the Stappen and Loppa highs were sites of shallower marine deposition and intermittent subaerial exposure from the mid-Carboniferous until the Late Permian.

The southern margin of the shelf and structural highs such as the Loppa High and the Stappen High in the western Barents Sea were uplifted during the Early Permian and Upper Sakmarian – Lower Artinskian sediments are also missing or very condensed in North Greenland and on the southernmost Finnmark Platform (Bugge et al. 1995; Stemmerik et al. 1996). This marginal uplift was linked to an episode of basinal subsidence in the offshore areas of the Barents Sea starting in the Late Sakmarian. This was followed by a widely recognised Kungurian tectonic event in the northern North Atlantic and western Barents Sea. This tectonic event is generally recognised by the rejuvenation of older lineaments. It connected the Boreal Ocean of the present day Arctic with sedimentary basins in central East Greenland and offshore mid-Norway and eventually extended as far south as the Zechstein basin of northern Europe (Stemmerik 1995).

Stratigraphy

Dating and correlation of the Upper Palaeozoic successions in the Arctic are based on many fossil groups, including fusulinids, conodonts, small foraminifers and palynomorphs. In the Barents Sea – North Greenland – Svalbard area palynomorphs have been used to date the non-marine, Upper Devonian to Lower Carboniferous Billefjorden Group (e.g. Playford 1962, 1963; Bugge et al. 1995; Lindström 2003). Fusulinids have proven useful in dating Bashkirian–Artinskian carbonates (e.g. Nilsson 1993; Nilsson & Davydov 1997; Davydov et al. 2001); the post-Artinskian succession is dated by a combination of small foraminifers, conodonts and palynomorphs (e.g. Nakrem 1991; Mangerud 1994; Stemmerik et al. 1996) and general biostratigraphic resolution in this part of the succession is poor. The palaeontological data gained over the last 30 years have improved and refined biostratigraphic resolution considerably. Unfortunately, most primary data are hidden in unpublished company reports and Ph.D. theses, and are difficult to evaluate. The most up-to-date biostratigraphic summaries are given by Nakrem et al. (1992), Bugge et al. (1995), Stemmerik et al. (1996), Nilsson & Davydov (1997), Stemmerik (2000), Davydov et al. (2001), Larssen et al. (2002) and Lindström (2003), and have been used for zonation and correlation (Fig. 2).

Correlation to the Upper Palaeozoic succession in the Sverdrup Basin of Arctic Canada is well established for the Carboniferous. Correlation is less straightforward in the Permian, partly because dating of the Sverdrup Basin succession to a large extent is based on conodonts, and only recently has it been realised that there is a discrepancy between conodont and fusulinid ages in the Sverdrup Basin succession (Beauchamp et al. 2001). In this paper we have used the ages in Beauchamp et al. (2001) and Beauchamp & Baud (2003) for regional correlation (Fig. 2).

The Lower Carboniferous to Upper Permian succession in the Barents Sea – Svalbard – North Greenland area consists of four second-order depositional sequences, each corresponding to a group in the lithostratigraphic scheme for Svalbard and the Norwegian Barents Sea (Fig. 2; Dallmann et al. 1999; Larssen et al. 2002, 2004). In the offshore areas of the southern Norwegian Barents Sea, it is possible to subdivide the succession into five regionally mappable seismic sequences (Larssen et al. 2002). Correlation between seismic stratigraphy and lithostratigraphy is well established on the basis of well ties on the Finnmark Platform (Ehrenberg et al. 1998a; Larssen et al. 2002; Samuelsberg et al. 2003) and the Loppa High (Elvebakk et al. 2002; Larssen et al. 2002) (Fig. 2).

The uppermost Devonian – Lower Carboniferous (Famennian – Lower Serpukhovian) Billefjorden

Group consists mostly of non-marine, fluvial and lacustrine sediments deposited in humid and warm climates. Temporary marine conditions are recorded during the Viséan on the Finnmark Platform in the eastern part of the Norwegian Barents Sea, and in the Sverdrup Basin towards the west, possibly corresponding to an overall global sea level maximum during this time interval. The sequence is unconformity bound and corresponds to seismic sequence 1 of Samuelsberg et al. (2003) (Fig. 2). The lower boundary is a first order tectonic unconformity that separates the sediments from Caledonian and Ellesmerian deformed rocks and the upper boundary records an episode of regional uplift and erosion of the shelf during the Serpukhovian. The Lower Carboniferous rocks are all dated by local palynological assemblages which, following the pioneering work of Playford (1962, 1963), have been correlated to the West European miospore zonation of Clayton et al. (1977) by e.g. Bugge et al. (1995) and Lindström (2003). Correlation to the Viséan Sortebakker Formation in North Greenland and the Emma Fiord Formation in the Sverdrup Basin is firmly established.

The mid-Carboniferous – Lower Permian (Upper Serpukhovian – Sakmarian/Lower Artinskian?) Gipsdalen Group is dominated by marine warm-water carbonates, $CaSO_4$ evaporites and local siliciclastics on the platform areas and halite in the deep basins. It was deposited in a warm and arid climate during a period characterised by high frequency and high amplitude glacioeustatic sea level fluctuations (Stemmerik 2000). The lower boundary is an unconformity of tectonic origin that separates Lower Serpukhovian and older rocks from Upper Serpukhovian and younger sediments throughout the shelf. The upper boundary is an erosional unconformity along the southern shelf margin and on structural highs. Elsewhere, it is a conformable, slightly erosive surface that coincides with a pronounced shift in depositional facies reflecting a climatic shift towards more temperate and possibly humid climatic conditions (e.g. Ehrenberg et al. 1998a). The Gipsdalen Group correlates to seismic sequences 2, 3 and the basal part of seismic sequence 4 in the offshore areas (Fig. 2; Samuelsberg et al. 2003). Dating of the sediments is mainly based on local fusulinid assemblages that have been correlated to the Russian standard fusulinid zones, supplemented by small foraminifers and palynomorphs in the lower part. The base of the group is highly diachronous and oldest in basinal axes. The basal non-marine red-bed succession contains palynomorphs indicating a Late Serpukhovian – Early Bashkirian age, and interbedded limestone bands in the Ebbadalen Formation in Spitsbergen contain small foraminifers of early and Middle Bashkirian age in the lower and middle part and fusulinids of Late Bashkirian age in the upper part (Mamet et al. 1993). The more marginal parts of the shelf, such as the Finnmark Platform and North Greenland were not transgressed until later, in Moscovian–Kasimovian times (Bugge et al. 1995; Stemmerik 1996). The Moscovian–Gzelian Kap Jungersen and Foldedal formations in North Greenland represent a condensed succession along the southern shelf margin. The uppermost part of this succession is dated as Early Sakmarian in core 7129/10-U-02 and well 7126/4-1 on the Finnmark Platform (Bugge et al. 1995; Ehrenberg et al. 1998a). In central Spitsbergen, the upper Wordiekammen Formation is of Early Sakmarian age (Nilsson & Davydov 1997); the overlying Gipshuken Formation, forming the uppermost part of the group on Spitsbergen, is dated in general terms as being Sakmarian–Artinskian in age (Nakrem et al. 1992). Better age constraints of this formation are urgently needed to better understand the timing of shift in climate and depositional style during the late Early Permian. In the Sverdrup Basin, the basal Borup Fiord Formation is assumed to be of Serpukhovian age, although poorly dated. The overlying Otto Fiord, Canyon Fiord, Nansen, Antoniette, Tanquary and Belcher Fiord formations span the Bashkirian – Early Sakmarian, the Hare Fiord Formation is Bashkirian to Late Sakmarian in age and the warm-water carbonates of the Raanes Formation are of Late Sakmarian to ?Early Artinskian age (see Beauchamp et al. 2001). Sediments deposited under warm and arid climatic conditions (c.f. Beauchamp 1994) thus seem to have a longer time range in the Sverdrup Basin than in the Barents Sea area (Fig. 2).

The base of the Lower Permian (Upper Sakmarian – Artinskian (lowermost Kungurian?)) Bjarmeland Group sequence coincides with a shift from warm subtropical carbonates to temperate cool-water carbonates. The Bjarmeland Group is missing or thin along the basinal margins and over structural highs (Stappen High, Spitsbergen, southern Finnmark Platform and North Greenland). The lower boundary is an unconformity or subaerial exposure surface and the sediments are separated from the overlying Tempelfjorden Group sediments by a subaerial exposure surface. This group corresponds to the upper part of seismic sequence 4 in Samuelsberg et al. (2003); the boundary between seismic sequence 3 and 4 correlates to a major flooding event and a shift from high frequency and high amplitude sea level fluctuations to low frequency and low amplitude fluctuations in the uppermost Gipsdalen Group (Fig. 2). Dating of the sediments is mainly based on local fusulinid assemblages that have been correlated to Russian fusulinid zones, supplemented by conodonts in the onshore areas. The Bjarmeland Group corresponds in age to the lower Kim Fjelde Formation in North Greenland, and the upper Hare Fiord, Raanes, Great Bear Cape and Trappers Cove formations of the Sverdrup Basin (Fig. 2; Stemmerik et al. 1996; Beauchamp et al. 2001). The Vøringen Member of the Tempelfjorden Group in Spitsbergen is also apparently of Late Artinskian age (Nakrem et al. 1992).

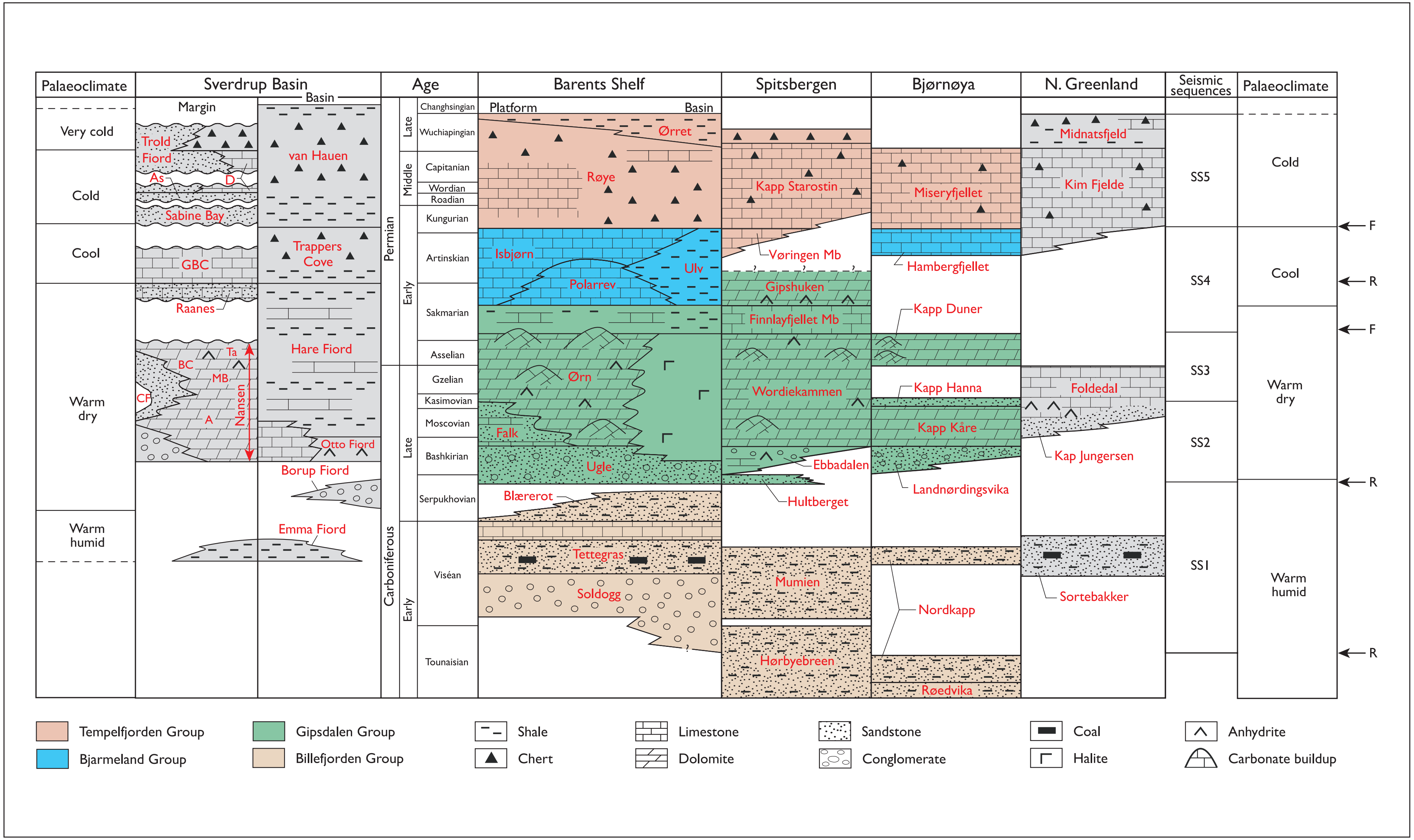

Fig. 2. Correlation of Upper Palaeozoic lithostratigraphic units between southern Norwegian Barents Sea, Svalbard, North Greenland and Arctic Canada with seismic sequences from the Finnmark Platform. Based on data in Dallmann et al. (1999), Beauchamp et al. (2001), Beauchamp & Baud (2003), Stemmerik (1997, 2000), Lindström (2003), Samuelsberg et al. (2003). A: Antoniette, D: Degerböls, BC: Belcher Canyon, CF: Canyon Fiord, MB: Mount Bayley, Ta: Tanquary, GBC: Great Bear Cape.

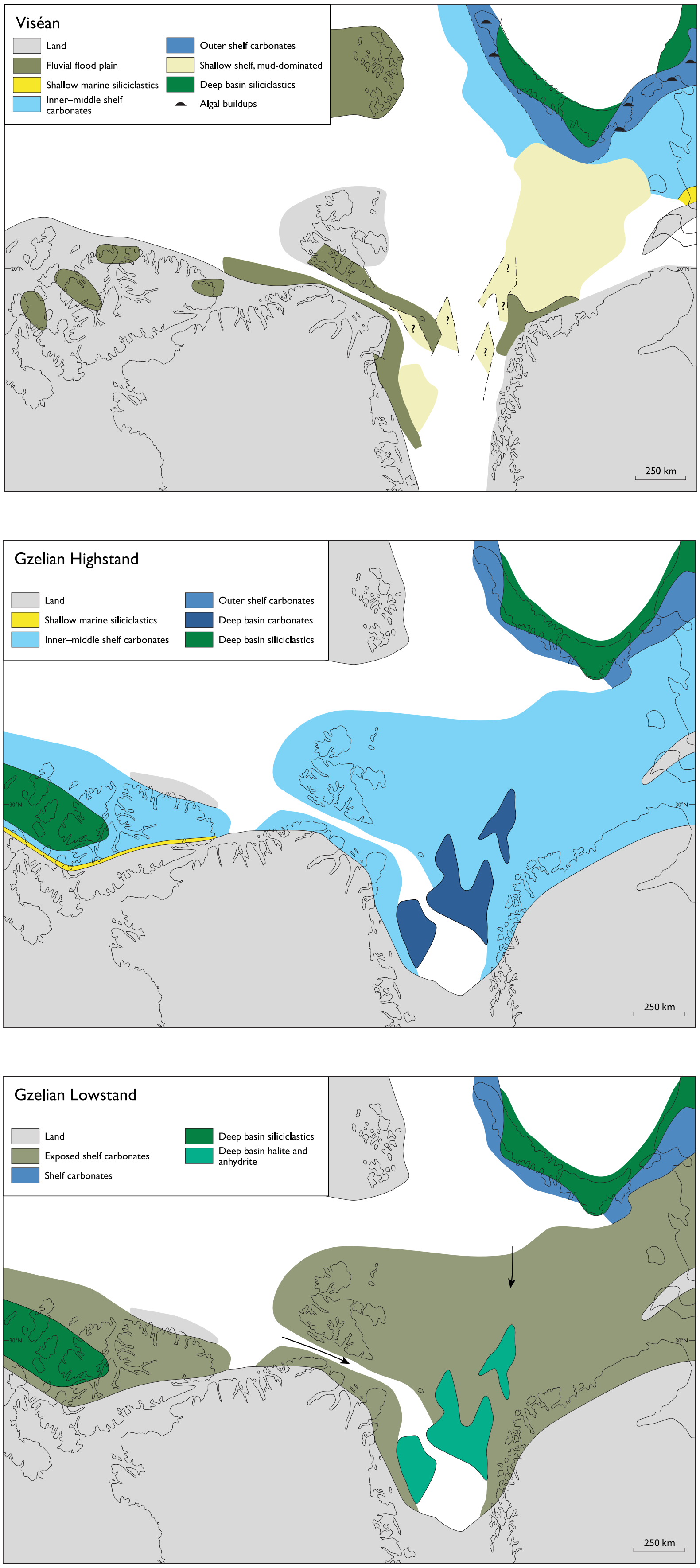

Fig. 3. Palaeogeographic reconstructions of the northern Pangaean shelf during the Late Palaeozoic.

A: Viséan warm and humid conditions with widespread flood plains along the southern shelf margin

B: Gzelian sea level highstand with widespread warm water carbonate deposition

C: Gzelian sea level lowstand and temporary subaerial exposure of huge shelf areas. The marine connection to the deep basins centrally on the shelf was restricted; arrows indicate possible connections

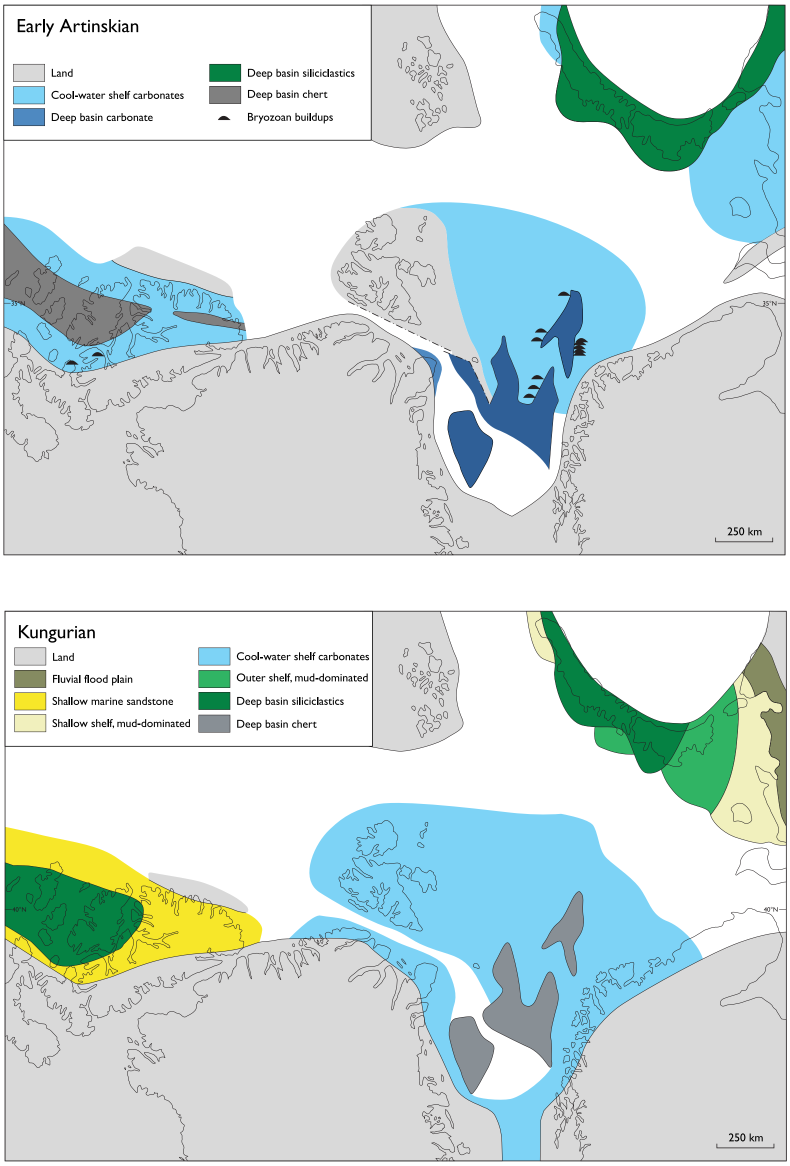

Fig. 3. cont.

D: Early Artinskian warm temperate conditions and widespread cool-water carbonate sedimentation

E: Kungurian temperate conditions

The Lower–Upper Permian (Kungurian–Wuchiapingian/-Changhsingian?) Tempelfjorden Group is separated from the underlying sediments by a subaerial exposure surface in the platform areas (Stemmerik et al. 1996; Ehrenberg et al. 1998a). The boundary reflects a shift in sedimentation from cool-water carbonates to a dominance of deeper water spiculites, shales and locally sandstones. The group correlates roughly with seismic sequence 5 of Samuelsberg et al. (2003). The upper boundary of the seismic sequence is defined by a change in seismic response, which reflects a profound lithological change is defined by a shift from spiculites to shales and is highly diachronous. Dating of the sediments is based on conodonts, palynomorphs and small foraminifers, and biostratigraphic resolution is poor compared to the underlying intervals. The post-Vøringen Member part of the Tempelfjorden Group can be correlated to the upper Kim Fjelde and Midnatfjeld formations in North Greenland (Stemmerik et al. 1996) and the Sabine Bay, Assistance, Trold Fiord, Degerböls and van Hauen formations of the Sverdrup Basin (Beauchamp et al. 2001).

Evolution of the shelf

Each of the depositional sequences recorded in the Barents Sea – Svalbard –North Greenland area represents a unique stage in the history of the central Pangaean shelf, partly reflecting shifts in latitudinal position and climate over time (Stemmerik 2000). The second order sequences have durations of approximately 15–30 Myr in the offshore areas according to the time scale of Gradstein et al. (2004); the Billefjorden succession is longer, up to 50 Myr on Svalbard. The

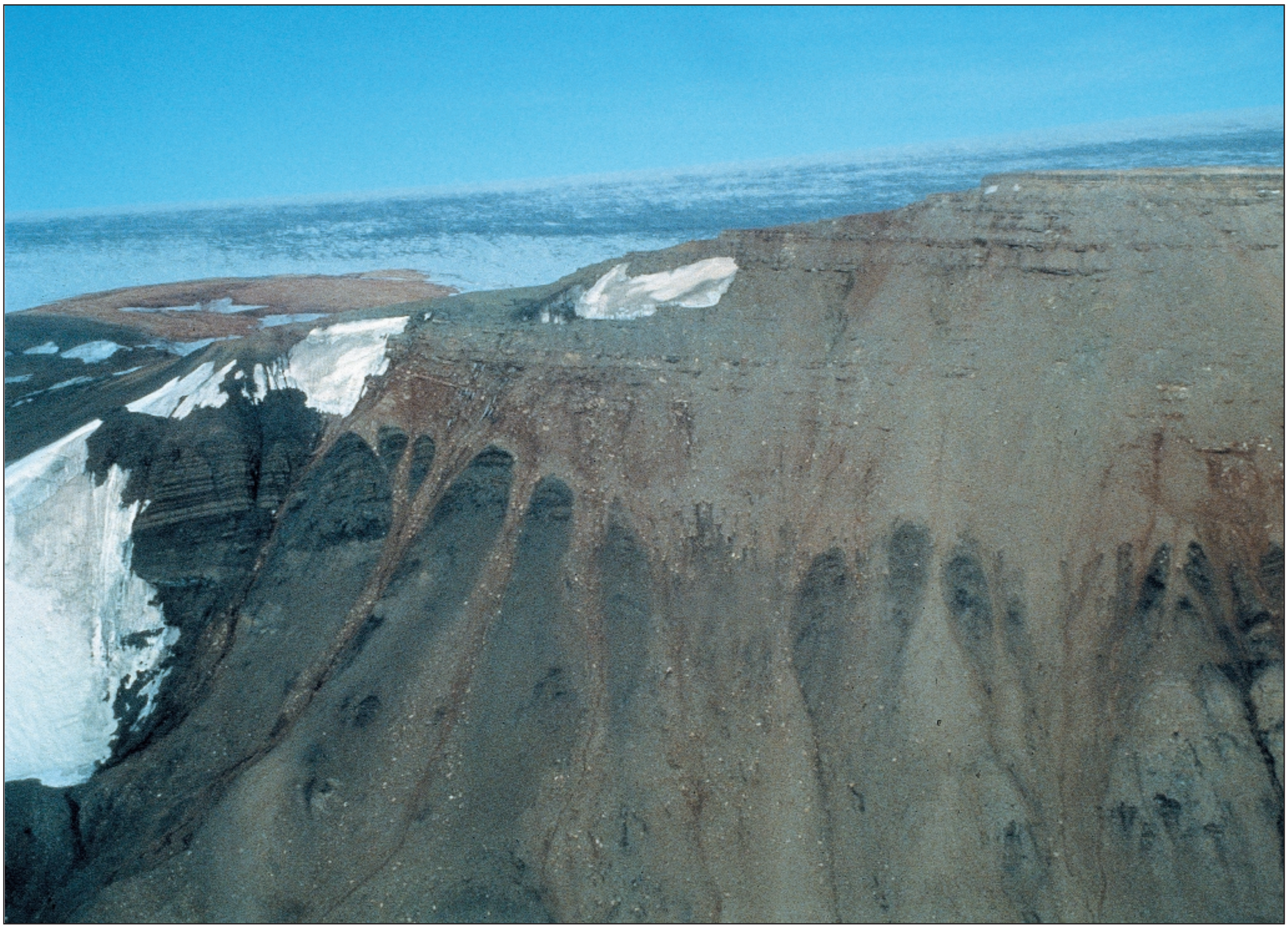

Fig. 4. Viséan fluvial sediments of the Sortebakker Formation unconformably overlain by Moscovian warm-water carbonates and siliciclastics of the Kap Jungersen Formation at southern Holm Land, North Greenland. The outcrop illustrates the regional mid-Serpukhovian uplift and the shift in climate from warm and humid during deposition of the Sortebakker Formation to warm and arid during deposition of the Kap Jungersen and Foldedal formations. Cliff is approximately 350 m high.

group boundaries record regional changes in relative sea level, palaeohydrographic conditions and palaeoclimate that not only are important for the evolution of the shelf but also have profound influence on hydrocarbon prospectivity, and they are most likely linked to the most important tectonic events in the North Atlantic and Arctic rift systems and the development of the Uralides (Stemmerik & Worsley 1995; Stemmerik 1997; 2000; Gudlaugsson et al. 1998; Stemmerik et al. 1999).

Onset of rifting

Deposition of fluvial and lacustrine sediments started during the Late Famennian – Tournaisian in isolated graben areas on Bjørnøya, Spitsbergen and in East Greenland (Steel & Worsley 1984; Vigran et al. 1999), and it is likely that the deep offshore basins also were areas of deposition at this time. More widespread deposition, however, did not start on the central Pangaean shelf until the earliest Viséan and during Viséan – earliest Serpukhovian times the area was part of a huge humid flood plain extending westwards from the Finnmark Platform across Bjørnøya, North Greenland and Spitsbergen to the central parts of the Sverdrup Basin (Fig. 3a). Data from the onshore areas indicate continued sedimentation in tectonically active half-grabens during Early to Middle Viséan stages of deposition and seismic data indicate that the Loppa High and the south-western part of the Finnmark Platform also were characterised by the extensive development of half-graben style basins (Steel & Worsley 1984; Stemmerik et al. 1991; Bugge et al. 1995; Larssen et al. 2002; Samuelsberg et al. 2003). Further eastwards on the Finnmark Platform there is apparently no evidence of Viséan rifting (Samuelsberg et al. 2003).

Seismic and well data indicate a gradual transition upwards towards deposition on a wide flood plain with abundant coal in the south-western Finnmark Platform and similar coal-bearing facies are also common in the onshore areas to the west (Fig. 3a). North-eastwards on the Finnmark Platform the flood plain gradually passes into deltaic and shallow marine deposits (see Bugge et al. 1995; Stemmerik 2000; Larssen et al. 2002; Samuelsberg et al. 2003) and further to the east marine Upper Viséan sediments have been reported from Novaya Zemlya and the Timan–Pechora Basin (Fig. 3a; Sobolev & Nakrem 1996). In the Sverdrup Basin to the far west, brief marine incursions have also been reported from the Viséan (Beauchamp et al. 1998), and it is likely that the deep offshore basins were sites of marine deposition during the Early Carboniferous.

From a hydrocarbon perspective the main unknowns are the extent of the marine deposits across the easternmost Finnmark Platform and into the deep rift basins. We should also note the source potential of the Emma Fiord Formation's lacustrine shales; in most cases, however, such as on the Finnmark Platform or in the Nordkapp Basin, possible potential source rocks - whether lacustrine or marine - would anyway have become deeply buried already early in the Mesozoic and have no remaining potential, while potential sandstone reservoirs are often quartzitic and tight because of quartz overgrowths formed under deep burial.

Serpukhovian uplift

During Serpukhovian times the northern margin of Pangaea was uplifted and the transition from the Lower Carboniferous Billefjorden Group and its Greenland and Sverdrup Basin equivalents to the Serpukhovian and younger Carboniferous sediments is represented by an erosional unconformity (Figs 2, 4; e.g. Steel & Worsley 1984; Stemmerik et al. 1991). The youngest sediments present below the unconformity are recorded in IKU shallow core 7029/03-U-01 from the Finnmark Platform and well 7120/2-1 from the Loppa High and belong to the Early Serpukhovian TK Miospore Zone (Bugge et al. 1995; Lindström 2003). The oldest deposits above the unconformity contain palynomorphs correlated to the Late Serpukhovian SO Miospore Zone (Lindström 2003). The depositional break is considerably longer along the platform margins and over structural highs. In North Greenland Serpukhovian–Bashkirian deposits are missing and the Viséan Sortebakker Formation is unconformably overlain by Moscovian warm-water carbonates and siliciclastics (Fig. 4; Stemmerik & Håkansson 1989). Over most of the Finnmark Platform sedimentation did not resume until the Late Moscovian (Bugge et al. 1995) and generally Bashkirian – Lower Moscovian deposits are confined to syntectonic half-grabens (Gjelberg & Steel 1983; Johannessen & Steel 1992; Stemmerik 2000). Further to the east on Novaya Zemlya, the margins of the northern carbonate platform were also uplifted during the Serpukhovian (Sobolev & Nakrem 1996).

In the Sverdrup Basin the transition from the Viséan Emma Fiord Formation to the Serpukhovian Borup Fiord Formation coincides with a climatic shift from warm and humid to warm and arid (Beauchamp 1994). In well 7120/2-1 on the Loppa High, palynological data indicate that the transition from humid to dry took place somewhat later, above the SO Miospore Zone, at the Serpukhovian–Bashkirian boundary (Lindström 2003).

Mid-Carboniferous rifting

Rifting was reactivated in the Barents Sea area in the latest Serpukhovian and the Bashkirian was characterised by deposition in a system of tilted half-grabens (Gjelberg & Steel 1983; Steel & Worsley 1984; Johannessen & Steel 1992). On Spitsbergen, deposition was dominated by coarse-grained siliciclastics along the graben margins and more fine-grained siliciclastics, carbonates and $CaSO4$ evaporites in more distal settings (Fig. 5; Johannessen & Steel 1992). Marine influence on sedimentation is documented both from facies studies and by the repeated occurrence of thin biogenic limestones (Johannessen & Steel 1992; Mamet et al. 1993; Hüneke et al. 2001). Data from offshore wells and shallow cores indicate that the same overall depositional settings characterised the half-grabens on the Finnmark Platform and the Loppa High (Larssen et al. 2002). There are no data from the deep rifts, such as the Nordkapp Basin, but we assume that deposition was dominantly marine.

During Late Bashkirian times relative sea level started to rise and gradually during the Moscovian the southern shelf margin and structural highs became flooded. This regional sea level rise took place during a time interval when the Earth system was characterised by icehouse conditions and high frequency and high amplitude fluctuations of sea-level (e.g. Veevers & Powell 1987; Wright 1992; Sohregan & Giles 1999). Siliciclastic provenance areas gradually drowned during the Late Moscovian – Kasimovian and by Gzelian times the central part of the north Pangaean shelf formed a mosaic of carbonate platforms separated by deeper water basins at times of high glacioeustatic sea-level (Fig. 3b). The Moscovian–Asselian carbonate platforms are dominantly composed of cycles of outer shelf, algal-, foraminifer-, fusulinid- and occasionally crinoid-rich wackestones and packstones capped by subaerial exposure surfaces. Updip on the platforms more grain-rich facies are locally present and thin sabkha cycles have been described from the southern Finnmark Platform (Stemmerik et al. 1995; Ehrenberg et al. 1998a). Scattered, isolated *Palaeoaplysina* – phylloid algal and bryozoan buildups are common across the platforms and stacked buildup complexes have been described from both outcrops and seismic data (e.g. Skaug et al. 1984; Lønøy 1988; Stemmerik et al. 1994; Stemmerik 1996, 2003; Elvebakk et al. 2002). The onshore complexes are dominated by *Palaeoaplysina* – phylloid algal buildups and it is proposed that most seismic buildups on the inner platforms are of a similar composition, whereas larger polygonal buildups

Fig. 5. Bashkirian siliciclastics and evaporites of the Ebbadalen Formation at Ebbadalen, central Spitsbergen. The outcrop shows the synrift succession in the Bashkirian Billefjorden half-graben and may serve as a model for time-equivalent successions in the offshore rift basins (see Johannessen & Steel 1992 for details).

downdip on the platforms and along the basin margins most likely are dominated by bryozoans and submarine cement (Elvebakk et al. 2002).

The carbonate platforms were repeatedly exposed in response to glacioeustatic lowering of sea level, and during times of low sea-level the central Pangaean shelf formed a huge plain of exposed carbonates dissected by isolated and semi-isolated basins (Fig. 3c). The presence of thick halite successions in deep rifts such as the Nordkapp and Danmarkshavn basins indicates extreme aridity and restricted connection between the central shelf and the northern ocean during sea level lowstands (Stemmerik 2000). This is in contrast to the Sverdrup rift along the western limits of the shelf and the Ural foredeep along the eastern margin of the shelf where connections were better and deposition is dominated by normal marine deep-water sediments (Fig. 2; Beauchamp 1993, 1994; Sobolev & Nakrem 1996; Stemmerik 2000).

The repeated patterns of deposition during high sea-level and subaerial exposure during low sea-level continued until latest Asselian – earliest Sakmarian times, and the Upper Carboniferous – Asselian platform successions consist of stacked, exposure-capped shallowing upwards cycles (e.g. Stemmerik & Larsen 1993; Stemmerik et al. 1994, 1995, 1996, 1998; Pickard et al. 1996; Stemmerik 1996, 2003; Stemmerik & Worsley 2000; Ehrenberg et al. 1998a, 1998b, 2001). These carbonates are often extensively dolomitised, particularly when associated with evaporites, and the repeated flushing by freshwater led to early dissolution of aragonite grains and development of secondary porosity. The Moscovian–Asselian warm water carbonates form the most prolific Upper Palaeozoic reservoir interval in the Barents Sea (see Stemmerik et al. 1999 for more detailed discussion). Recently, detailed studies of 3D seismic data from the Loppa High have provided further insight into the semi-regional facies variations of these platform carbonates and their resultant reservoir properties (Elvebakk et al. 2002, 2003), confirming that the best reservoir properties are expected to be updip on the platforms and in inner shelf buildups (Fig. 6).

Early Sakmarian flooding

The Early Sakmarian flooding event corresponds to the base of seismic sequence 4 of Samuelsberg et al. (2003)

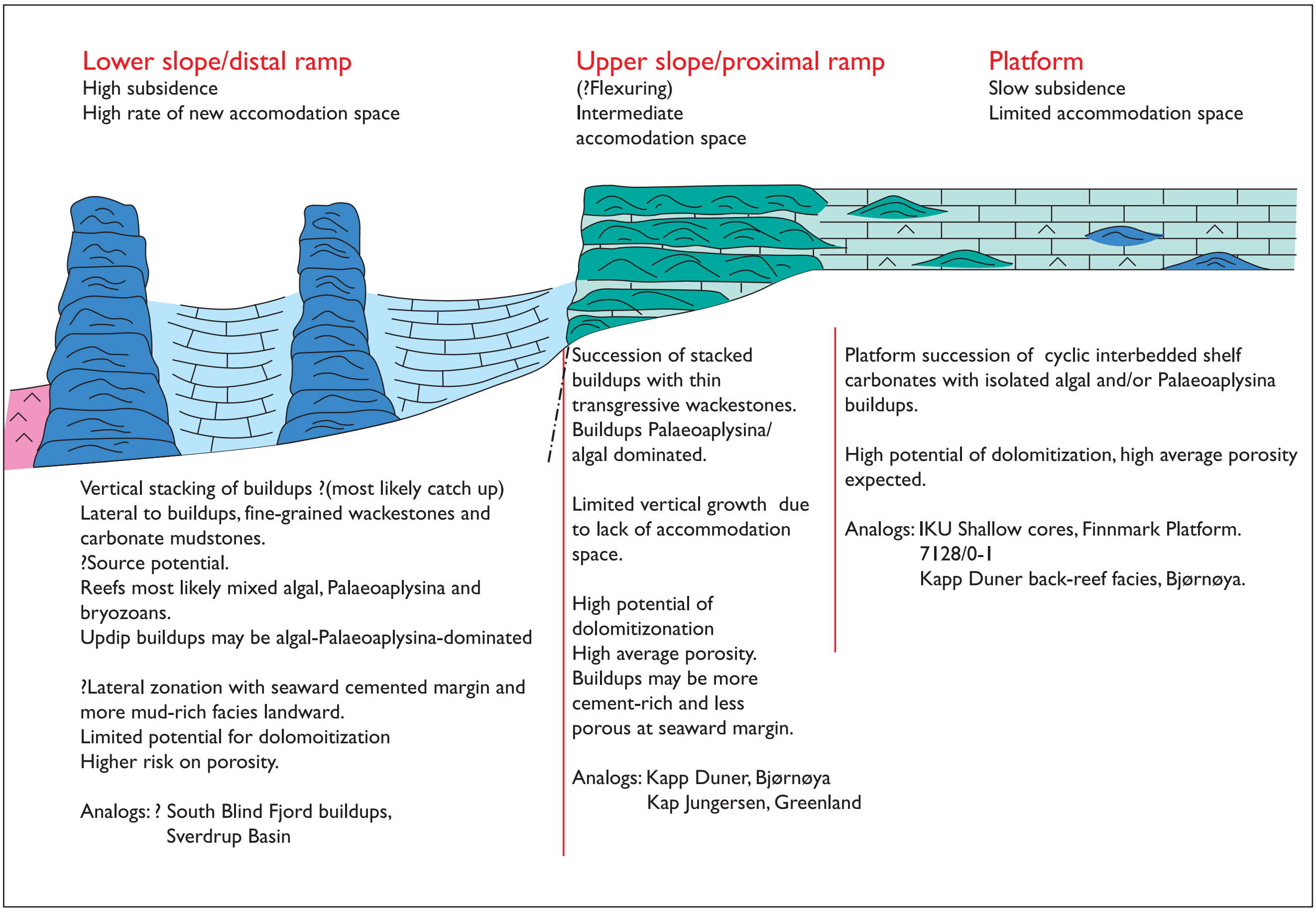

Fig. 6. Reservoir model for the Moscovian-Asselian warm-water carbonates in the Barents Sea area. The model shows a generalised facies pattern from the shallow proximal parts of the platforms to the deep, partly evaporite-filled basins.

and is easily recognisable in both seismic data, well logs and cores from the southern Norwegian Barents Sea (Larssen et al. 2002). It corresponds to the base of L7 of Ehrenberg et al. (1998a) and is characterised by two prominent peaks on the Gamma Ray log in well 7128/6-1, corresponding to shales with abundant glauconite and pyrite in the core. The GR peak is easily correlated to adjacent wells on the Finnmark Platform, in the Nordkapp Basin and westwards to the Loppa High. The flooding records a major shift in depositional conditions on the central Pangaean shelf. It marks the end of halite deposition in the deep basins (see Fig. 2) and in the shelf areas it marks the end of cyclic, often exposure-capped carbonate deposition (Ehrenberg et al. 1998a; Stemmerik 2000). In wells 7128/6-1 and 7128/4-1 the Lower Sakmarian succession is dominated by deeper shelf crinoid- and foraminifer-rich wackestones and shales with rare, more shallow marine grainstones. The flooding event is also recorded in the southern, more proximal parts of the Finnmark Platform by a succession of fine-grained siliciclastics in IKU shallow core 7129/10-U-02 (Bugge et al. 1995; Ehrenberg et al. 2001). We suggest that this correlates to the base of the Finnlayfjellet Beds, upper Wordiekammen Formation of Spitsbergen, which was regarded as a marine flooding surface by Samuelsberg & Pickard (1999).

The Lower Sakmarian succession is separated from the overlying cool-water carbonates of the Bjarmeland Group by a subaerial exposure surface in well 7128/6-1 on the Finnmark Platform and by a major hiatus further updip in IKU shallow core 7129/10-U-2 (Bugge et al. 1995; Ehrenberg et al. 1998a, 2001). At Boltonbreen, Spitsbergen it is separated from the overlying Gipshuken Formation grainstones by a well-developed karstic surface (Stemmerik, pers. obs. 2004; Fig. 7). The succession forms a distinctive depositional event across the central Pangaean shelf characterised by a deepening upward succession of open marine, often crinoid-dominated wackestones and fine-grained siliciclastics overlain by a thin highstand succession of often coral-capped shallowing upward cycles (see Groves & Wahlmann 1997; Ehrenberg et al. 1998a, 2001; Samuelsberg & Pickard 1999). The shelf fauna indicates deposition in warm-water conditions (c.f. Beauchamp 1994; Beauchamp & Desrochers 1997; Stemmerik 1997, 2000) but in contrast to the older, Bashkirian–Asselian succession there is no evidence of exposure-capped cycles and evaporites in the lower Sakmarian succession.

Fig. 7. Karst surface developed at top of the Wordiekammen Formation prior to deposition of the Gipshuken Formation. Boltonbreen, central Spitsbergen. The karst relief is 10–15 cm. Photo: Geir Elvebakk.

Data from the offshore areas thus indicate that the Early Sakmarian flooding event defines the top of the prolific reservoir interval of dolomitised and often highly porous warm-water carbonates corresponding to seismic sequences 2 and 3 (Fig. 2; c.f. Stemmerik et al. 1999). This is in contrast to data from Spitsbergen, where interbedded warm-water carbonates (often oolitic grainstones) and evaporites of the Gipshuken Formation were apparently deposited following the Sakmarian flooding event, in (post-) Early Sakmarian times: The Gipshuken Formation is found throughout much of Spitsbergen and on western Nordaustlandet and equivalents have been penetrated in deep wells e.g. on Hopen. In its type area in central Spitsbergen the unit is up to 280 m thick, but only the lower third constitutes the formation's generally assumed "typical" rhythmic intercalations of sabkha evaporates and dolomites: in contrast, the upper 100–150 m comprise thinly interbedded dolomites and marls, with only one evaporitic interval near the top of the formation. Although the formation is generally characterised by supra- to intertidal sedimentation on evaporitic and carbonate flats, often with intraformational collapse breccias, shallow marine and lagoonal influences become more marked upwards, and some horizons show clearly marine faunas with dolomitised brachiopods, crinoids, bryozoans and corals. It is also interesting that the upper parts of the formation on Nordaustlandet show increasing marine influence accompanied by silicification, together with the appearance of plant fossils, root structures and even thin coal beds, perhaps heralding increasingly both marine and humid conditions following the long-lasting arid phases of deposition since the mid-Carboniferous.

Late Sakmarian – Artinskian marginal uplift and differential subsidence

The transition from the Gipsdalen Group to the Bjarmeland Group reflects a major re-organisation of the central Pangaean shelf. The marginal parts of the shelf and structural highs like Spitsbergen and the Stappen High were uplifted and Upper Sakmarian – Lower Artinskian sediments are missing in most of North Greenland and on Bjørnøya. (Worsley et al. 2001). In Spitsbergen, there is a major hiatus corresponding to the ?Late Sakmarian – Early Artinskian between the Gipshuken Formation and Vøringen Member of the Tempelfjorden Group and along the

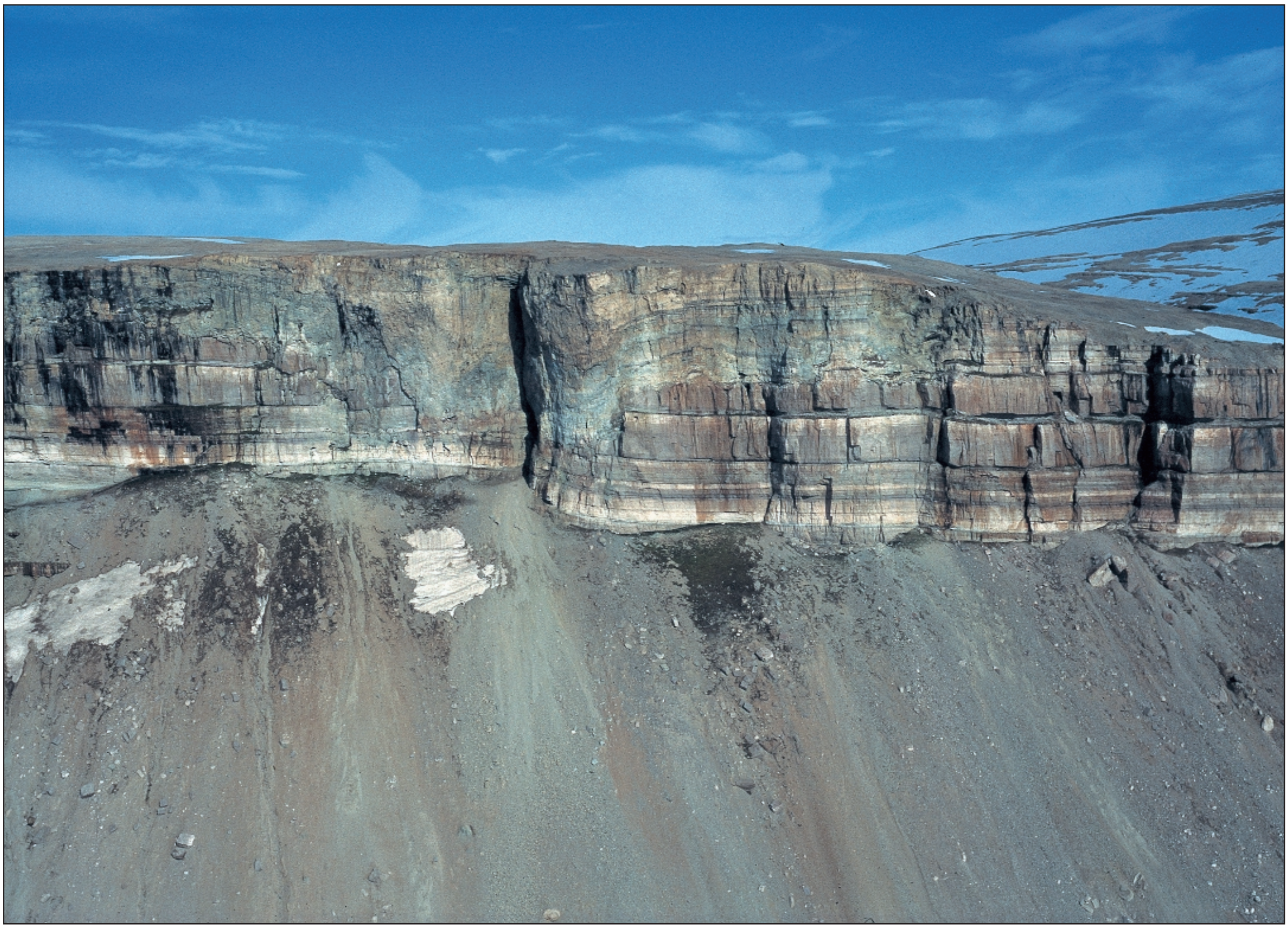

Fig. 8. Seismic scale karst feature in Upper Carboniferous cyclic warm-water carbonates, northern Holm Land, North Greenland. Karstification is related to prolonged Asselian – early Artinskian uplift and subaerial exposure. The outcrop may serve as a model for better understanding of the effects of Permian karstification in the offshore areas. Cliff is approximately 150 m high.

margins of the Sverdrup Basin there was a prolonged break in sedimentation during the Sakmarian (Fig. 2; e.g. Beauchamp et al. 2001). The proximal parts of the Finnmark Platform, represented by the IKU shallow cores also show evidence of breaks in sedimentation and condensation (see Bugge et al. 1995; Ehrenberg et al. 2001). However, further northwards on the Finnmark Platform well 7128/6-1 drilled a stratigraphically complete succession of Upper Sakmarian – Lower Artinskian cool-water, shelf carbonates and even further northwards bryozoan–*Tubiphytes* buildups of this age form a trend along the platform margin towards the Nordkapp Basin (Bruce & Toomey 1993; Nilsen et al. 1993). The shelf margins and structural highs were transgressed during the mid-Artinskian and during Late Artinskian time the central Pangaean shelf formed part of huge cool-water carbonate shelf extending westwards to the Sverdrup Basin. The facies variations on this shelf are well documented (Stemmerik 1997, 2000; Beauchamp & Desrochers 1997).

The Gipsdalen–Bjarmeland Group transition represents a shift from tropical–subtropical warm-water carbonates to temperate cool-water carbonates. It is tempting to relate this abrupt depositional shift to changing oceanographic circulation caused by changing tectonic configurations, possibly related to the development of the Uralides. The corresponding shift in fauna and carbonate depositional style in the Sverdrup Basin is reported to have taken place 5–8 Myr later, in the Early Artinskian (Beauchamp 1994; Beauchamp & Henderson 1994; Beauchamp & Desrochers 1997), although – as noted earlier – possible discrepancies may also reflect differing emphases on conodont- and fusulinid-based biozonations.

Generally, the cool-water succession is believed to be non-prospective because of intense early cementation by calcite (Stemmerik et al. 1999). However, the extended Late Sakmarian – Early Artinskian uplift let to subaerial exposure along the shelf margin and over structural highs, and older, Bashkirian–Sakmarian platform carbonates were subjected to freshwater dissolution and cementation (Fig. 8). The effect of Late Sakmarian – Early Artinskian karst processes is well documented from Spitsbergen, where collapse breccias

Fig. 9. Tilted cold-water carbonates and spiculites of the Kapp Starostin Formation, Akseløya, western Spitsbergen. Stratigraphic up is towards the right. The outcrop has served as a model for the Tempelfjorden Group in wells 7128/6-1 and 7128/4-1 on the Finnmark Platform (see Ehrenberg et al. 2001 for details).

have been described from both the Gipshuken Formation and the Minkinfjellet Formation (e.g. Lauritzen 1981; Eliassen & Collinson 2003a, 2003b). Karst features related to this event have also been described from Bjørnøya and North Greenland (Fig. 8; Worsley & Edwards 1976; Stemmerik et al. 1996; Worsley et al. 2001), and possibly the semi-regional karst systems on the Loppa High started to form at this time (see Elvebakk et al. 2002, 2003). From a hydrocarbon prospectivity point of view the Late Sakmarian – Early Artinskian uplift event is important in setting up regional freshwater systems, which modified reservoir properties in the underlying Bashkirian – Lower Sakmarian warm-water carbonates. Prediction of these modifications based on 3D seismic data seems to be one of the major tasks in future reservoir evaluation.

Kungurian drowning

The Kungurian flooding event corresponds to the base of seismic sequence 5 of Samuelsberg et al. (2003) and is easy recognisable both in seismic data, well logs and cores from the offshore areas (Larssen et al. 2002, 2004). The cool-water shelf carbonates of the Bjarmeland Group are overlain by deeper water spiculites over most platform areas and carbonate deposition was restricted to isolated structural highs and the southern, updip margins of the shelf (Fig. 9; Stemmerik 1997; Ehrenberg et al. 2001). In the Hammerfest Basin the Tempelfjorden Group is dominated by fine-grained siliciclastics in the lower part and interbedded shallow marine sandstone and shale in the upper ?Wuchiapingian part of the succession in wells 7120/12-4 and 7120/12-2 from the southern margin of the basin. Fine-grained siliciclastics dominate the northern part of the basin and spread gradually eastwards to the Bjarmeland Platform and the Nordkapp Basin.

Upper Permian shales and spiculites have limited amounts of TOC, but some horizons may have limited source potential. Sandstones from the uppermost part of the succession in western and eastern Spitsbergen and from wells 7120/12-1 and 7120/12-4 along the margins of the Finnmark Platform, introduce interesting reservoir perspectives. The nature of the Permian–Triassic transition is still unclear, but there appears to be a significant hiatus spanning parts of the Wuchiapingian and the Changhsingian. It has to be considered further and linked to the latest Permian – earliest Triassic rifting events in the Norwegian–Greenland Sea area (c.f. Seidler et al. 2004). Secondary porosity developed during this break may give rise locally to interesting reservoir properties, even in normally tight spiculitic limestones – as evidenced by the unexpected minor oil find in well 7128/4-1 on the Finnmark Platform.

Discussion

Although much data has been collected over the last 30 years and the zonation of the Bashkirian–Asselian warm water carbonate succession has been considerably refined, there is still a lack of biostratigraphic data, particularly from the post-Asselian strata in Spitsbergen and North Greenland. Correlation is still poorly constrained in this part of the succession with the precise age of the Gipshuken Formation as one of the major puzzles. Proper correlation of this formation to the offshore areas is not only of academic interest but also important for reservoir prediction in the north-western part of the southern Norwegian Barents Sea, since the Gipshuken Formation forms a unit with reservoir potential which has not been drilled offshore. The correlation proposed in Fig. 2 places the formation in the base of seismic sequence 4, above the predicted main reservoir interval on the Finnmark Platform (Samuelsberg et al. 2003).

Improved biostratigraphic resolution of the post-Asselian succession is also important for better correlation to the Sverdrup Basin during Sakmarian and younger intervals and for correlation to the Russian offshore areas, Novaya Zemlya and the Timan–Pechora Basin. Such data would help to clarify if the transition from warm-water conditions to temperate cool-water conditions in the Early Permian is diachronous, – as the present age assignments may indicate (see Fig. 2), or occurred synchronously across the entire northern Pangaean shelf.

The four-fold lithostratigraphic subdivision of the Upper Palaeozoic succession as proposed by Dallmann et al. (1999) and Larssen et al. (2002) reflects the main stages of shelf evolution. However, better integration of the surface and subsurface data sets indicates that the shelf evolution can be further refined: the most important event not yet properly reflected in the lithostratigraphic schemes is the Early Sakmarian flooding event at the base of seismic unit 4. Also, the presence of humid-type palynomorphs in the base of the Gipsdalen Group needs more attention.

Conclusions

1) The four-fold lithostratigraphic division of the Barents Sea – Svalbard succession reflects long, 15–50 Myr periods of relatively stable depositional conditions at the central Pangaean shelf separated by abrupt changes at the group boundaries.
2) The present biostratigraphical data base indicates that shifts in climate and depositional conditions occurred diachronously across the northern Pangaean shelf.
3) The transition from warm and humid climate to warm and arid climate took place in the early Serpukhovian in the Sverdrup Basin and several Myr later, at the Serpukhovian–Bashkirian boundary in the southern Norwegian Barents Sea.
4) The transition from warm-water carbonate deposition to cool-water deposition took place in the mid-Sakmarian in the southern Norwegian Barents Sea and 5–8 Myr later, in the Early Artinskian in the Sverdrup Basin.
5) The prolonged period of halite deposition in the Nordkapp, Tromsø and Danmarkshavn basins indicates extreme aridity and isolation of the deep rift basins during Late Bashkirian – Asselian sea-level lowstands.
6) Moscovian–Asselian warm-water carbonates form the most prospective reservoir rocks in the southern Norwegian Barents Sea. Post-depositional freshwater modification of the carbonates took place locally during Artinskian and younger Permian uplift and subaerial exposure, and mapping of Permian karst systems is a major task for better reservoir prediction.

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