Wandel Sea Basin: basin analysis – a summary

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In 1991 a three year research project was initiated by the Geological Institute, University of Copenhagen with financial support from the Ministry of Energy, the Danish Natural Science Research Council and the Carlsberg Foundation. The 'Wandel Sea Basin: basin analysis' project was carried out in collaboration with the Geological Survey of Greenland and included field work in North Greenland; in eastern Peary Land in 1991 and Amdrup Land in 1993 (Fig. 1; Håkansson *et al.*, 1994).

The project is a continuation of earlier investigations in the Wandel Sea Basin carried out during geological mapping of North Greenland by the Geological Survey of Greenland in 1978–1980 and during later expeditions to the area (e.g. Håkansson, 1979; Håkansson *et al.*, 1981, 1989, 1991, 1994). Hydrocarbon related studies of the Wandel Sea Basin were continued during the 1994 field season (Stemmerik *et al.*, this report) and further activities are planned for the 1995 season.

The main purpose of the project was to provide detailed sedimentological and biostratigraphical data for an improved evaluation of the hydrocarbon potential onshore eastern North Greenland, and to evaluate the structural history of the basin in order to understand the distribution of the now scattered sedimentary outcrops. The completed report comprises 22 technical reports and 4 appendices (Håkansson *et al.*, 1994).

Geological overview

The Wandel Sea Basin was an area of accumulation throughout the Early Carboniferous – Early Tertiary, located at the north-eastern margin of the stable Greenland craton where the Caledonian and Ellesmerian fold belts intersect (Fig. 1). The sedimentary succession rests with a regional unconformity on a mosaic of Precambrian to Silurian rocks, which have been in part deformed by either the Caledonian or Ellesmerian orogenies. Deposition has largely been confined to a fairly narrow fringe along the Greenland craton delimited by three major fault zones: the Harder Fjord fault zone, the Trolle Land fault zone, and the East Greenland fault zone (Fig. 1).

Two main but unrelated epochs in basin evolution have been distinguished, an early Late Palaeozoic epoch characterised by a simple system of grabens and half-grabens developed parallel to the craton margin, and a later Mesozoic epoch dominated by strike-slip movements which in part reactivated existing extensional fault systems (Håkansson & Stemmerik, 1989).

In pre-drift reconstructions the Wandel Sea Basin is located in close proximity to the Sverdrup Basin of Arctic Canada, and the sedimentary basins of Svalbard and the Barents Shelf. It is closely related to these basinal areas. Pronounced differences exist, however, both in terms of basinal dynamics and depositional character. Most differences are directly related to the development of a strike-slip dominated plate boundary across the north-eastern corner of Greenland within the Mesozoic: the Wandel Hav strike-slip mobile belt. When substantial plate reorganisation commenced in this part of the Arctic, with the initiation of the North Atlantic and Arctic Oceans, the plate boundary separating Greenland and Europe shifted to its present position, and activity ceased in the Wandel Sea Basin area.

Upper Palaeozoic

Biostratigraphic studies have been concentrated mainly in the mid-Moscovian to Kazanian succession of eastern Peary Land, while new sedimentological data have been obtained from both eastern Peary Land and from Amdrup Land (Stemmerik & Elvebakk, 1994; Stemmerik *et al.*, 1995, in press). The new biostratigraphic and sedimentological data have greatly improved understanding of the depositional and tectonic evolution of the Wandel Sea Basin during the Upper Palaeozoic (Fig. 2).

The marine Moscovian to Kazanian succession is composed of three major depositional units that can be correlated with sedimentary units in Arctic Canada, Svalbard and the Barents Sea. Large scale correlation between these areas has previously been suggested, but the improved biostratigraphic framework allows correlation on a more detailed scale (Stemmerik & Worsley, 1989, 1995; Nilsson, 1994). Although the Wandel Sea succession to some degree resembles the equivalent successions in the Arctic region, new biostratigraphic data also indicate some major differences. The most important are:

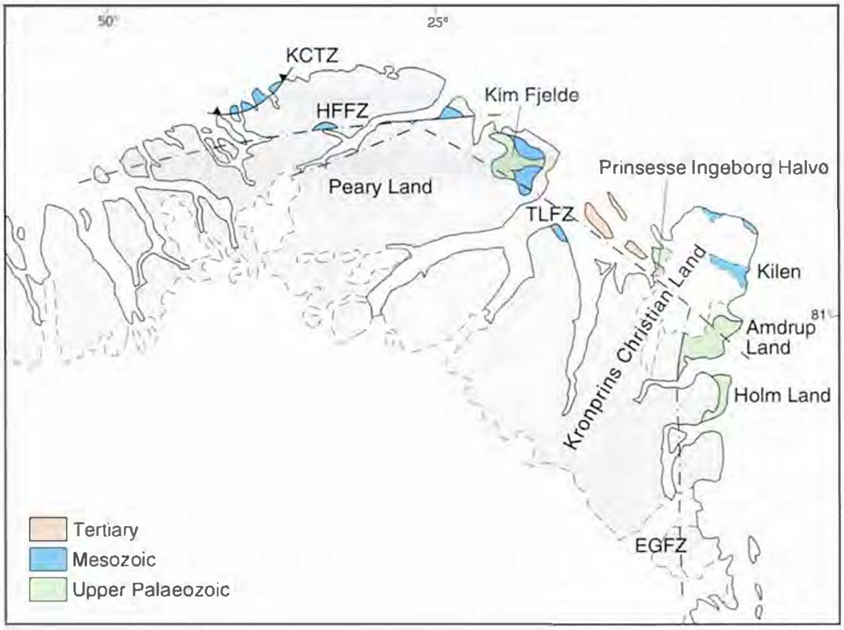

Fig. 1. Simplified map showing distribution of Wandel Sea Basin sediments. HFFZ: Harder Fjord fault zone; EGFZ: East Greenland fault zone; KCTZ: Kap Cannon thrust zone; TLFZ: Trolle Land Fault Zone.

- The mid-Carboniferous transgression in North Greenland is Moscovian. The first marine pulse is Serpukovian in the Sverdrup Basin while the main transgression in the Sverdrup Basin and Spitsbergen took place during late Bashkirian rifting.

- Asselian and early Sakmarian deposits have a restricted distribution in the Wandel Sea Basin where they are limited to the highly tectonised outcrops on Prinsesse Ingeborg Halvø. These units are missing on Bjørnøya, but elsewhere in the Arctic region two transgressive-regressive cycles were deposited during this time interval (e.g. Beauchamp *et al.*, 1989).

- Lower Artinskian deposits are missing in the Wandel Sea Basin. Elsewhere in the Arctic region, the early Artinskian forms a large scale transgressive-regressive cycle. Both in the Barents Sea and in the Sverdrup Basin major bryozoan-*Tubiphytes* build-ups formed during this time interval (e.g. Beauchamp, 1993).

Late Carboniferous (Moscovian–Gzelian)

The Moscovian to Gzelian succession forms a large scale transgressive-regressive unit which is separated from the overlying Permian deposits by a major hiatus. A comparable transgressive-regressive development is seen in the Sverdrup Basin (Beauchamp *et al.*, 1989), on Bjørnøya (Worsley *et al.*, 1990) and on the Finnmark Platform (Bugge *et al.*, 1995). Dating of the Moscovian to Gzelian succession is based on fusulinids (Nilsson, 1994; Stemmerik *et al.*, 1995, in press). Six local fusulinid zones have been identified and correlation to adjacent areas can be established on zone level.

The Moscovian succession is up to 600 m thick and was deposited during a period with increased subsidence in the Wandel Sea Basin. Small scale block faulting has previously been recorded from this part of the succession, and the depositional patterns appear to some degree to be fault controlled. In most areas the Moscovian succession is composed of stacked cycles of interbedded shelf carbonates and shallow marine sandstones (Fig. 3). In southern Amdrup Land carbonate build-ups are common in the Moscovian succession, and occasionally they stack to form up to 100 m high, carbonate dominated platforms. Deposition took place in a semi-arid climate and dolomitisation is widespread.

The Moscovian succession in Amdrup Land is composed of seven third order depositional sequences (Stemmerik, 1994). They form an overall retrogradational succession with maximum flooding during the latest Moscovian. The overlying latest Moscovian to Gzelian succession is highly progradational and forms an overall regressive unit. The Kasimovian–Gzelian succession is composed of stacked shoaling upward carbonate cycles throughout North Greenland, locally with abundant *Palaeoaplysina* and phylloid algae build-ups (Stemmerik & Elvebakk, 1994). The succession is capped by a major karst surface in eastern Peary Land, Amdrup Land and Holm Land, and in these areas most of the Lower Permian is missing.

Source rocks have not been identified in the Moscovian to Gzelian succession in North Greenland. However, the abundance of carbonate build-ups and widespread dolomitisation makes this succession a good reservoir unit. In

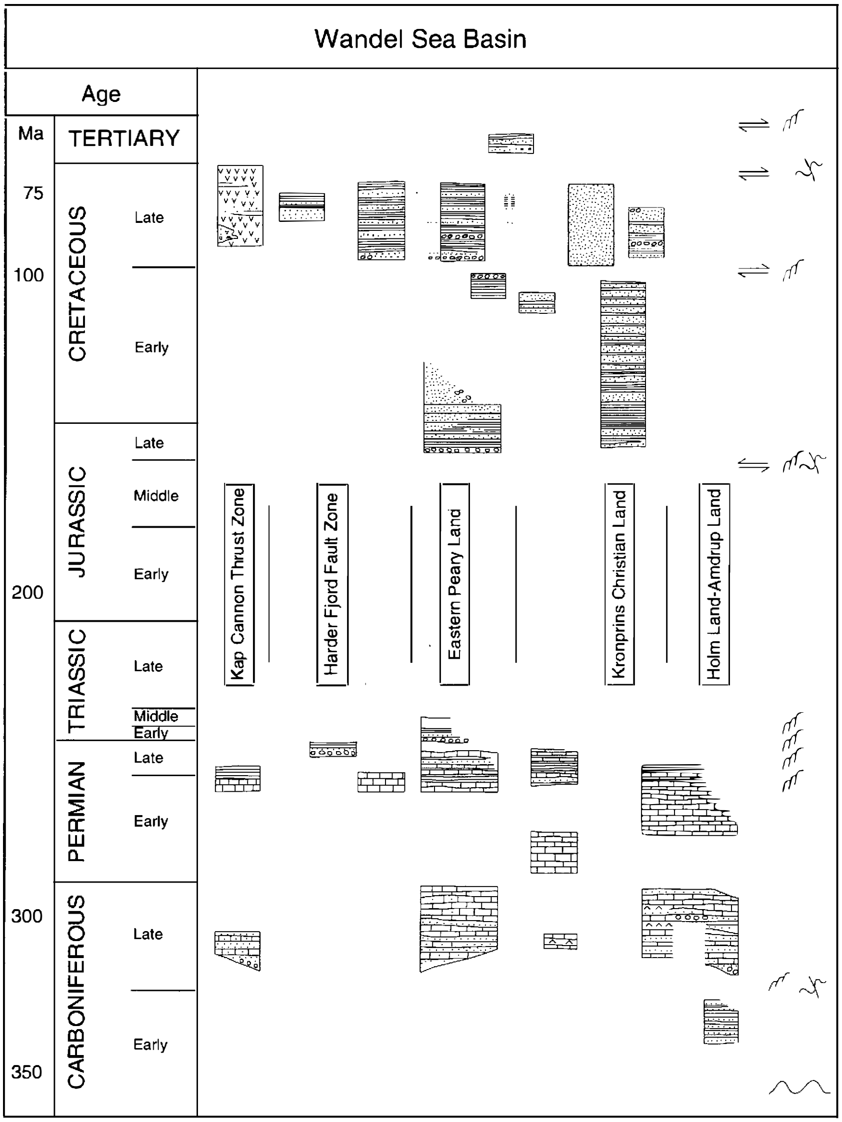

Fig. 2. Simplified stratigraphy of the Wandel Sea Basin succession.

eastern Peary Land an isolated ***Palaeoaplysina*** build-up contains bitumen and has once acted as a reservoir for hydrocarbons.

Mid-Permian (Late Artinskian – Kungurian)

In eastern Peary Land and on Amdrup Land and Holm Land, late Artinskian deposits directly overlie Gzelian carbonates. This transgressive event can be correlated with major transgressions in the Sverdrup Basin, and the sedimentary basins of Svalbard and the Barents Sea (Stemmerik & Worsley, 1995). The upper Artinskian to Kungurian succession is dated by a combination of conodonts, small foraminifera and palynomorphs (Stemmerik *et al.*, in press). Conodonts are rare in the Wandel Sea Basin succession, and only one conodont zone has been identified (Rasmussen & Håkansson, submitted manuscript). Age assignments based on small foraminifera and palynomorphs are less precise and correlation within this part of the succession is generally on stage level.

The succession is dominated by shallow shelf carbonates in southern Kim Fjelde, and on Amdrup Land. These sediments contain a distinctive fauna with large productid and spiriferid brachiopods, and large trepostome bryozoans. In northern Kim Fjelde, the succession is dominated by finely bedded resedimented carbonates with abundant chert. In this area the succession shows a gradual upward deepening, and the upper Kungurian part is dominated by interbedded chert and shale. Deposition of this unit appears to have been related to large scale subsidence and tilting of the Wandel Sea Basin, as is the case in other basins in the Arctic region. This tectonic event was associ-

Fig. 3. Upper Carboniferous, Moscovian–Gzhelian sediments in eastern Holm Land. The lower part consists of cyclic interbedded shelf carbonates and siliciclastic deposits; the upper part is dominated by shelf carbonates. Cliff height is approximately 350 m.

ated with a major change in climate or circulation. In the Wandel Sea Basin the mid-Permian fauna differs significantly from that seen in the underlying Foldedal Formation; deposition apparently took place in a relatively cold, temperate climate.

The change in climatic conditions prior to deposition of the late Artinskian carbonates is reflected by diagenetic processes which have had influence on the reservoir potential. Most carbonates are cemented by stable low-Mg calcite or chert and there is little or no porosity in the rocks. A similar pattern is seen in the Barents Sea area; Artinskian and younger Permian carbonates appear to have little economic potential in the Arctic region.

Late Permian (Kazanian)

The succession in Kim Fjelde, eastern Peary Land is dated on the basis of small foraminifera and palynomorphs as Kazanian; a more precise age assignment is not possible. The base of the Kazanian is a major flooding surface that marks a rapid drowning of the depositional basin (Fig. 4). In south-eastern Kim Fjelde large scale resedimentation and slumping of carbonates suggest that this drowning event was associated with active faulting. The Kazanian succession is composed of two shallowing upwards cycles of deeper water shales and inner shelf carbonates or shelf sandstones.

The basal parts of the two cycles consist of black laminated and bioturbated shales. These shales have low organic content and little potential as source rocks for hydrocarbons. The shales are overlain by bryozoan and brachiopod dominated shallow marine limestones with abundant chert in south-eastern Kim Fjelde. In northern Kim Fjelde the shales pass upwards into a thick succession of bioturbated shelf sandstone.

The limestones were deposited under climatic conditions similar to those dominant during the Kungurian and have little or no porosity. This unit therefore has very limited reservoir potential.

Mesozoic to Paleogene

Early Triassic

Early Mesozoic sedimentation in the Wandel Sea Basin was apparently restricted to the Skythian–Anisian. Two shallowing upward sequences are distinguished in the Peary Land area, the Parish Bjerg and Dunken Formations.

The Parish Bjerg Formation rests on Palaeozoic sediments with a low angle unconformity, whereas the relationship between the Parish Bjerg and Dunken Formations is not discernible in the field. Both sequences show evidence of rapid deepening with thin intervals of deep-water turbiditic facies rapidly giving way to silty and sandy shales with gradually increasing sand content. Mid- to shallow shelf conditions were maintained throughout deposition of the thick sands forming the top of both sequences. The presence of reasonably well preserved macro-plant fossils in the Anisian sandstone may point to deposition on a fairly narrow shelf.

The age of the two transgressive-regressive cycles recorded in the Parish Bjerg and Dunken Formations is not particularly well documented. However, newly collected ammonites from the lower part of the Dunken Formation indicate the presence of the Skythian *Euflemingites romunderi* Zone, and it therefore seems likely that both flooding events took place during the Skythian. The shelf sands of the Dunken Formation contain an Early Anisian fauna in their lower part; very poorly preserved ammonite faunas from the top of the formation indicate that deposition was terminated in the early part of the Anisian.

Shales from the Triassic Dunken Formation generally have very low contents of organic matter (<0.25%) of mixed terrestrial and marine composition. The organic content is mature with respect to oil generation, with a Hydrogen Index (HI) of 100 on average.

Late Jurassic – Early Cretaceous

No sediments are preserved from the long interval of time between the Anisian and the Oxfordian (Fig. 2), and it is most likely that the strike-slip regime of the Wandel Hav strike-slip mobile belt governing the remaining part of the Wandel Sea Basin history was established during this period. There is some evidence to suggest repeated activity in the Trolle Land fault zone throughout the period, but the first clearly discernible event is the extensional Ingeborg event, which locally created subsidence of the order of 1–2 km along normal listric faults. Related compressive structures in Kim Fjelde point to a sinistral transpressive element during this event.

The topography created by the Ingeborg event was transgressed during an apparent global rise in sea level, which reached North Greenland in the latest Oxfordian *serratum-rosenkrantzi* Zones. Maximum flooding occurred very soon after, close to the Oxfordian–Kimmeridgian boundary, while global sea level had its maximum in the early Volgian. Continuous differential movement along the Trolle Land fault zone influenced deposition in two, partly independent sub-basins recognised in the Wandel Sea Basin. In Kilen renewed subsidence maintained open shelf conditions throughout the Early Cretaceous, whereas terrestrial conditions prevailed in the Peary Land region until late in the Aptian.

Oil source rocks with economic potential have not been found in the Jurassic–Cretaceous succession of the Wandel Sea Basin. Very subordinate, thin shale beds with source rock quality (HI > 100) do occur in the Jurassic – Lower Cretaceous sequence but are not widespread. By contrast, widely distributed mid-Cretaceous shales do not have source quality, as the organic content is terrestrially derived.

Late Cretaceous – Early Tertiary

The Late Cretaceous Kilen event is the second major episode along the strike-slip mobile belt. It is dominated by dextral strike-slip movements in an overall extensional regime, leading to the formation of at least six fairly small, rapidly deepening pull-apart basins across North Greenland, each with a marine depositional signature (Håkansson & Pedersen, 1982; Birkelund & Håkansson, 1983). Two of these basins remained terrestrial throughout their entire history, one is mixed terrestrial-marine, while three remained marine. There is nothing to indicate that any direct connection existed between these basins, nor do they have any obvious relationships to basins outside North Greenland. However, comparatively small basins on the Barents Shelf which contain Upper Cretaceous strata may be structurally related to the series of pull-apart basins in North Greenland. All basins have been disturbed by subsequent compression, and all Upper Cretaceous sediments in North Greenland have suffered severe thermal degradation.

Two basins are located in Kronprins Christian Land. The *Kilen Basin* contains at least 1500 m of marine sediments of Middle Turonian to Early Coniacian age which documents several pulses of basin deepening. The *Nakkehoved Basin* contains at least 600 m of marine sediment, but the sparse bivalve fauna does not permit an age determination better than Late Cretaceous. The remaining basins are all located in Peary Land. The *Herlufsholm Strand Basin* in eastern Peary Land is strongly folded and thrusted; it contains a succession of more than 400 m of fluvial sediments. A shallow marine incursion containing a restricted inoceramid fauna, establishes the age as Late Cretaceous, possibly within the Turonian–Coniacian interval. The *Depot Bugt Basin* is located in the eastern part of the Harder Fjord fault zone; it contains more than 500 m of fluvial sediments. Plant remains occur, but so far no definite age indication has been achieved. The *Frigg Fjord Basin* positioned centrally in the Harder Fjord fault zone contains approximately 400 m of marine sediments deposited in a rapidly deepening basin; the top of the sequence contains a

Fig. 4. Bedded chert-rich carbonates of the Kim Fjelde Formation abruptly overlain by black laminated shales of the Midnatfjeld Formation reflecting a major Late Permian drowning event in the Wandel Sea Basin.

Late Santonian fauna. The *Kap Washington Basin* at the north coast of Peary Land is bordered by the Kap Cannon thrust zone to the south. This basin contains in the order of 5 km of extrusive volcanic rocks and volcanogenic sediments, with a few intervals of fluvial sediments. Upper Cretaceous plant fossils occur at several levels, and the top of the volcanic suite has been dated to about the Cretaceous–Tertiary boundary.

All Upper Cretaceous deposits in North Greenland have suffered compressional deformation to a varying degree. While compression in the main Wandel Sea Basin, in eastern Peary Land and Kronprins Christian Land, took place close to the Cretaceous–Tertiary boundary, compression along the Harder Fjord fault zone and the Kap Cannon thrust zone may have occurred later in the Tertiary as part of the Eurekan orogeny.

Post-compressional late Paleocene – early Eocene fluvial plain sediments with locally abundant plant debris are largely restricted to the central part of the Trolle Land fault system. The facies distribution indicates an overall drainage towards the south and south-west.

Subsidence rates varied greatly during the Mesozoic due to the differential movements along the Trolle Land fault system, and only in the Kilen area has the presence of a substantial sedimentary succession been documented. The thermal history revealed by the Wandel Sea Basin sediments has therefore been found to be influenced more by particular thermal events than by their burial history.

Two significant events may be distinguished. One thermal pulse in the end-Cretaceous is related to the contractional forces which caused considerable thermal alteration (locally reaching greenschist facies) in areas of maximum compression. The second pulse occurred later in the Tertiary, after sediment accumulation in the Wandel Sea Basin had ceased, and was focused in northern Kronprins Christian Land; its source remains uncertain.

Hydrocarbon potential

The onshore parts of the Wandel Sea Basin are thought to have limited hydrocarbon potential on the basis of present investigations. The main problems are thermal maturity and the absence of any obvious source rocks within the basin.

Carboniferous to Cretaceous sediments exposed in northern Kronprins Christian Land are thermally post-mature due to local heating. While these areas are unprospective due to increased heating, southern Kronprins Christian

Land, Amdrup Land and Holm Land suffer from lack of adequate burial. Here the Carboniferous–Permian sediments are immature to early mature at surface and have never been buried deeply enough to generate hydrocarbons.

So far, no laterally persistent organic-rich units have been identified within the Carboniferous to Cretaceous succession in eastern Peary Land, and exploration models have to rely on sourcing from older, Cambrian or Silurian organic-rich shales in this region. The Lower Palaeozoic sediments directly beneath the Wandel Sea Basin are thermally postmature with respect to hydrocarbon generation, and exploration models have therefore to involve large scale lateral migration. Models relying on sourcing from older sediments cannot be used in Holm Land and Amdrup Land where the succession rests directly on Caledonian-affected basement.

While the onshore potential of the basin seems to be limited, the succession appears to have much higher potential offshore northern East Greenland. Increased knowledge of the basin history and structural style within the onshore basin will improve evaluation of these offshore areas.

References

Beauchamp, B. 1993: Carboniferous and Permian reefs of Sverdrup Basin, Canadian Arctic: an aid to Barents Sea exploration. *In* Vorren, T. O. *et al.* (ed.) Arctic geology and petroleum potential. *Spec. Publ. Norwegian Petrol. Soc.* **2**, 217–242.

Beauchamp, B., Harrison, J. C. & Henderson, C. M. 1989: Upper Paleozoic stratigraphy and basin analysis of the Sverdrup Basin, Canadian Arctic Archipelago: Part 2, Transgressive-regressive sequences. *Geol. Surv. Canada Pap.* **89–1G**, 105–113.

Birkelund, T. & Håkansson, E. 1983: The Cretaceous of North Greenland – a stratigraphic and biogeographical analysis. *Zitteliana* **10**, 7–25.

Bugge, T., Mangerud, G., Elvebakk, G., Mørk, A., Nilsson, I., Fanavoll, S. & Vigran, J. O. 1995: The Upper Paleozoic succession on the Finnmark Platform, Barents Sea. *Norsk Geol. Tidsskr.* **75**, 3–30.

Håkansson, E. 1979: Carboniferous to Tertiary development of the Wandel Sea Basin, eastern North Greenland. *Rapp. Grønlands geol. Unders.* **88**, 73–83.

Håkansson, E. & Pedersen, S. A. S. 1982: Late Paleozoic to Tertiary tectonic evolution of the continental margin in North Greenland. *Can. Soc. Petrol. Geol. Mem.* **8**, 331–348.

Håkansson, E. & Stemmerik, L. 1989: Wandel Sea Basin – A new synthesis of the late Paleozoic to Tertiary accumulation in North Greenland. *Geology* **17**, 683–686.

Håkansson, E., Heinberg, C. & Stemmerik, L. 1981: The Wandel Sea Basin from Holm Land to Lockwood Ø, eastern North Greenland. *Rapp. Grønlands geol. Unders.* **106**, 47–63.

Håkansson, E., Madsen, L. & Pedersen, S.A.S. 1989: Geological investigations of Prinsesse Ingeborg Halvø, eastern North Greenland. *Rapp. Grønlands geol. Unders.* **145**, 113–118.

Håkansson, E., Heinberg, C. & Stemmerik, L. 1991: Mesozoic and Cenozoic history of the Wandel Sea Basin area, North Greenland. *Bull. Grønlands geol. Unders.* **160**, 153–164.

Håkansson, E., Birkelund, T., Heinberg, C., Hjort, C., Mølgaard, P. & Pedersen, S. A. S. 1993: The Kilen Expedition 1985. *Bull. geol. Soc. Denmark* **40**, 9–32.

Håkansson, E., Heinberg, C., Madsen, L., Mølgaard, S., Pedersen, S. A. S., Piasecki, S., Rasmussen, J. A., Stemmerik, L. & Zinck-Jørgensen, K. 1994: Wandel Sea Basin: Basin Analysis. EFP-91 Project No. 0012; Completion report to the Ministry of Energy. Unpublished report, Geological Institute, University of Copenhagen, 400 pp.

Nilsson, I. 1994: Upper Palaeozoic fusulinid assemblages, Wandel Sea Basin, North Greenland. *Rapp. Grønlands geol. Unders.* **161**, 45–71.

Rasmussen, J. A. & Håkansson, E. submitted MS: First Permo-Carboniferous conodonts from North Greenland. Submitted to *Geol. Mag.*

Stemmerik, L. 1994: Sequence stratigraphy of a mixed carbonate, siliciclastic and evaporite succession, Upper Carboniferous, North Greenland. *In* High resolution sequence stratigraphy: Innovations and applications. Abstract Volume, 159–160. Liverpool: University of Liverpool.

Stemmerik, L. & Elvebakk, G 1994: A newly discovered mid-Carboniferous – ?Early Permian reef complex in the Wandel Sea Basin, eastern North Greenland. *Rapp. Grønlands geol. Unders.* **161**, 39–44.

Stemmerik, L. & Worsley, D. 1989: Late Palaeozoic sequence correlations, North Greenland, Svalbard and the Barents Shelf. *In* Collinson, J. D. (ed.) *Correlation in hydrocarbon exploration*, 99–111. London: Graham & Trotman for the Norwegian Petroleum Society.

Stemmerik, L. & Worsley, D. 1995: Permian history of the Barents Shelf area. *In* Scholle, P. A., Peryt, T. M. & Ulmer-Scholle, D. S. (ed.) *The Permian of northern Pangea* **2**: *Sedimentary basins and economic resources*, 81–97. Berlin: Springer Verlag.

Stemmerik, L., Nilsson, I. & Elvebakk, G. 1995: Gzelian–Asselian depositional sequences in the western Barents Sea and North Greenland. *In* Steel, R. *et al.* (ed.) Sequence stratigraphy on the northwest European margin. *Spec. Publ. Norwegian Petrol. Soc.* **5**, 529–544.

Stemmerik, L., Håkansson, E., Madsen, L., Nilsson, I., Piasecki, S., Pinard, S. & Rasmussen, J. A. in press: Stratigraphy and depositional evolution of the Upper Palaeozoic sedimentary succession in eastern Peary Land, North Greenland. *Rapp. Grønlands geol. Unders.*

Worsley, D., Agdestein, T., Gjelberg, J. & Steel, R. J. 1990: Late Palaeozoic basinal evolution of Bjørnøya: implications for the Barents Sea. *Geonytt* **1**, 124–125.

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