Sequence stratigraphy of source and reservoir rocks in the Upper Permian and Jurassic of Jameson Land, East Greenland

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Approximately half of the hydrocarbons discovered in the North Atlantic petroleum provinces are found in sandstones of latest Triassic – Jurassic age with the Middle Jurassic Brent Group, and its correlatives, being the economically most important reservoir unit accounting for approximately 25% of the reserves. Hydrocarbons in these reservoirs are generated mainly from the Upper Jurassic Kimmeridge Clay and its correlatives with additional contributions from Middle Jurassic coal, Lower Jurassic marine shales and Devonian lacustrine shales. Equivalents to these deeply buried rocks crop out in the well-exposed sedimentary basins of East Greenland where more detailed studies are possible and these basins are frequently used for analogue studies (Fig. 1).

Investigations in East Greenland have documented four major organic-rich shale units which are potential source rocks for hydrocarbons. They include marine shales of the Upper Permian Ravnefjeld Formation (Fig. 2), the Middle Jurassic Sortehat Formation and the Upper Jurassic Hareelv Formation (Fig. 4) and lacustrine shales of the uppermost Triassic – lowermost Jurassic Kap Stewart Group (Fig. 3; Surlyk *et al.* 1986b; Dam & Christiansen 1990; Christiansen *et al.* 1992, 1993; Dam *et al.* 1995; Krabbe 1996).

Potential reservoir units include Upper Permian shallow marine platform and build-up carbonates of the Wegener Halvø Formation, lacustrine sandstones of the Rhaetian–Sinemurian Kap Stewart Group and marine sandstones of the Pliensbachian–Aalenian Neill Klinter Group, the Upper Bajocian – Callovian Pelion Formation and Upper Oxfordian – Kimmeridgian Hareelv Formation (Figs 2–4; Christiansen *et al.* 1992).

The Jurassic sandstones of Jameson Land are well known as excellent analogues for hydrocarbon reservoirs in the northern North Sea and offshore mid-Norway. The best documented examples are the turbidite sands of the Hareelv Formation as an analogue for the Magnus oil field and the many Paleogene oil and gas fields, the shallow marine Pelion Formation as an analogue for the Brent Group in the Viking Graben and correlative Garn Group of the Norwegian Shelf, the Neill Klinter Group as an analogue for the Tilje, Ror, Ile and Not Formations and the Kap Stewart Group for the Åre Formation (Surlyk 1987, 1991; Dam & Surlyk 1995; Dam *et al.* 1995; Surlyk & Noe-Nygaard 1995; Engkilde & Surlyk in press). The presence of pre-Late Jurassic source rocks in Jameson Land suggests the presence of correlative source rocks offshore mid-Norway where the Upper Jurassic source rocks are not sufficiently deeply buried to generate hydrocarbons. The Upper Permian Ravnefjeld Formation in particular provides a useful source rock analogue both there and in more distant areas such as the Barents Sea.

The present paper is a summary of a research project supported by the Danish Ministry of Environment and Energy (Piasecki *et al.* 1994). The aim of the project is to improve our understanding of the distribution of source and reservoir rocks by the application of sequence stratigraphy to the basin analysis. We have focused on the Upper Permian and uppermost Triassic–Jurassic successions where the presence of source and reservoir rocks are well documented from previous studies. Field work during the summer of 1993 included biostratigraphic, sedimentological and sequence stratigraphic studies of selected time slices and was supplemented by drilling of 11 shallow cores (Piasecki *et al.* 1994). The results so far arising from this work are collected in Piasecki *et al.* (1997), and the present summary highlights the petroleum-related implications.

Source and reservoir rocks in a sequence stratigraphic framework

Sequence stratigraphic concepts have greatly improved our understanding of the genetic, spatial and stratigraphic distribution of depositional units, including source and reservoir rocks. Accordingly, such studies
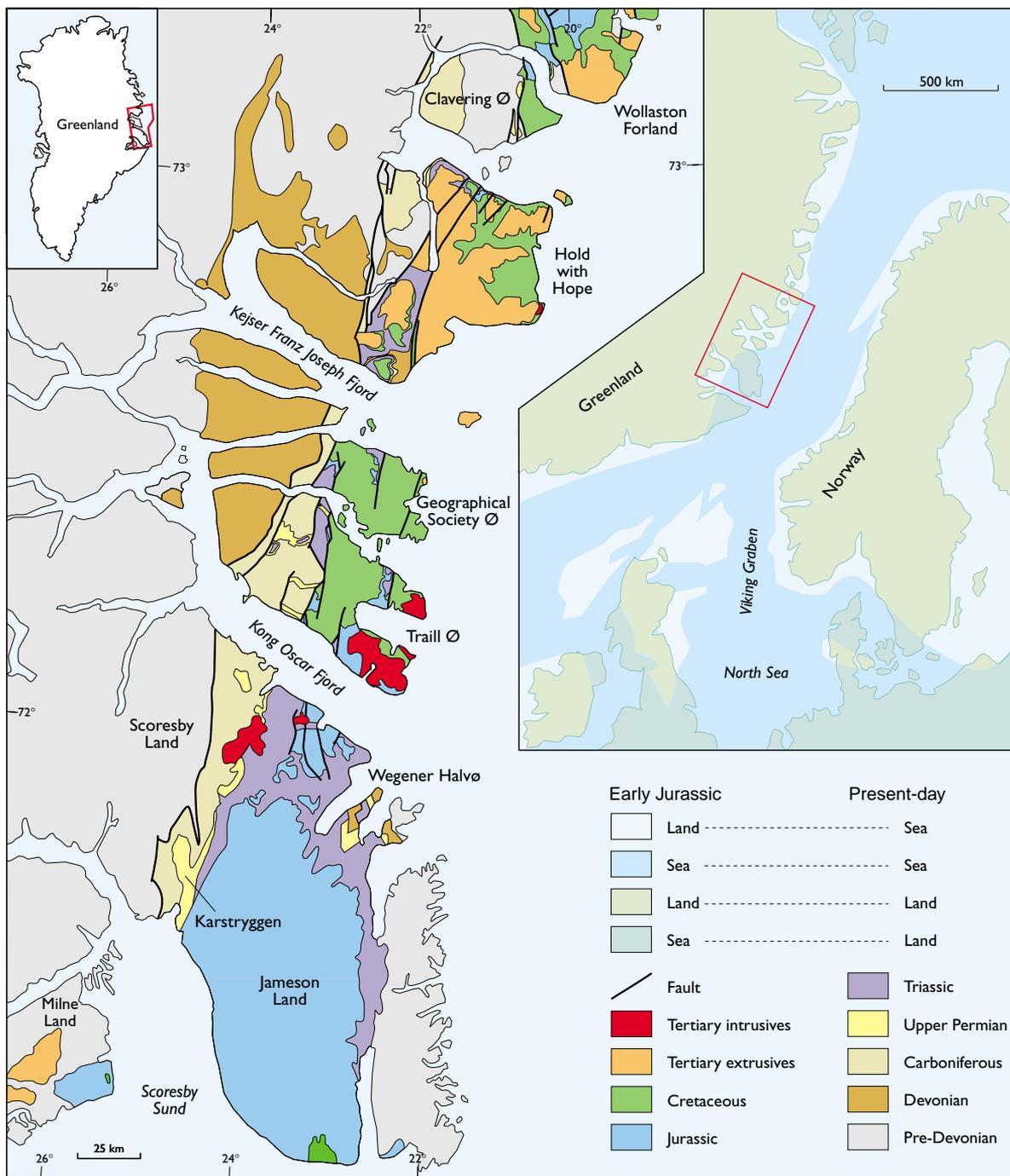
Fig. 1. The position of Greenland and Norway in an Early Jurassic pre-drift reconstruction with a simplified geological map of East Greenland showing Upper Palaeozoic to Mesozoic sediments and Tertiary igneous rocks. Geological map modified from Stemmerik *et al.* (1997); pre-drift position from Dam & Surlyk (1995).
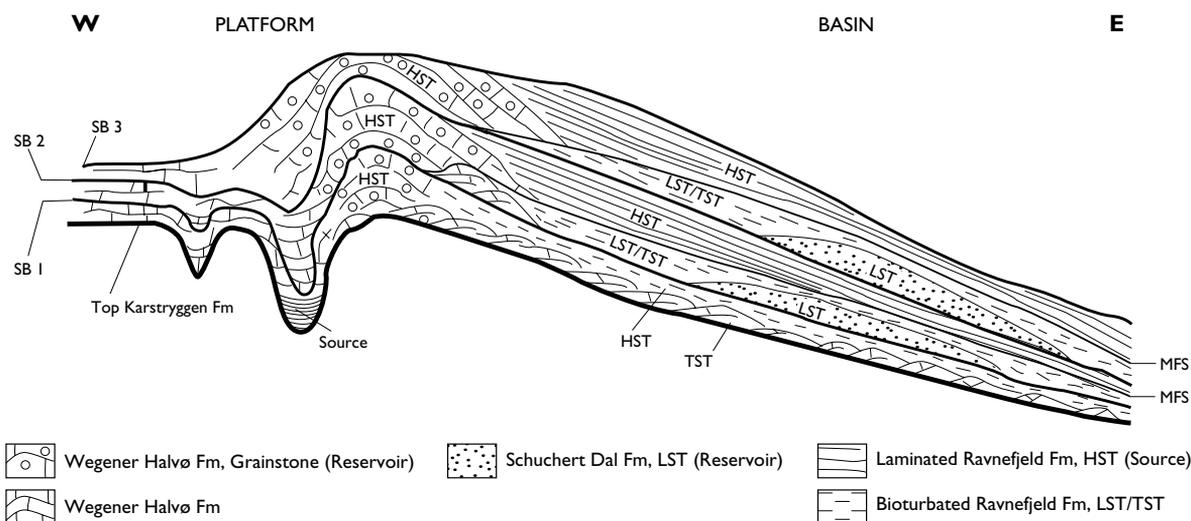
Fig. 2. Sequence stratigraphic model of the Upper Permian Wegener Halvø, Ravnefjeld and Schuchert Dal Formations in Jameson Land. Potential source and reservoir rocks are indicated. SB: sequence boundary; MFS: maximum flooding surface; LST, TST and HST: lowstand, transgressive and highstand systems tracts.

of well-exposed sedimentary basins can be used for more confident predictions of deeply buried potential source and reservoir rocks, and their spatial distribution in offshore basins with limited data sets. The most important implications are the genetic links between sea-level changes and the spatial distribution of sand depocentres and organic-rich, source-prone shales (e.g. in the Kap Stewart Group and the Hareelv Formation in East Greenland). Generalised models thus predict seaward displacement of sand depocentres during falling sea-level and deposition of sand-prone facies in basinal settings during sea-level lowstands. The best quality source rocks are predicted to occur during rising sea-level particularly during time intervals of high global sea-level. In the Jameson Land Basin, the sea-level control of source and reservoir rock distribution and quality can be studied in detail in well exposed and well dated successions of Late Permian and latest Triassic – Jurassic age.

The Upper Permian Foldvik Creek Group provides an example of a semi-arid carbonate-dominated depositional system where organic-rich, basinal shales were deposited during transgressions and early highstands and potential carbonate reservoir rocks formed along the margins of the surrounding carbonate platforms. The Rhaetian–Sinemurian lacustrine Kap Stewart Group consists of organic-rich shales deposited during lake-level rise and highstand alternating with sandy reservoir rocks formed during lake-level fall and lowstand. The overlying Pliensbachian–Volgian succession provides exam-

ples of marine siliciclastic systems with multiple reservoir rocks. Deposition of potential source rocks for oil mainly occurred during pronounced transgressive phases in the Aalenian and the Late Oxfordian – Kimmeridgian.

Upper Permian: Wegener Halvø and Ravnefjeld Formations

Sediments included in the Upper Permian Foldvik Creek Group are subdivided into two low order sequences and at least six higher order sequences. The basin fill outlines a temporal development from a shallow marine, evaporitic basin to a normal marine carbonate-dominated system with a deep central shale basin. Eventually the carbonate system was completely drowned and the final basinal fill is composed of deep-water turbidites and shales (Surlyk et al. 1986a,b; Kreiner-Møller 1998).

The present study focuses on the upper, normal marine part of the Foldvik Creek Group corresponding to the Wegener Halvø and Ravnefjeld Formations when the basin was divided into shallow water carbonate platforms and a deep marine, central shale basin (Fig. 2; Surlyk et al. 1984, 1986a; Piasecki & Stemmerik 1991; Christiansen et al. 1993; Stemmerik et al. 1993). Extensive organic-rich shales of the Ravnefjeld Formation with source potential for petroleum were deposited in the central parts of the basin. New data from cores drilled in a back-barrier position on the Karstryggen carbonate platform show that organic-rich shales were also

deposited in intraplatform lows (L. Stemmerik, unpublished data 1998). Reservoir rocks are mainly confined to shallow carbonate grainstones and build-ups located along the margins of the platform. Lowstand sandy turbidites occurring in a basinal position may represent an additional hitherto unrecognised type of reservoir (Stemmerik *et al.* 1997).

Three long-term sea-level cycles with a duration of about 1 Ma each are suggested to have occurred during the time interval of the Wegener Halvø – Ravnefjeld Formations. In the basinal areas the sea-level fluctuations led to deposition of interbedded organic-lean, bioturbated shales and organic-rich, laminated shales. The laminated shales are interpreted as having been deposited during sea-level rise and early highstand when siliciclastic material was sequestered in basin margin areas. The organic-rich intervals thin towards basin margins and the interbedded bioturbated shales grade into turbiditic sandstones representing lowstand fans. Deposition of shallow-water carbonates in platform areas was restricted to times of sea-level rise and highstand whereas the platforms were subaerially exposed during lowstand (Scholle *et al.* 1993). Well developed build-ups and grainstones are restricted to the uppermost high order sequence in the Wegener Halvø Formation where carbonate production was able to keep pace with the sea-level fluctuations (L. Stemmerik, unpublished data).

The sequence stratigraphic interpretation of the upper Foldvik Creek Group predicts that organic-rich shales are expected to have been deposited not only throughout the Jameson Land Basin but also in other onshore and offshore basins in the rifted seaway between Greenland and Norway. The thickness and quality of the source rock units are uniform in most areas, although the shales formed during the latest sea-level cycle show some thinning and dilution towards platform margins. The source-prone units are much thinner and of sub-economic interest in sand-dominated lowstand fan areas.

Deposition and diagenesis of potential carbonate reservoir rocks are closely related to sea-level fluctuations. Deposition took place during rising and high relative sea-level when the platforms were flooded, whereas carbonate porosity was enhanced and preserved during periods of subaerial exposure and dissolution. This type of reservoir is therefore confined to up-dip areas that were subaerially exposed during lowstand. Localised carbonate lowstand reservoirs composed of resedimented, poor reservoir quality carbonates off carbonate platforms, are predicted to occur in basinal areas, whereas good quality siliciclastic sandstone reservoirs are predicted to occur in areas with poorly developed carbonate platforms marking entry points of rivers and deltas.

Uppermost Triassic – lower Middle Jurassic: Kap Stewart and Neill Klinter Groups

Sediments included in the Rhaetian–Sinemurian Kap Stewart Group and the Pliensbachian–Aalenian Neill Klinter Group were deposited in a basin open to the south and closed to the west, east and north (Dam & Surlyk 1993, 1995, 1998). The Kap Stewart Group was deposited in an extensive lake which alternated between hydrologically closed and open states. Along the margins, alluvial-plain, delta-plain and delta-front environments dominated whereas lacustrine conditions characterised the central part of the basin.

Depositional patterns changed in the Pliensbachian when the basin underwent marine transgression. During the early stages of deposition of the Neill Klinter Group, the area formed a shallow marine embayment dominated by shoreface, tidal channel, subtidal shoal and offshore transition deposits (Fig. 3). In Aalenian – Early Bajocian times a sea-level rise resulted in deposition of restricted shelf mudstones of the Sortehat Formation throughout the basin.

Organic-rich shales with source potential are well documented both from the open-lacustrine shale succession of the Kap Stewart Group (Dam & Christiansen 1990; Krabbe 1996) and the basal, transgressive part of the Sortehat Formation (Krabbe *et al.* 1994; Krabbe 1996), whereas thick sandstones are present in both the fluvial-lacustrine Kap Stewart Group and the shallow marine Neill Klinter Group along the eastern, western and northern basin margins.

High-resolution sequence stratigraphic analysis of the lacustrine Kap Stewart Group indicates that deposition took place in response to two orders of lake-level variations. The lake was low-lying and marine areas were located nearby in the seaway between Greenland and Norway. Long term cyclicity in lake level was possibly controlled by fluctuations in sea-level whereas high frequency fluctuations were more likely controlled by Milankovitch-type climate cycles (Dam & Surlyk 1993). Repeated climatically controlled lake-level falls and associated forced regressions resulted in deposition of sheet deltaic sandstones towards the basin centre whereas dark organic-rich lacustrine shales were deposited during periods of rise and highstand.

Fig. 3. Sequence stratigraphic scheme of Kap Stewart and Neill Klinter Groups. Slightly modified from Dam & Surlyk (1998, fig.3).

The Neill Klinter Group is subdivided into seven sequences, each with an overall sheet geometry and a duration of 1–2 Ma (Fig. 3; Dam & Surlyk 1995, 1998). Most sequences are characterised by near absence of well-defined parasequences, which is interpreted as reflecting a high rate of influx of sand. Continuous filling of accommodation space and erosion led to poor development of facies cyclicity and to amalgamation of parasequences. A direct correlation of systems tracts on a scale of a few tens of metres between East Greenland and the mid-Norwegian shelf seems to be possible (Dam & Surlyk 1995) and the Neill Klinter Group sequences are being used by several major oil companies as direct analogues to major Norwegian oil fields.

Sequence stratigraphic analysis of the Kap Stewart Group predicts a thick shale-dominated unit of interbedded organic-rich and organic-lean units to be present in the central part of Jameson Land. High frequency lake-level fluctuations controlled the organic content of the shales and the source-prone intervals are suggested to have formed during high lake-level stand (Dam & Christiansen 1990). The low order lake-level falls caused progradation of alluvial and deltaic sediments and the model predicts thick lowstand fan deposits to be present in the buried central parts of the lacustrine basin. Thinner lowstand deltaic sandstones are associated with high frequency, lake-level falls.

Sequence stratigraphic analysis of the overlying Neill Klinter Group constrains the lateral distribution and internal architecture of four major potential reservoir units. They occur in the upper Elis Bjerg Member, the Astartekløft Member, the Nathorst Fjeld, Harris Fjeld and Lepidopteriselv Members, and the Trefjord Bjerg Member (Fig. 3). Organic-rich shales with source rock potential are not associated with the reservoir units but are confined to the overlying Sortehat Formation deposited during the Aalenian – Early Bajocian sea-level rise.

The dominant depositional motif of the Elis Bjerg Member is aggradational to progradational stacking of amalgamated tidal channel and subtidal shoal facies packages of the transgressive systems tract followed by the highstand systems tract. Deposition took place during conditions of high sediment influx into a flat-bottomed basin with a moderate rate of creation of new accommodation space. The highstand systems tract is characterised by the development of major tidal channel complexes, forming some of the best potential hydrocarbon reservoirs in the Neill Klinter Group. The Elis Bjerg Member is capped by offshore transition zone mudstones of the subsequent transgressive systems tract.

The base of the Astartekløft Member is a major unconformity marking the incoming of subtidal shoal and tidal channel deposits corresponding to a marked seaward shift in facies. The deposits are interpreted as a thickly developed lowstand systems tract and constitute a major reservoir unit in the south-eastern part of the basin.

The overlying Nathorst Fjeld and Harris Fjeld Members consist of a single coarsening-upward unit composed of offshore transition zone mudstones grading upward into shoreface sandstones. The Nathorst Fjeld Member interfingers with seaward-prograding low-angle clinoform-bedded ebb-tidal delta deposits of the Harris Fjeld Member and is referred to the transgressive systems tract. Towards the north, the deposits of the Nathorst Fjeld and Harris Fjeld Members pass into coarse-grained tidal channel and fine-grained shoreface deposits of the Lepidopteriselv Member (Fig. 3). The complex formed by the Nathorst Fjeld, Harris Fjeld and Lepidopteriselv Members is capped by offshore transition zone mudstones of the Skævdal Member. The Skævdal Member shows a slight coarsening-upward trend grading into shoreface deposits and is interpreted as highstand deposits.

The Skævdal Member is truncated by a prominent basin-wide erosional unconformity draped by a lag conglomerate. The unconformity marks a basin-wide seaward shift in facies and is interpreted as a sequence boundary. It is overlain by coarse-grained tidal channel and subtidal shoal and shoreface sandstones of the Trefjord Bjerg Member, interpreted as a transgressive systems tract (Dam & Surlyk 1995, 1998). The sandstones of the Trefjord Bjerg Member are capped by offshore mudstones of the Sortehat Formation.

At several localities, the sandstones of the Trefjord Member and the mudstones of the Sortehat Formation are separated by a pebble strewn drowning surface. This surface has, on the basis of field appearance, macrofossil content, organic geochemistry and the palynological assemblages been interpreted as a coalesced sequence boundary and transgressive surface (cf. Dam & Surlyk 1998).

Middle–Upper Jurassic

The Middle–Upper Jurassic deposits of the Jameson Land Basin have served for many years as an excellent analogue model for the petroliferous strata of the northern North Sea and mid-Norwegian shelf. The succession forms a long-term overall transgressive-regressive cycle that was initiated with maximum regression in the
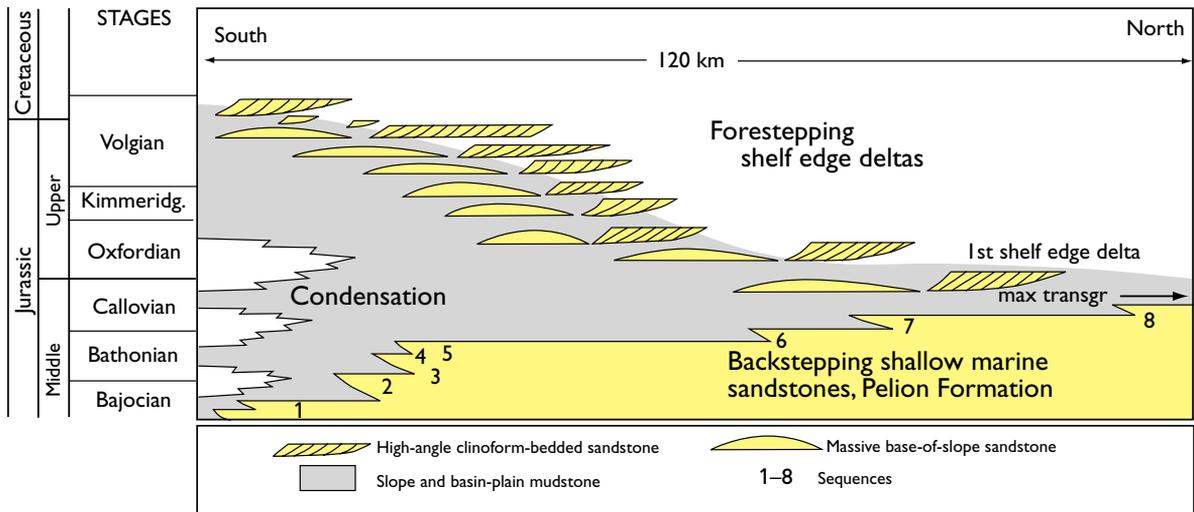
Fig. 4. Sequence stratigraphical model of the Middle and Upper Jurassic succession in Jameson Land. Numbers 1 to 8 mark eight composite third order sequences (VK 1–8) in the Pelion and Fossilbjerget Formations. The forestepping system of shelf edge deltas, base-of-slope sandstones and basinal mud refers to the Hareelv, Olympen and Raukelv (including the Sjællandselv Member) Formations.

early Late Bajocian, had a first transgressive maximum in the Middle Callovian, an Oxfordian regressive interlude, maximum transgression and turn around point in the Early Kimmeridgian and maximum regression in the latest Volgian. The duration of the complete long term transgressive-regressive cycle is 31 Ma. The Late Bajocian – Early Callovian transgressive portion of the cycle lasted for 11–12 Ma, the Oxfordian regressive pulse had a duration of 8 Ma, and the upper regressive part of 19–20 Ma (time scale after Gradstein *et al.* 1995).

Upper Bajocian – Middle Callovian: Pelion and Fossilbjerget Formations

The lower boundary of the sandy Pelion Formation is a regional unconformity. It marks a major reorganisation of the drainage system and the depositional basin, reflecting initiation of the main Mesozoic rift phase in the North European – North Atlantic region. Onset of marine sand deposition is essentially isochronous throughout Jameson Land, Traill Ø and Geographical Society Ø (Upper Bajocian *borealis* Chronozone). The upper boundary of the Pelion Formation is highly diachronous and youngs in a south–north direction from the Upper Bajocian to the Lower Callovian. The Late Bathonian – Early Callovian time interval was characterised by the influx of enormous amounts of relatively well-sorted, medium-grained quartzose sands deposited in a major deltaic system that was reworked by marine processes, notably tides and waves. The deltaic succession has the same overall style and architecture as the contemporaneous delta systems of the Brent Group and the Fangst Group which constitute the main reservoir units in the Viking Graben of the northern North Sea and mid-Norwegian shelf, respectively. The sandy Pelion Formation delta prograded southward along the basin axis. The basin axis had a very low inclination, and deposition was sensitive to even small changes in relative sea-level. Minor, high order sea-level changes with a duration of a few hundred thousand years caused the shorelines to advance or retreat in a north–south direction over tens to several hundred kilometres. The formation consists almost exclusively of marine sandstones deposited in shoreface, transition zone and offshore environments (Heinberg & Birkelund 1984; Engkilde & Surlyk in press).

The Pelion Formation and the correlative offshore Fossilbjerget Formation comprise a total of 28 high order sequences, with an average duration of about 360 Ka (Engkilde 1994; Engkilde & Surlyk in press). They can be grouped into eight composite third order sequences termed VK 1–8 with an average duration of 1–2 Ma. The stacked third order sequences form the lower transgressive part of the long-term Middle–Late Jurassic transgressive-regressive cycle (Fig. 4).

The Upper Bajocian sequences VK 1–2 include the most basinally positioned shallow marine sandstones,

deposited during major sea-level lowstands. Lowstand deposition was separated by significant marine flooding events during which the area of sand deposition shifted far northward up the rift axis. The uppermost Bajocian – Middle Bathonian sequences VK 2–4 show an overall aggradational stacking pattern. The base of VK 5 coincides with the top of the Pelion Formation in south central Jameson Land and marks a major shift from shoreface to offshore environments. Large-scale backstepping took place during deposition of the Upper Bathonian – Middle Callovian sequences VK 5–8, and was followed by maximum transgression in the Late Callovian during which the marine-reworked delta of the Pelion Formation was finally drowned (Fig. 4). Distally, in southern Jameson Land this level is represented by a highly condensed unit spanning the uppermost Bathonian – Middle Oxfordian interval.

The backstepping clastic wedge of the Upper Bajocian – Middle Callovian Pelion Formation is composed of clean, well sorted quartzose sandstones. Pebbly sandstones occur at some levels, whereas mudstones are virtually absent. There are thus no significant permeability barriers within the formation but many flooding surfaces have been lithified by early carbonate cement and these horizons may exert some control on vertical fluid flow (Engkilde 1994). The sequences are dominated by coarsening-upward sandstone units, normally 0.3 m to tens of metres thick, which show high, slightly upwards-increasing porosity and permeability values and excellent reservoir quality. The distal thickness of the Pelion Formation sandstones is about 10 m, increasing gradually northward over a distance of more than 200 km to a thickness of the order of 600 m. The formation thus constitutes a huge potential reservoir body with extremely uniform facies. It is overlain by, and passes southwards into, the micaceous silty mudstones of the Fossilbjerget Formation.

Upper Callovian – Middle Oxfordian: Olympen Formation

Drowning of the Pelion Formation delta was completed by the Late Callovian coinciding with a change of the depositional system from transgressive to regressive (Fig. 4). The Late Jurassic time interval was characterised by marked progradation punctuated by a major Kimmeridgian transgression and subsequent minor flooding events. By the end of the Jurassic period, progradation of shallow marine sandstones had reached southernmost Jameson Land. The north–south distance of Late Jurassic progradation amounts to more than 200 km.

The Upper Callovian – Middle Oxfordian Olympen Formation represents the first regressive deposits after the Late Callovian maximum flooding of the basin. The formation was deposited during two southward progradational phases separated by a major drowning event in the Early Oxfordian (Larsen & Surlyk in press). The first phase was marked by the incoming of massive mass-flow slope and base-of-slope sandstones, but the delta front and top did not reach the area of present exposure. The second phase was initiated with a thick slightly progradational mudstone succession indicating that the deltaic deposition had shifted far to the north during the drowning event. Southward progradation of the delta was heralded by the incoming of massive base-of-slope sandstones, and this time the cross-bedded and clinoform bedded sandstones of the delta front and delta top reached the area.

The mudstones of the top of the underlying Fossilbjerget Formation and the lower massive sandstone unit of the Olympen Formation form an undifferentiated highstand – falling stage – lowstand systems tract. The top of the sandstone represents the basinal correlative of the transgressive systems tract and an organic-rich level in the overlying mudstones represents the maximum flooding zone. The remainder of the mudstone unit and the overlying massive sandstones of the second progradational phase form the highstand systems tract. The succeeding cross-bedded delta front sandstones are placed in the falling stage systems tract and their sharp base is interpreted as a marine regressive surface of erosion. The sharp base of the overlying clinoform bedded sandstones is a sequence boundary and these sandstones are referred to the lowstand systems tract.

The Olympen Formation provides an interesting analogue for important Upper Jurassic oil and gas reservoirs of the mid-Norwegian shelf, especially the giant Troll gas field.

Upper Oxfordian – Volgian: Hareelv Formation

Subsequent Late Jurassic progradation is only represented by slope and base-of-slope deposits of the Hareelv Formation which forms the youngest preserved unit in much of southern Jameson Land (Surlyk 1987). It consists of black organic-rich mudstones with thick, highly irregular, lenticular bodies of massive, well-sorted sandstones. The Upper Oxfordian part of the formation has roughly equal proportions of sandstone and mudstone whereas the Kimmeridgian–Volgian Sjællandselv

Member, has a very low content of mudstones and is dominated by thick massive sandstones.

The mudstones were deposited from suspension in poorly oxygenated slope and basinal environments. The content of organic carbon varies from 1–13% but the Hydrogen Index is less than 350 due to dominantly type II kerogen.

The sandstones were deposited in slope and base-of-slope gullies from sandy debris flows and erosive, high-density turbidity currents. They do not show any vertical or lateral trends in thickness and stacking pattern and form a completely disorganised sedimentary system. The sands were liquefacted subsequent to deposition. Major overhanging load structures were developed along the margins of the sand bodies, and sand was intruded as dykes and sills into the surrounding mudstones. The timing of liquefaction is difficult to estimate. There is evidence for some penecontemporaneous liquefaction and intrusion. Most of the soft sediment deformation seems, however, to have taken place after burial by a relatively thick cover of mudstone. The mudstones were mainly compacted at the time of sand intrusion as indicated by the angular shapes of mudstone clasts or rafts, the sharp boundaries of sandstone dykes and sills, and lack of mixing between mudstone and sandstone. The top of the sandstone bodies is very irregular and commonly shows onion-shaped mounds with abundant soft-sediment flow moulds on the surface. This indicates liquefaction and intrusion of the whole sand body after burial under as much as several tens of metres. The intrusive sandstone bodies provide a unique analogue model for enigmatic Paleogene reservoir bodies in the North Sea (cf. Dixon *et al.* 1995).

The dominance of sandstone in the upper part of the Hareelv Formation reflects an increase in eustatic fall at the end of the Jurassic period and associated long-distance southwards progradation to the shelf edge. The Sjællandselv Member thus represents an extremely sand-rich slope and base-of-slope reservoir of mass-flow origin which passes up-dip into cross-bedded sandstones representing shelf-edge deltas.

Volgian: Raukelv Formation

Progradation of shelf-edge deltas reached southernmost Jameson Land in the Volgian (Surlyk & Noe-Nygaard 1991, 1995, 1998; Surlyk *et al.* 1993). A succession of at least five, up to 50 m thick, high-angle clinoform-bedded sandstone sheets makes up the Raukelv Formation, and represents a forestepping set of shelf edge deltas. They prograded eastwards to the outermost shelf and shelf-edge areas during sea-level fall and lowstand. There is abundant evidence for tidal activity in the sand bodies; they were not directly attached to a river mouth but were reworked by marine longshore tidal and storm-induced currents.

The high-angle, clinoform-bedded, marine reworked shelf-edge deltas wedge out gradually towards the western basin margin where they are represented by a major hiatus. They are topped by pebble lags and are separated by glauconitic transgressive sandstones.

In some exposures, the transition from the delta front to slope and base-of-slope can be directly observed. When the delta reached the shelf-edge, progradation continued over the upper slope, the delta front started to collapse and mass flows were triggered down the slope. The upper slope thus shows a range of transitions from cross-bedded to massive sandstones separated by scours and slide planes. In the lower slope, base-of-slope and proximal basin, only massive mass flow sandstones were deposited. The proportion of mudstone increases gradually southwards in the axial direction from close to zero in the slope area up to 100% in the most distal exposed part of the basin.

The forestepping stack of marine-reworked shelf-edge delta sand bodies shows a clear time trend towards coarser grain-sizes, more basinal position and increased fluvial influence. This culminated with the development of a marked red-stained pebble strewn erosional surface at the top of the youngest delta. A large valley was incised in the edge and upper slope of the delta and a system of fluvial tributary channels leading towards the valley margins was developed. The valley was probably formed by fluvial incision of the shelf edge enlarged by retrogressive slumping and marine erosion during succeeding transgression. The valley was filled by onlapping mudstones which towards the top coarsen upwards into fossiliferous sandstones which form the top of the valley fill. The unconformity at the top of the Raukelv Formation and the associated incised valley mark the end of the long-term Middle–Late Jurassic transgressive-regressive cycle.

The high-angle clinoform bedded sandstone packages of the Raukelv Formation form an excellent analogue for several important hydrocarbon reservoirs in the northern North Sea. Furthermore, the formation is a rare exposure of a complete shelf, shelf edge, slope, base-of-slope and proximal basin. It provides a highly illustrative example of shelf-edge delta progradation, delta front collapse, mass flow initiation and deposition.

Conclusions

High resolution sequence stratigraphic analysis of Permian and uppermost Triassic – Jurassic successions in Jameson Land, East Greenland provides new knowledge and a much better understanding of the importance of relative sea-level changes, tectonism and basin physiography for the development and distribution of potential source and reservoir rocks.

1. It is demonstrated that deposition of the oil-prone Upper Permian Ravnefjeld Formation extended to intraplatform lows during highstand, and that lowstand sandy turbidites represent an additional potential reservoir type (Fig. 2).

    High-resolution sequence stratigraphic analysis of the Rhaetian–Aalenian succession (Fig. 3) suggests the possibility of long-distance correlation at a systems tract level, on a scale of a few tens of metres, between East Greenland and the mid-Norwegian shelf across the present North Atlantic Ocean.

    The Middle and Upper Jurassic succession was deposited during an overall long-term transgressive-regressive cycle from the Late Bajocian to the latest Volgian with a first major flooding in the Early Callovian, and a second in the Early Kimmeridgian. The Pelion and Fossilbjerget Formations were deposited in a shallow marine basin with very low inclination of the basin axis and with rapid shoreline migration over tens to several hundred kilometres in a north–south direction. The overlying Olympen, Hareelv and Raukelv Formations were deposited in a deep marine basin with a steep basin axis. The significantly variable sand to shale ratio in the formations mainly reflects present-day preservation of shelf edge delta, slope and base-of-slope deposition during overall Late Jurassic regression (Fig. 4).

2. Four major potential source rocks for oil are identified in the Permian and Jurassic successions of the Jameson Land Basin and multiple clastic or carbonate potential reservoir rocks occur throughout the same succession. Sequence stratigraphic analysis of the succession shows that the spatial distribution and the formation of the potential source and reservoir rocks are closely linked to relative sea and lake-level variations.

    Fine-grained, organic-rich sediments were deposited in distal settings of transgressive and highstand systems tracts at many levels in the studied succession, but became oil-prone only when deposited in low oxygen environments, e.g. in the Ravnefjeld Formation (marine), the Kap Stewart Formation shales (lacustrine), the lower Sortehat Formation (marine, brackish) and the Hareelv Formation (marine).

    Based on sequence stratigraphic models it is predicted that correlative sedimentary units with source potential occur not only in East Greenland but also in other basins of the North Atlantic region. This applies to the marine Ravnefjeld Formation and the marine–brackish Sortehat Formation.

3. Carbonate reservoirs (Wegener Halvø Formation build-ups and platforms) associated with potential source rocks (Ravnefjeld Formation) were deposited during highstands but subaerial exposure during lowstands enhanced and preserved porosity.

    Clastic sedimentary units with reservoir potential directly associated with potential source rocks were formed both as lowstand fans (Schuchert Dal Formation), basinal forced regressive sheet sands deposited during repeated lake-level falls (Kap Stewart Group) and slope to base-of-slope gully sandstones slumped from lowstand shelf edge deltas (Hareelv Formation).

4. Most large oil and gas fields in the North Atlantic region have depositional analogues in the Jameson Land Basin, that may be used for comparative studies.

Acknowledgements

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