Petroleum geological activities in East Greenland in 1997

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In 1997, petroleum geological activities were continued in East Greenland in order to increase existing knowledge on the sedimentology and biostratigraphy of the Upper Permian – Mesozoic succession, and to better define and describe the petroleum systems of the basin. The activities form part of the multidisciplinary research project 'Resources of the sedimentary basins of North and East Greenland' initiated in 1995 with financial support from the Danish Research Councils, and were mostly continuations of pre- and post-doctoral research (Stemmerik *et al.* 1996, 1997). Some new activities were initiated during the 1997 season with financial support from Saga Petroleum a.s.a., Norway; they included an evaluation of the thermal effects and diagenetic changes resulting from Paleogene intrusions and a more detailed sedimentological study of the newly identified Jurassic succession of northern Hold with Hope (Stemmerik *et al.* 1997). Five teams worked in the region in July and August 1997 studying the Upper Permian – Lower Triassic of Wegener Halvø, northern Scoresby Land and Traill Ø, the Middle Jurassic – Lower Cretaceous of Hold with Hope and the Cretaceous of Traill Ø and Geographical Society Ø (Fig. 1). The work was logistically integrated with the Survey's other mapping activities in the region (see Henriksen 1998, this volume).

Upper Permian – Lower Triassic of Wegener Halvø

The study of the Upper Permian Foldvik Creek Group and the Lower Triassic Wordie Creek Formation of Wegener Halvø (Fig. 1) focused on the interplay between tectonic movements and sedimentation in the latest Permian to earliest Triassic. Facies mapping of the Upper Permian Foldvik Creek Group revealed a more complex pattern than suggested by Stemmerik (1979) and Stemmerik *et al.* (1989, 1993). The original model was a simple carbonate platform to shale basin transition with the shallow water facies distributed along the south-eastern side of the peninsula along Nathorst Fjord and the deeper water facies along the north-western, Fleming Fjord side. This simple proximal–distal facies distribution suggested deposition on a north-westward tilted fault block.

However, more detailed mapping shows that the peninsula is divided into two separate, north-westward tilted fault blocks. Thick shallow water carbonate successions of the Wegener Halvø Formation are located over the crests of the two fault blocks, respectively, along the Nathorst Fjord and in a NE–SW trend across the central part of the peninsula. The carbonates thin rapidly towards the north-west and thick successions of Ravnefjeld Formation shales are found in local subbasins. The two fault blocks continued to be important basin controlling structures also during the latest stages of the Permian where siliciclastic sediments dominated the basin fill. Shallow water sandy facies accumulated mainly over the fault crests whereas distal, shale-dominated facies were deposited in the deeper parts.

The Wegener Halvø area was uplifted in latest Permian or earliest Triassic times and up to *c.* 50 m deep and *c.* 550 m wide channels were eroded into the Permian strata. The channels are filled with a mixture of large blocks of Permian limestone and siliciclastic material. Sedimentation resumed during the Early Triassic (Griesbachian), and facies mapping of the Wordie Creek Formation shows that sedimentation was controlled by the same structural lineaments as influenced the Permian sedimentation. The thinnest and most proximal part of the Wordie Creek Formation is found towards the east-south-east on the relatively uplifted parts of the hanging wall. There, the formation is dominated by shoreface sandstones and coastal plain mudstones with evidence of periodic subaerial exposure. The formation becomes thicker (up to *c.* 380 m) and more fine grained towards the north-west, where it is dominated by offshore shales and turbidites.

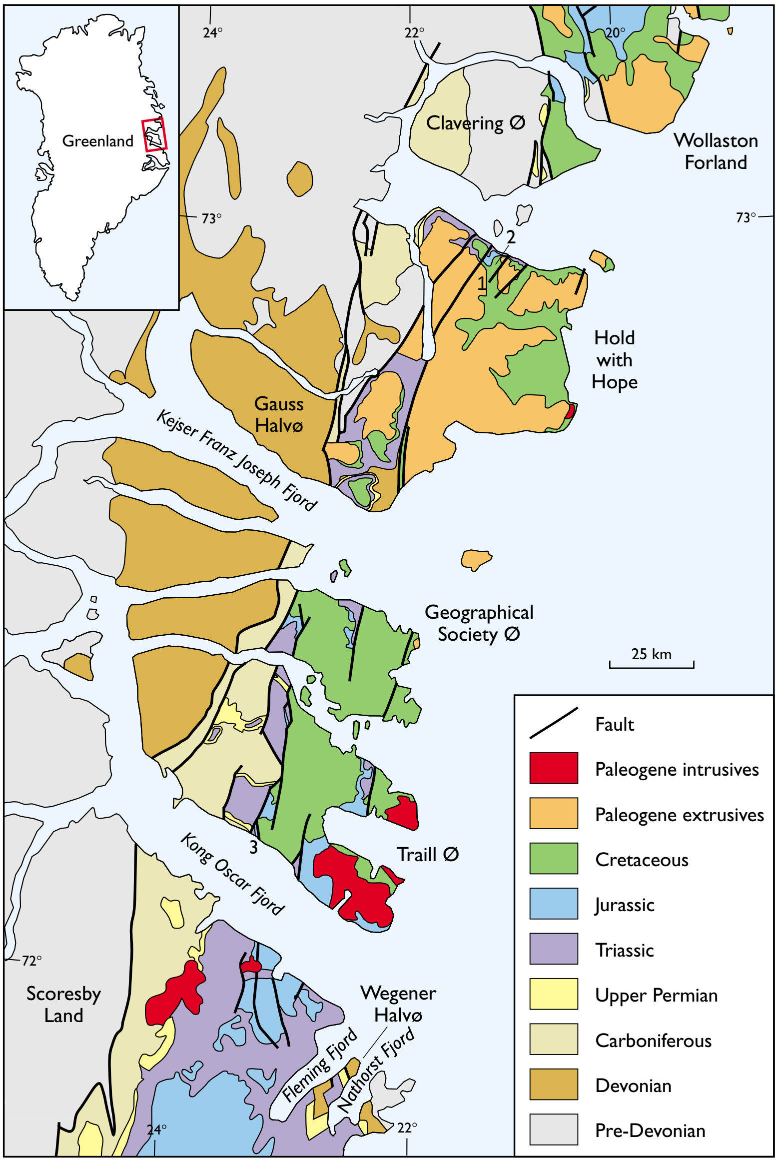


Fig. 1. Simplified geological map of part of East Greenland showing the distribution of Late Palaeozoic – Mesozoic sediments and Paleogene volcanic rocks. Numbers refer to localities mentioned in the text: 1, Gulelv; 2, Steensby Bjerg; 3, Svinhufvud Bjerge. Modified from Koch & Haller (1971).

In the offshore succession a network of incised valleys can be traced with drainage towards the west and north-west. This contrasts with earlier interpretations that stated valley directions were towards the south-west (Birkenmajer 1977). The valley fills consist of conglomerates and sandstones deposited mainly as sandy high density turbidites (Fig. 2).

One incised valley has been traced laterally and shows a change in valley width from *c.* 100 m up-dip to *c.* 565 m down-dip. This, in combination with a more gentle slope, resulted in deposition of a turbidite delta with prograding clinoforms of pebbly sandstones. The turbidite delta is 22 m thick and most likely thickens distally outside the outcrop area at the end of the slope. Deposition of the clastic turbidite system was controlled mainly by active faulting and an increase in sediment supply from the east. The fault activity induced a higher dip of the hanging-wall slope and exposure of the hanging-wall crest leading to erosion of the underlying Permian and older sediments.

The prograding turbidite deltas at the end of the hanging-wall dip slope form an important and hitherto poorly recognised reservoir analogue in the Lower Triassic succession. The turbidite deltas are composed

Fig. 2. Incised valley in the proximal reaches of the turbidite system in Wegener Halvø. The lower white bluff 30 m high consists of carbonate build-ups of the Upper Permian Wegener Halvø Formation (WHF). This is overlain by black shales of the Upper Permian Ravnefjeld Formation (RF). The shales are cut by an incised valley *c.* 250 m wide, filled with conglomerates and sandstones of the Triassic Wordie Creek Formation (WCF). Tents encircled for scale at top left.

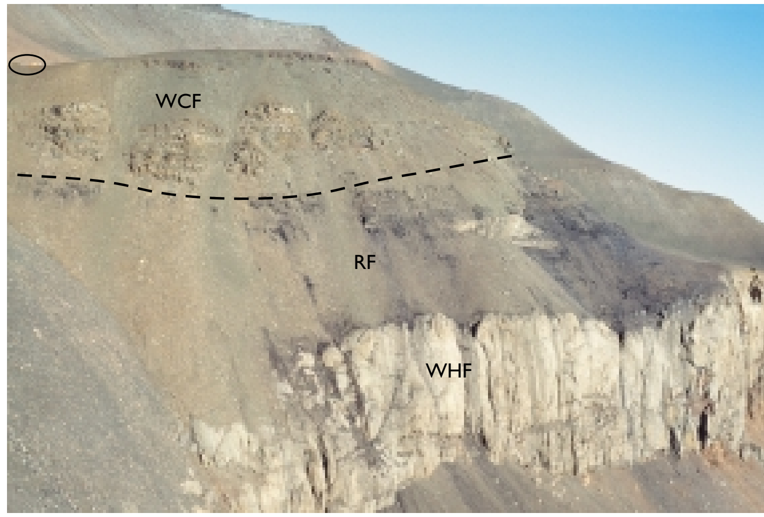
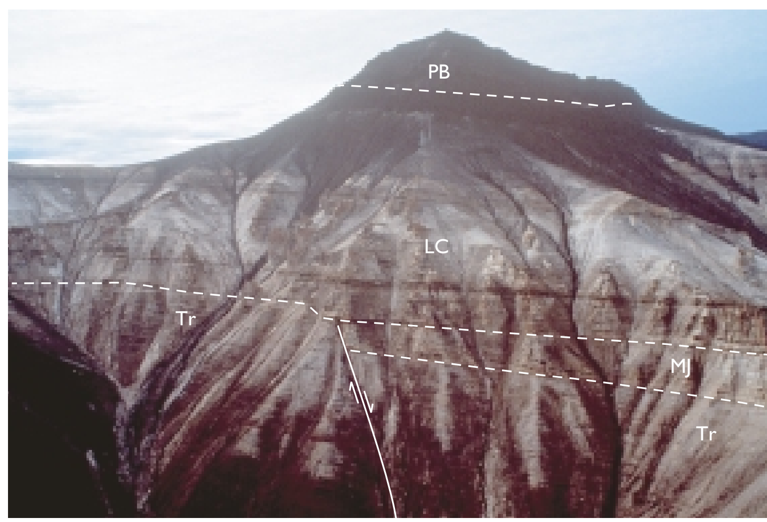


Fig. 3. The Triassic–Paleocene succession exposed at Steensby Bjerg in northern Hold with Hope (Fig. 1, loc. 2). The Triassic (Tr) and Middle Jurassic (MJ) sediments dip towards the south-west and are unconformably overlain by Lower Cretaceous (LC) sediments. Note the pre-Cretaceous normal fault which offsets the Triassic and Jurassic sediments. The exposure shown is *c.* 200 m high and topped by Paleocene basalts (PB). View towards the south.



of well-sorted sand encased in offshore shales acting as seal and cover large areas compared to the more stringer-like feeding channels found to the east.

Middle Jurassic – Lower Cretaceous of Hold with Hope

A coarse-grained sandstone succession was mapped in northern Hold with Hope in the summer of 1996 and dated to be of Middle Jurassic – Lower Cretaceous age (Stemmerik *et al.* 1997; Fig. 1). The Jurassic part of the succession was studied in more detail during the 1997 field season and new sections and studies of ammonite and dinoflagellate cyst stratigraphy show that the sediments also span the Late Jurassic (Oxfordian–Kimmeridgian).

The Jurassic sediments occur in small fault blocks dipping towards the west or south-west with the most complete succession preserved down-dip on the hanging-wall. Bedding planes within the Triassic and Jurassic successions seem to be parallel whereas they form an angular unconformity to the overlying Cretaceous succession (Fig. 3). This and the presence of normal faults cutting the Triassic and Jurassic succession, but stopping at the base of the Cretaceous, indicate that block rotation took place in post-Kimmeridgian but pre-Early Cretaceous time (Fig. 3).

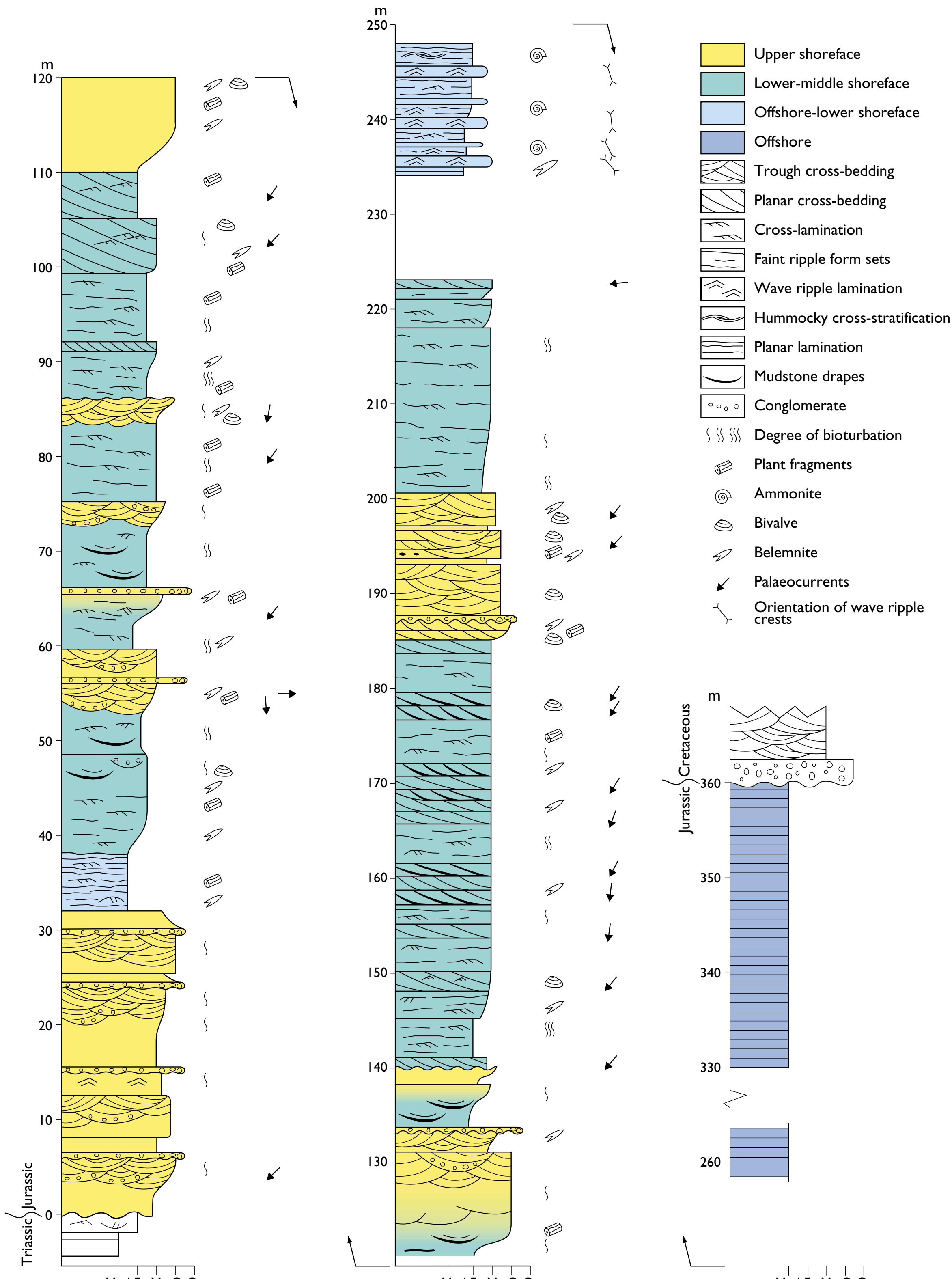


Fig. 4. Sedimentary section of the Middle–Upper Jurassic succession at Gulelv in northern Hold with Hope (Fig. 1, loc. 1). See text (opposite) for full explanation:

The thickest and most complete Jurassic succession, *c.* 360 m thick, is exposed in a fault block that dips *c.* 15° towards the south-south-west along the river Gulelv (Figs 1, 4). At this locality the basal *c.* 30 m of the succession consists of pebbly, medium- to coarse-grained quartz-dominated shoreface sandstones. The sandstones are trough cross-bedded or structureless and form coarsening-upward units, 6–8 m thick topped by a strongly bioturbated, pebbly sandstone lag.

A characteristic silty to very fine-grained, lower shoreface sandstone occurs 30–40 m above the base (Fig. 4). It is horizontally laminated, structureless or contains thin, subtle wave or current cross-laminated sandstones with thin organic-rich mudstone drapes. Coalified wood and belemnites are abundant and a single ammonite of Early Callovian age (P. Alsen, personal communication 1997) was found near the base.

The 40–250 m interval of the succession (Fig. 4) consists mainly of lower to middle shoreface wave- and current-rippled heteroliths and cross-bedded fine- to medium-grained sandstones with foresets separated by mud drapes or reactivation surfaces. Locally these deposits coarsen upwards into upper shoreface trough cross-bedded, coarse-grained sandstones showing palaeocurrents towards the south to south-west (Fig. 4). Belemnites and bivalves are common, and in the heteroliths silicified and coalified wood fragments, up to 1 m long, together with impressions of leaves are abundant. In places the heteroliths are strongly bioturbated. Ammonites of the Upper Oxfordian Glosense Zone (J.H. Callomon & P. Alsen, personal communications 1997) occur around the 240 m level.

The upper part of the succession consists of structureless or poorly exposed laminated offshore mudstones, and the thickness estimates are based mainly on simple geometrical calculations. The Jurassic succession on Hold with Hope closely resembles the Upper Bathonian – Kimmeridgian early syn-rift succession of the Wollaston Forland basin further to the north (Maync 1947; Surlyk 1977; Alsgaard *et al.* in press).

The overlying Lower Cretaceous sediments rest with an angular unconformity on the Jurassic. They consist of a conglomerate, locally up to 6 m thick, overlain by a thick deltaic and shallow marine sandstone succession, up to 150 m thick. These sandstones are trough cross-bedded, medium- to coarse-grained sandstones deposited as Gilbert-type deltaic units separated by marine flooding surfaces (see sedimentary section in Stemmerik *et al.* 1997). The sandstones are capped by mudstones of late Early Cretaceous age.

Diagenetic studies

Diagenetic studies were initially focused on the Middle Jurassic succession on Traill Ø and Geographical Society Ø, which forms a well-exposed analogue for reservoirs in the Norwegian offshore areas. The preliminary results of this study are outlined below. They indicate that the diagenesis is locally greatly influenced by the adjacent Paleogene intrusions, and therefore a new project was initiated during the 1997 field season to investigate more closely the thermal effects of Paleogene sills and dykes on diagenesis of Carboniferous to Cretaceous sediments. Published studies from other basins have mainly focused on the thermal effect on organic rich shales and have documented that the influenced zone roughly corresponds to the thickness of the intrusion (George 1992; Esposito & Whitney 1995). In order to investigate the diagenetic alteration of coarse-grained sediments, sandstones were collected with increasing spacing from the contact-metamorphic zone near the intrusion to a distance of two to three times the thickness of the intrusion. Reference samples of unaffected sediments were collected further away.

Coarse-grained sediments in contact with intrusions were found to be more resistant to weathering and often crop out in the terrain. The ability to resist weathering is due to a temperature-related cementation in the contact-metamorphic zone near the intrusion. This contact-metamorphic closing of the sandstone reservoirs near the intrusions could act as seals or barriers for fluid transfers in the reservoirs.

The diagenetic history of Middle Jurassic sandstones was investigated in samples from a 500 m thick succession at Svinhufvud Bjerge on the south coast of Traill Ø (Fig. 1, locality 3; Stemmerik *et al.* 1997). The lower part the succession is intruded by a 30–40 m thick Paleogene sill and it is cut diagonally by a 15 m thick dyke. The sandstones consist of quartz with minor feldspar, rock fragments, mica, clay matrix and traces of heavy minerals and are mostly quartz arenites and subarkoses *sensu* Folk (1968). However, most of the secondary porosity is derived from dissolution of feldspars and the pre-diagenetic composition of the sandstones was probably closer to subarkoses.

The main authigenic phases in the sandstones comprise quartz cement, carbonate cement, kaolinite and illite, while chlorite, titaniferous oxides and pyrite are minor components. Authigenic quartz occurs as euhedral crystals overgrowing detrital grains (Fig. 5A). The quartz partly encloses kaolinite and illite crystals indicating that it is synchronous with or post-dates kaolin-

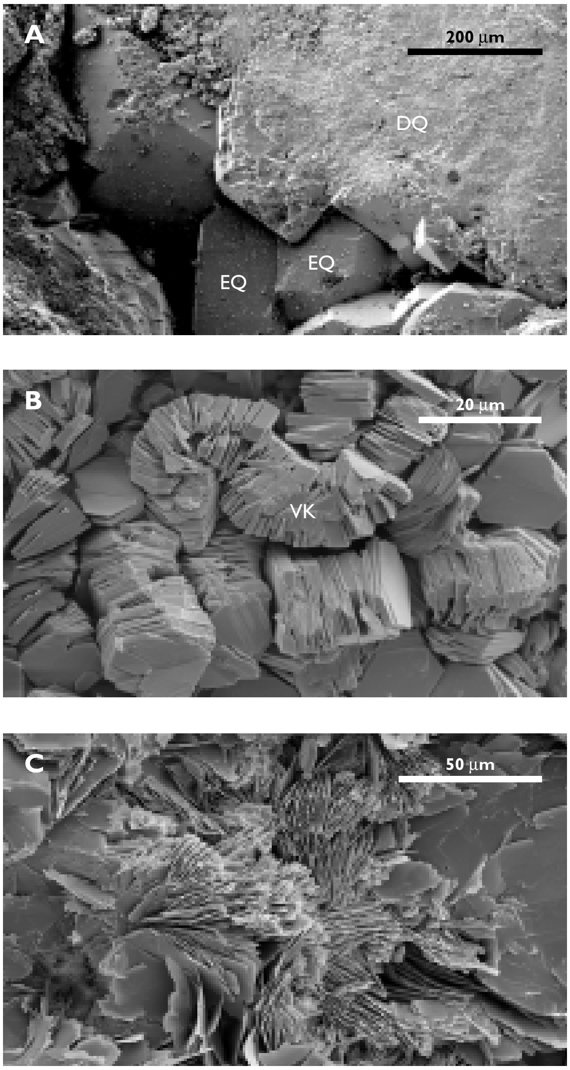


Fig. 5. Scanning electron photomicrograph of Middle Jurassic sandstones showing; **A**: large euhedral quartz overgrowths (EQ) developed on adjacent detrital quartz grains (DQ) resulting in nearly total occlusion of the porosity; **B**: vermiform kaolinite aggregate (VK) and booklets of kaolinite; **C**: large illite flakes in pore space. Photographs processed at: Acc. V; 10.0 kV; Spotsize: 5.0.

ite and illite. Kaolinite often occurs as pore-filling clusters of booklets or more rarely as vermiforms (Fig. 5B), whereas illite generally occurs as curving flakes with irregular edges (Fig. 5C), coating detrital grains and filling in pores. Illite is often seen densely packed in pore spaces (Fig. 5C) as well as large crystal flakes, up to *c.* 100 µm, scattered in the pore spaces or making up pseudomorphs. In a few isolated horizons carbonate cement consisting of calcite and dolomite-ankerite occludes pore space totally. Carbonate, however, most commonly occurs as isolated crystals of which some show dissolution and replacement by goethite.

Random vitrinite reflectance (R_o) analyses, Total Organic Carbon (TOC, wt%) and Rock-Eval pyrolysis (T_{max}) determinations were performed on coal samples from coarse-grained fluvial and finer-grained floodplain-lacustrine sediments. Coal from the fluvial unit show R_o values of approximately 4% and non-detectable T_{max} values indicating a very high maturation level (post-mature). In contrast analyses of the coals from the floodplain-lacustrine unit indicate a much lower maturation stage with R_o values around 1.1% (a single sample shows 1.74%) and T_{max} values in the range from 449°C to 461°C (mature stage).

Along with the coals both the fluvial mudstones and sandstones seem affected by heat from the nearby intrusions and hydrothermal fluids. This is seen as traces of talc and pyrophyllite in the mudstones just beneath the post-mature coals indicating very low-grade metamorphism (Frey 1987) and the presence of large illite crystals and illitised pseudomorphs in the sandstones. The differences in maturation and authigenic minerals between the fluvial and the floodplain–lacustrine unit may be a function of grain size. The sandstones in the finer grained floodplain–lacustrine unit have, thus, been protected and isolated from direct influence of hydrothermal fluids induced from the intrusions.

Petroleum systems

The petroleum geology of the region has previously been treated in a number of Survey studies (e.g. Surlyk *et al.* 1986; Christiansen *et al.* 1992; Stemmerik *et al.* 1993). The new data gained from the current field work may be used to improve the understanding of the petroleum systems in East Greenland. The Upper Jurassic petroleum system is based on the petroleum generating potential of the marine shales of the Bernbjerg Formation (Fig. 6). The formation is well known from the southern part of the area on Traill Ø and has previously been suggested to occur in the subsurface of eastern Hold with Hope (Stemmerik *et al.* 1993). In the 1997 field season Upper Jurassic shales with a fair source potential (TOC around 2%) were mapped out for the first time in the area around Gulelv on Hold with Hope.

The petroleum system has previously included Middle Jurassic sandstones of the Pelion Formation as the main reservoir unit. The work in the Hold with Hope area,

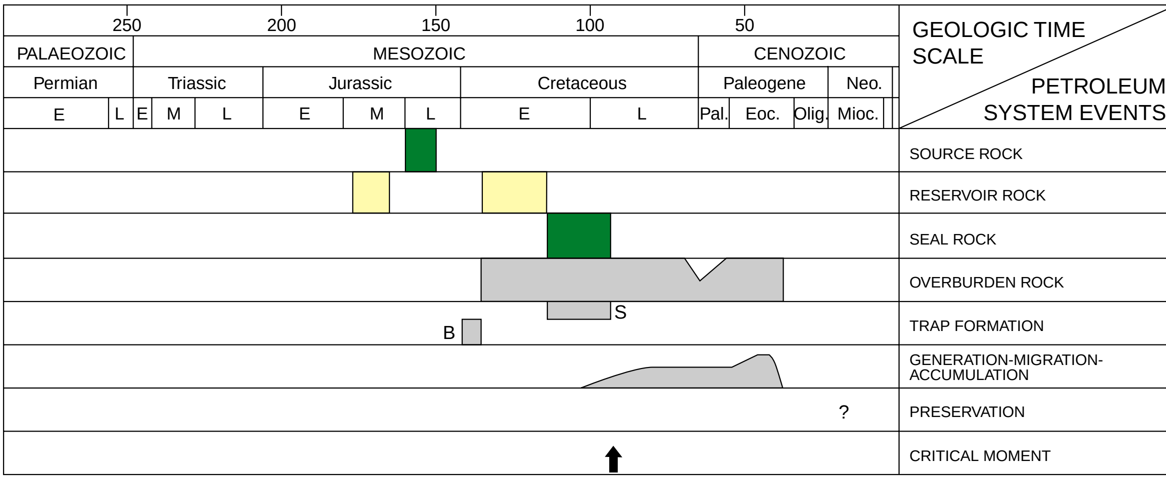


Fig. 6. Preliminary interpretation of the Upper Jurassic (Bernbjerg Formation) petroleum system in the northern part of the region following the terminology of Magoon & Dow (1994). Letters designate trap forming process, B; block faulting and rotation; S: stratigraphic pinch-out. The interpretation is based on data in Upton *et al.* (1980), Christiansen *et al.* (1992), Stemmerik *et al.* (1993), Price & Whitham (1997) and the present field work.

however, shows that the initial thickness of this reservoir unit may be highly reduced or it may be totally absent due to block rotation and erosion in the Late Jurassic – earliest Cretaceous (Fig. 3). Thick Lower Cretaceous sandstones exposed in Hold with Hope may, however, form an excellent reservoir unit, which has not been considered in previous studies. The fluvial, deltaic and shallow marine nature of these sandstones may suggest that coarse-grained sediments have been deposited in basins further east or south-east on the East Greenland shelf.

The new data also influence the previously suggested play model for the Middle Jurassic reservoir sandstones based on structural traps (Stemmerik *et al.* 1993; Price & Whitham 1997). The down-faulted Jurassic sandstones on Hold with Hope are thus not sealed by onlapping Cretaceous mudstones as seen on Traill Ø and Geographical Society Ø and a potential hydrocarbon play will depend on the presence of stratigraphic traps in the Lower Cretaceous. The succession in Hold with Hope probably formed in a platform or terrace area with an episodic depositional history and thus differs from the better known basinal areas further south.

Little is presently known on the possible generation, migration and accumulation history of hydrocarbons in the region, but ongoing studies aim at a better understanding of these processes. Thermal effects of Paleogene intrusions are, thus, important in the maturation history and have locally led to over-maturation of the otherwise immature source rock (Stemmerik *et al.* 1993).

Future work

The appraisal of petroleum systems helps to identify areas where further research is needed. In the 1998 field season petroleum geological research will focus on the Upper Cretaceous – Lower Paleocene (pre-basaltic) succession as an analogue to offshore northern North Atlantic basins. Geological mapping of the Upper Palaeozoic – Mesozoic succession is planned to take place on Clavering Ø, Gauss Halvø, Geographical Society Ø and the easternmost parts of Traill Ø. The study of the thermal effects of Paleogene dykes and sills will continue with field work on Traill Ø and Geographical Society Ø. The sandstones will be subjected to petrographic investigations to reveal the diagenetic changes and their effect on reservoir quality. Further investigations on both mudstones and sandstones will show whether mineral assemblages can be related to the distance from the intrusion and thereby determine the width of the reaction zone and the thermal regime of the intrusion.

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