DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2012/33

The geology of Store Koldewey, North-East Greenland, 76°–76.45°N. Implications for offshore petroleum geology

Executive Report
Enclosed DVD with Store Koldewey GIS Project

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

G E U S

This Store Koldewey research project contributes with a significant increase in the understanding of the geology of the Store Koldewey island previously only studied by a few parties during the last century (Fig. 1). The first geological data from the island wre reported by the “Danmark Ekspeditionen” 1906–1908. This expedition made landfall in North-East Greenland first at Store Koldewey and found a winter harbour for the ship “Danmark” just north of Store Koldewey - now a weather station known as Danmarkshavn. Fieldwork by dog sledge on the winter sea ice by Hakon Jarner provided the first collections of rocks and fossils from the sedimentary areas on Store Koldewey which were studied by J.P.J. Ravn (1911). Lauge Koch (1929) published the first geological map of Store Koldewey and in the summer 1933, Eigil Nielsen collected rich fossil faunas in the ravines along the east-coast of the island. From then on, the isolated island was barely visited by geologists until the late 1980es, when the Geological Survey of Greenland (now GEUS) re-mapped East Greenland from 72°N and northwards. L. Stemmerik and S. Piasecki (Stemmerik & Piasecki 1990; Piasecki *et al.* 2004) obtained 8 days of fieldwork during the mapping campaign and provided data for a new Store Koldewey map (GEUS 2007).

The Store Koldewey Project addresses the need for improving the understanding of basic geological data onshore in order to better interpret the large offshore basins on the North-East Greenland shelf with respect to future petroleum exploration. The sediment pockets on Store Koldewey are the northernmost of its kind and the closest outcrop of Mesozoic sediments to the offshore basins, especially the Danmarkshavn Basin (Fig. 2). The GEUS initiated project thus provides the best possible data set to aid the offshore exploration in its early phase.

Participants with extensive field experience in sedimentary basins in East Greenland formed three field teams and a drilling team. The teams spent 11 days on the logistically quite inaccessible island in August 2010 and brought back much new valuable data and observations, a large number of samples and approximately 110 m of core to be analysed in laboratories.

The comprehensive outcome of this project is reported in a Store Koldewey GIS product (DVD included in this report) to maximise and provide easy access to the output of data, figures, illustrations and reports for the recipients. The present report provides an overview of the results.

The concluded Store Koldewey study has broad attention to a number of issues that have significant bearings on the hydrocarbon potential of the region. The final section in this report is devoted to a discussion of future studies that may help resolve these issues and thus contribute to the understanding of the offshore petroleum potential.

Basement and structural development

Store Koldewey is situated in a basement province composed of Caledonian high-pressure metamorphic rocks formed at least from earliest Devonian through Early Carboniferous time. The Caledonian orogeny thus seems to have persisted significantly longer in this part of North-East Greenland than reported elsewhere along the North Atlantic margin (Fig. 3).

Overlying the basement, Jurassic and Lower Cretaceous sediment pockets constitute remnants of a once widely distributed sedimentary cover across Store Koldewey connected to the offshore basins. The preserved sedi-

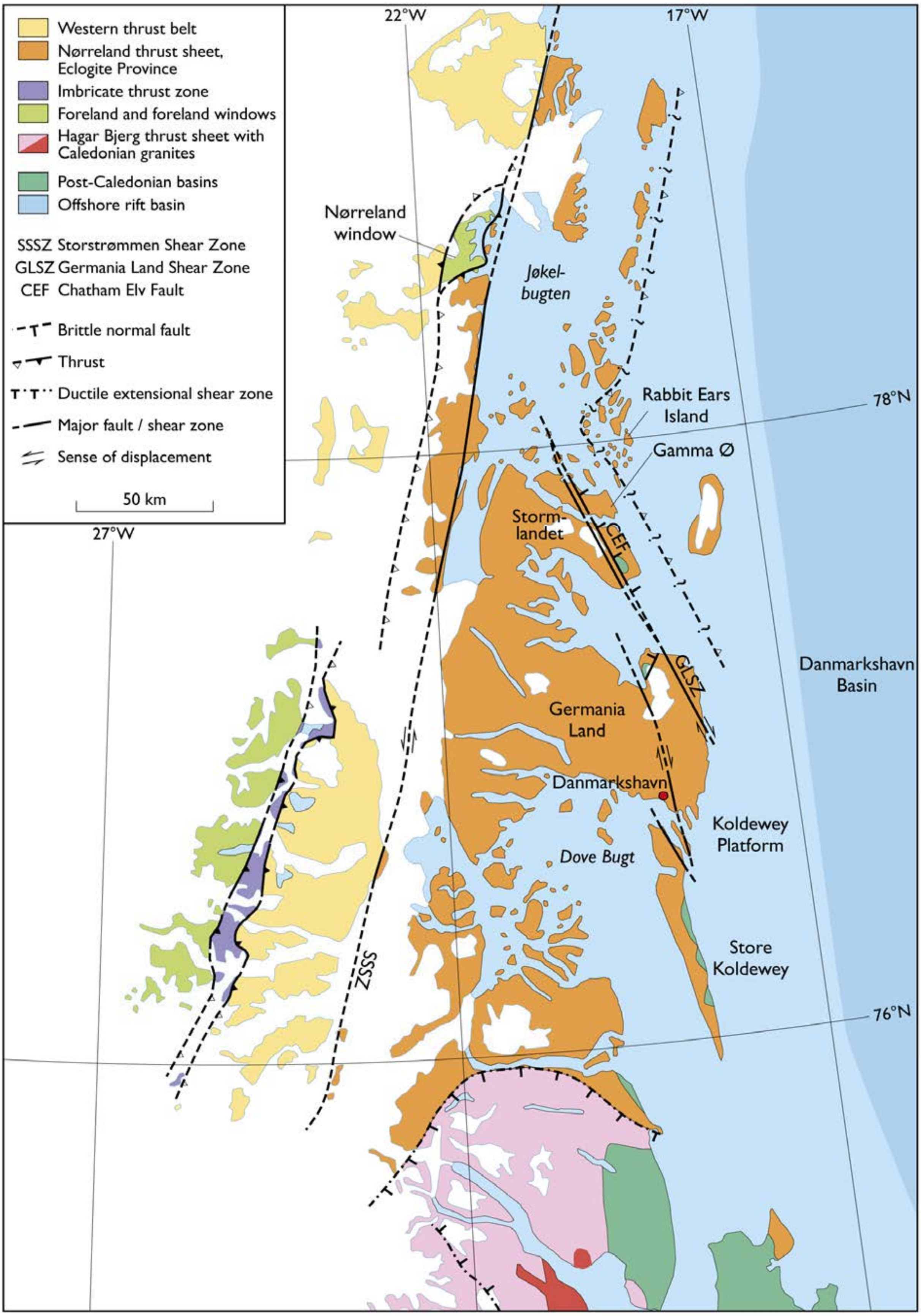

Fig. 1 *Geological outline of North-East Greenland. Modified after Henriksen and Higgins (2009).*

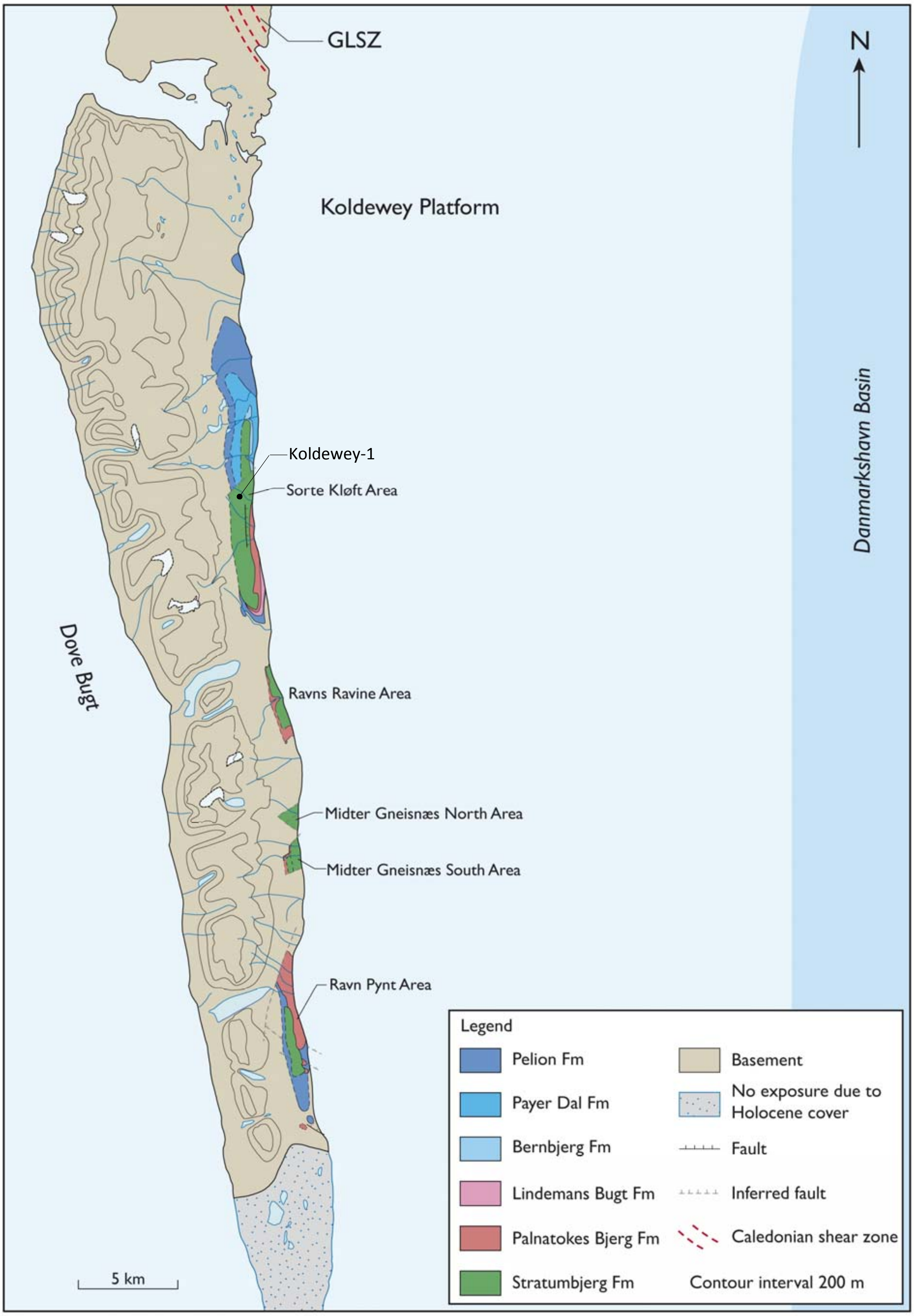

Fig. 2 *Revised geological map of Store Koldewey showing the four sediment areas treated in the text. The Koldewey Platform and Danmarkshavn Basin is indicated. GLSZ is the dextral (Devonian – Carboniferous) Germania Land Shear Zone.*

ments are deformed by faulting and significant post-depositional tilting. Ryazanian and Valanginian coarse grained sediments unconformably cap the Jurassic and are down-faulted towards the basement and thus document an Early Cretaceous rift-phase. Barremian and latter fault activity is evident by the depositional style and 10°–30° eastwards tilt of strata.

Recognition of the Mesozoic fault trend is generally obscured by the limited nature of outcrops. Northeast–southwest, northwest–southeast and north–south fault trends are tentatively interpreted in the area in places suggesting a corrugated fault outline. However, the corrugated fault shape may have been affected by syn-rift footwall incision and degradation. The strong depositional tilt observed on Store Koldewey may suggest the presence of a larger extensional fault situated slightly west of the outcropping sediment pockets.

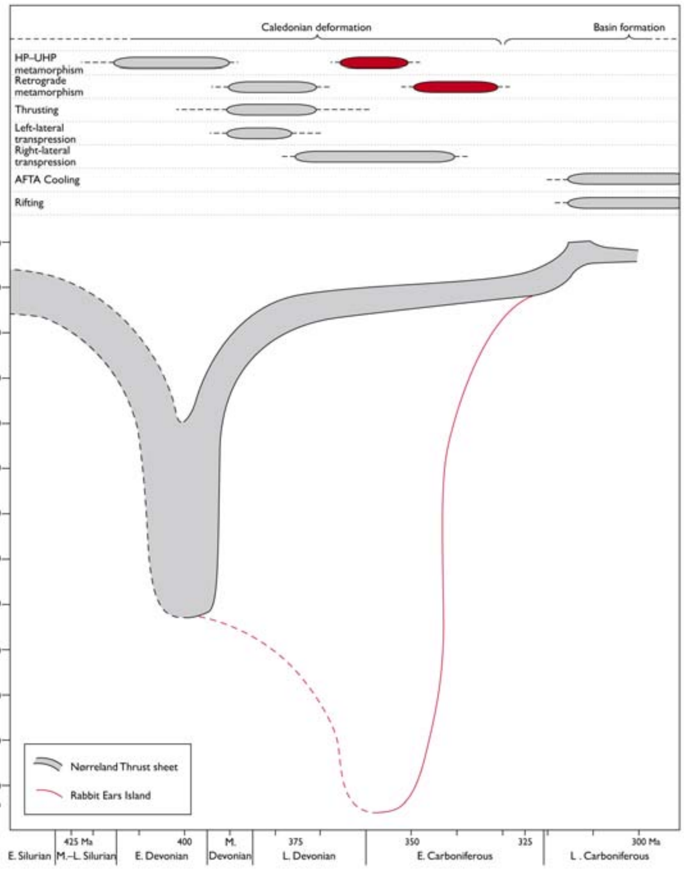

Fig. 3 *Palaeozoic Exhumation/cooling history of the basement in the Store Koldewey region. The grey and red uplift curves reflect the orogenic activities lasting throughout Devonian time and continuing long into the Carboniferous. The grey and red bars above denote the contemporary tectonic activities affecting the region.*

Lithostratigraphy

As part of the Store Koldewey study a revised lithostratigraphic scheme is erected for the Jurassic, Cretaceous and Pleistocene of the island (Table 1). The Mesozoic part of the scheme largely adopts the Jurassic and Cretaceous stratigraphy studied in greater detail farther south in North-East Greenland. The lithostratigraphic results are presented here and include five Middle to Upper Jurassic formations: the Bathonian fluvial Bastians Dal Formation, the Callovian terrestrial Muslingebjerg Formation, the Bathonian – Callovian shallow marine Pelion Formation, the Oxfordian shallow marine Payer Dal Formation and the Kimmeridgian – Volgian offshore Bernbjerg Formation. The former two formations have not previously been recorded from Store Koldewey. The Cretaceous succession is subdivided into four formations: Ryazanian submarine slope deposits of the Lindemans Bugt Formation, Valanginian – lower Upper Barremian rift related submarine fan and gully fill of the

Toula, 1874 Ravn 1911 Koch 1929	Stemmerik & Piasecki 1990	Piasecki *et al.* 2004 Bennike *et al.* 2010 Formation	Member	This study Group	Formation	Member	Chronostratigraphy
		Store Koldewey			Store Koldewey		Pliocene–Pleistocene
					Stratumbjerg		Up. Barremian – Aptian
						Sorte Kløft	Up. Barremian
							Up. Barremian
				Wollas-ton For-land	Palnatokes Bjerg	Ravn Pynt	Up. Valanginian – Lo. Barremian
Kap Ham-burg Fm						Midter Gneisnæs	Up Ryazanian? –Lo. Valanginian
					Lindemans Bugt		Lo. – Up. Ryazanian
		Bernbjerg		Hall Bredning	Bernbjerg		Up. Kimmeridgian – Lo. Volgian
Kløft I Fm		Payerdal		Varde-kløft	Payer Dal		Oxfordian – Kimmeridgian
Trækpas Fm	Trækpas Fm	Pelion	Spath Plateau		Pelion	Spath Pla-teau	Callovian
							Bathonian
					Muslingebjerg		Callovian
					Bastians Dal		Bathonian

Table 1 *Proposed lithostratigraphic chart of Store Koldewey compared with previous studies.*

Palnatokes Bjerg Formation, Upper Barremian – Aptian submarine slope deposits of the Stratumbjerg Formation including the late rift-slope-gully deposits of the Sorte Kløft Member. Two new members are erected in the Palnatokes Bjerg Formation: the high energy coarse-grained Midter Gneisnæs Member and the low energy fine-grained Ravn Pynt Member.

Geological map

A revised geological map focussing on the Mesozoic succession on Store Koldewey was produced as part of the study (Fig. 2). The Pleistocene – Holocene cover is not indicated apart from farthest to the south on the island where older geology is completely concealed underneath young sediments. The map constitutes a significant improvement compared with existing maps and will aid future field work on Store Koldewey.

Four main sedimentary areas are present on Store Koldewey. Described from south to north these include:

1) The Ravn Pynt Area that to the south shows a Middle Jurassic basement onlap and prominent channel shaped erosional unconformities between Middle Jurassic Pelion Formation and lowermost Cretaceous Palnatokes Bjerg Formation. A marked drowning surface occurs in the lower part of the Lower Cretaceous Stratumbjerg Formation.

2) The Midter Gneisnæs Area that is characterised by a syn-sedimentary basement fault against the coarse-grained Lower Cretaceous Palnatokes Bjerg Formation. It is not known if pre-Cretaceous deposits are present in the hanging wall block below this formation. At the top of the formation there is an erosional unconformity covering Hauterivian – Lower Barremian. The Upper Barremian Stratumbjerg Formation is represented by a sandstone unit (Sorte Kløft Member, 110 m thick) overlain by mudstones.

3) The Ravns Ravine Area that is characterised by Lower Cretaceous basement onlap with strata dipping towards the east. The dominantly fine-grained Palnatokes Bjerg Formation has a basal fossil-rich lag, and the

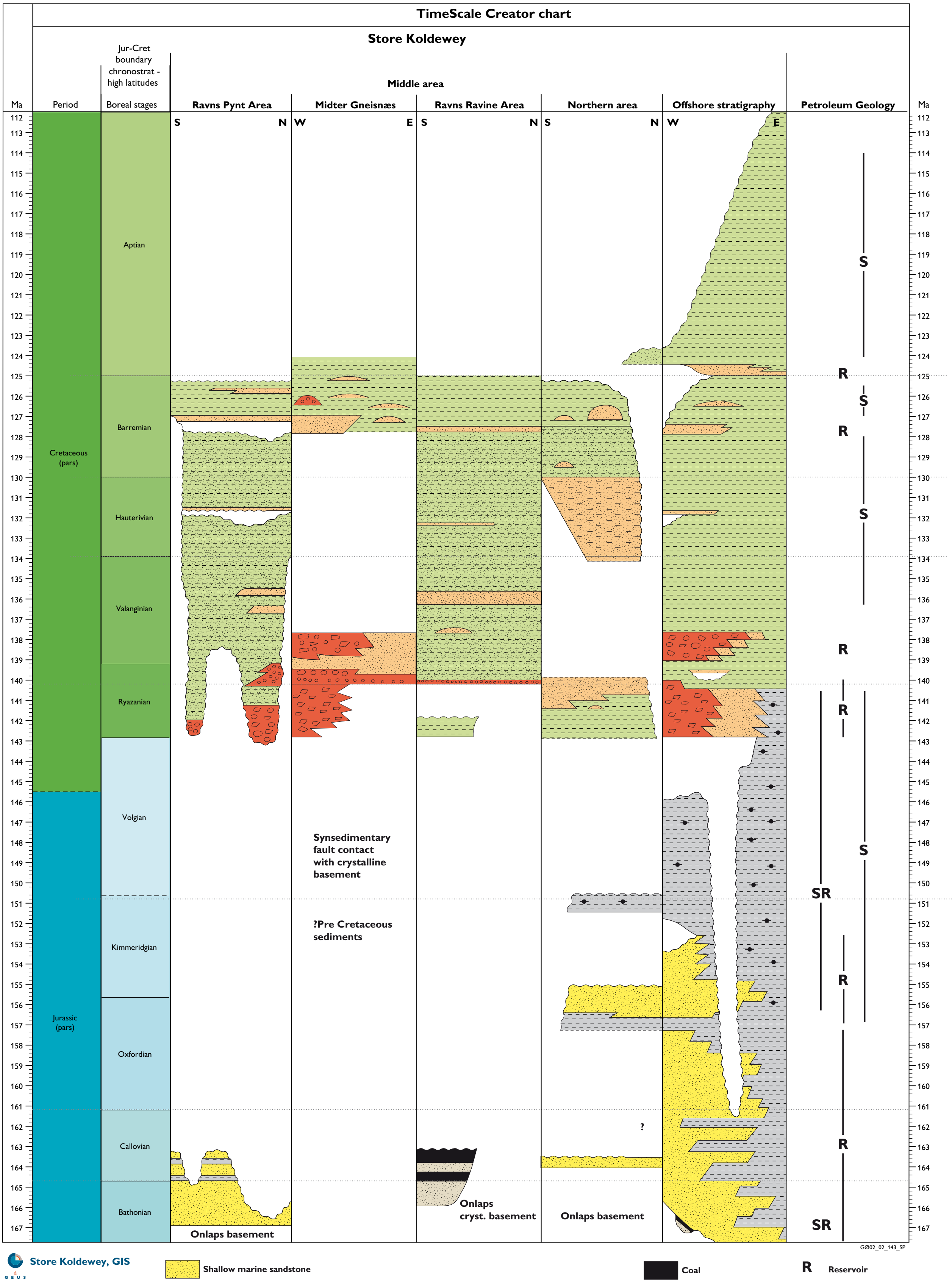

Fig. 4 *Composite Mesozoic stratigraphic outline of the four discrete sediment covered areas juxtaposed towards a conceptual outline of the offshore coeval stratigraphy. Potential source rock, reservoir, and seal intervals are noted to the right.*

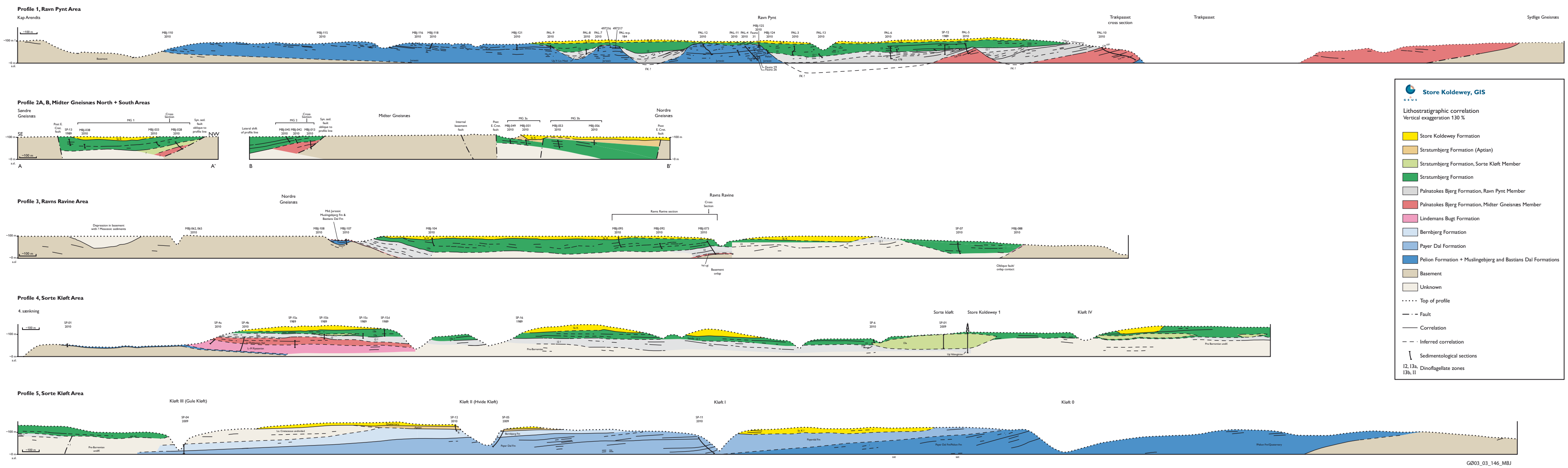

Fig. 5 *Simplified north to south trending cross sections across the sedimentary pockets on Store Koldewey indicating the stratigraphic and structural outline of the areas. A high-resolution edition of the figure is present in the GIS compilation.*

formation is conformably overlain by the Stratumbjerg Formation. The Middle Jurassic Bastians Dal, and Muslingebjerg Formations constituted by coarse grained channel sand and coals respectively are exposed in the southern part of the area.

4) The Sorte Kløft Area that shows a Middle Jurassic basement onlap of the Pelion Formation. In the south the formation is erosionally overlain by Ryazanian fine-grained deposits of the Lindemans Bugt Formation followed by a fine-grained Palnatokes Bjerg Formation and Stratumbjerg Formation. In the north, the Upper Oxfordian Payer Dal Formation onlaps the basement and is conformably overlain by the Bernbjerg Formation. In turn, the latter is erosionally overlain by Stratumbjerg Formation of Aptian age.

In all areas the upper boundary of the Mesozoic sediments is an angular unconformity widespreadly draped by Lower Pleistocene deposits (not shown on map).

Sedimentological development

The base of the sedimentary succession on Store Koldewey is formed by the up to ~70 m thick Middle Jurassic (Bathonian – Lower Callovian) Pelion Formation that onlaps the basement and elsewhere is seen in fault contact with the basement (Figs 4, 5). Sedimentological data suggest that these strata were deposited in various wave- and tide-influenced shallow marine and terrestrial depositional environments. The sedimentary facies of the Bathonian deposits point to relatively high-energy, wave-dominated shoreface and inner shelf environments in the Ravn Pynt Area. The Lower Callovian depositional environments are interpreted to include tidally-influenced delta, barrier island and tidal inlet complexes (Fig. 6). In the Ravns Ravine Area, coal-bearing fluvial channels were formed at this time. Both the Bathonian and the Callovian deposits were probably influenced by a south flowing alongshore current system.

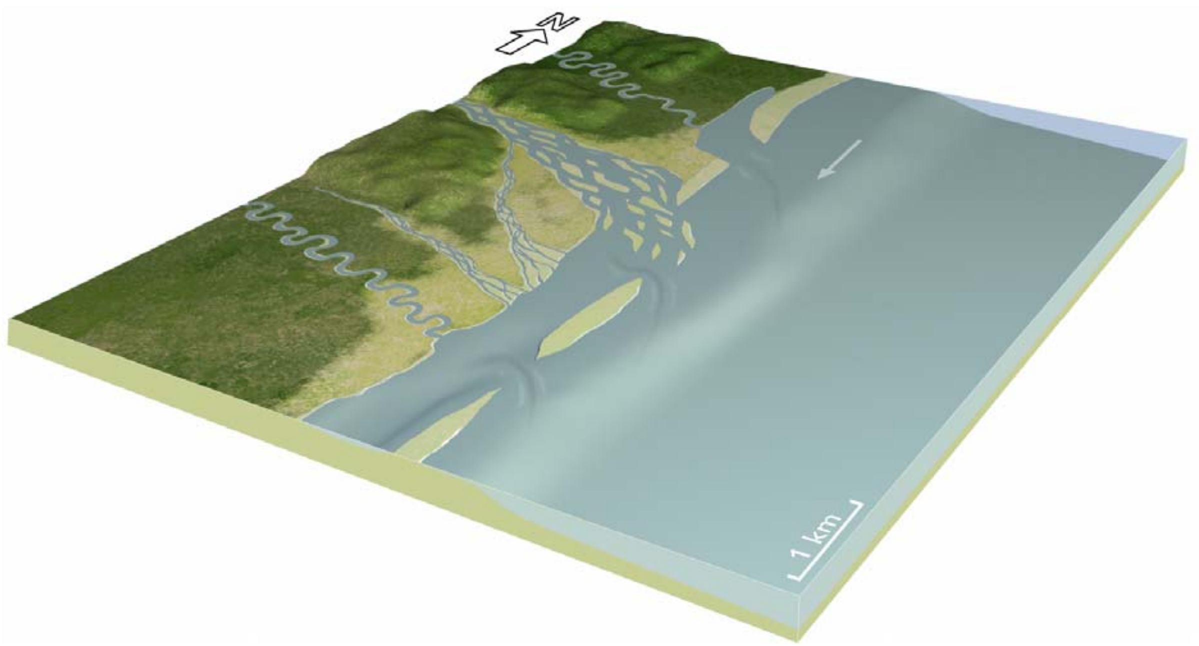

Fig. 6 *Depositional model summarizing the interpreted Lower Callovian depositional setting in Store Koldewey. The model shows fluvial channels, alluvial/delta plain, tidally-influenced delta, tidal-inlets, barrier islands and lagoons distributed along a generally wave-dominated coastline. The along shore current direction was towards the south.*

The Upper Jurassic succession comprises parallel bedded sand (40–70 m thick) superposed by grey-black, monotonous mud (40–50m thick); both units contains a scattered marine fauna. The Upper Oxfordian – lowermost Kimmeridgian sand is deposited in an inner shelf environment and the uppermost Kimmeridgian – lowermost Volgian mudshales is deposited in a slightly deeper environment on the shelf. The lithological transition is sharp and represents a significant hiatus. The organic content of the mud is dominated by terrestrial material reflecting a significant input sourced from nearby land and that the area was only partly subject to the protracted North Atlantic anoxia. The facies resemble that of other Upper Jurassic East Greenland localities along basin margins towards the palaeo-coast (west). Correspondingly, much more oil-prone shales are recorded farther basinwards.

The Middle Jurassic deposits are commonly erosionally overlain by the ?Upper Ryazanian/Lower Valanginian – Lower Barremian Palnatokes Bjerg Formation. The deposition occurred in variably developed slope apron-related channels/gullies, which were distributed along a north – south oriented uplifted basement ridge (Fig. 7). The slope channel or gully complexes show variable dimensions and phases of offset truncation and fill. The individual channels appear to have been 200 m – 1.5 km wide. The combined thickness of the sediments infilling individual channels may signify a channel depth of roughly 50 – 100 m. The basal incised valley confining the channel complexes is poorly exposed, but may be as wide as ~5 km. Overall; the slope apron complex forms a generally upward fining succession from conglomerate- to mudstone-dominated deposits reflecting a general deepening trend in the depositional system.

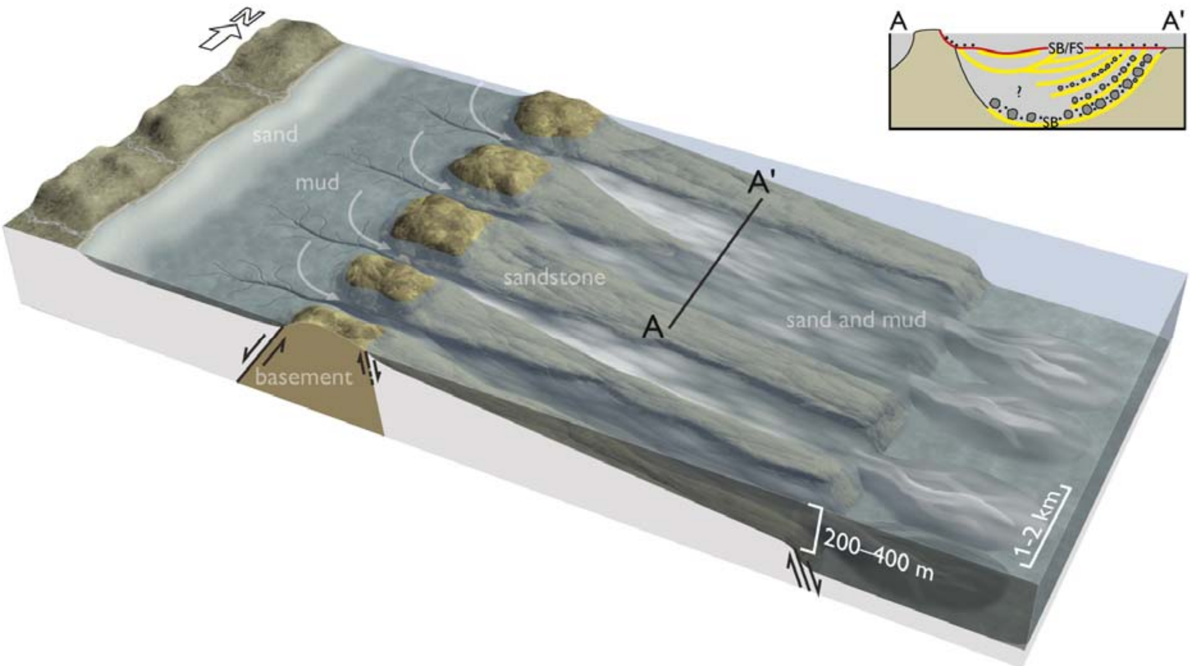

Fig. 7 *Depositional model showing a possible Late Valanginian – Early Barremian depositional scenario in southern Store Koldewey. The model shows a drowning slope apron system that contains a series of slope channels/gullies distributed along an uplifted basement ridge. The tectonic model as well as the presence of shallow shelf in the current Dove Bugt area, are hypothetic.*

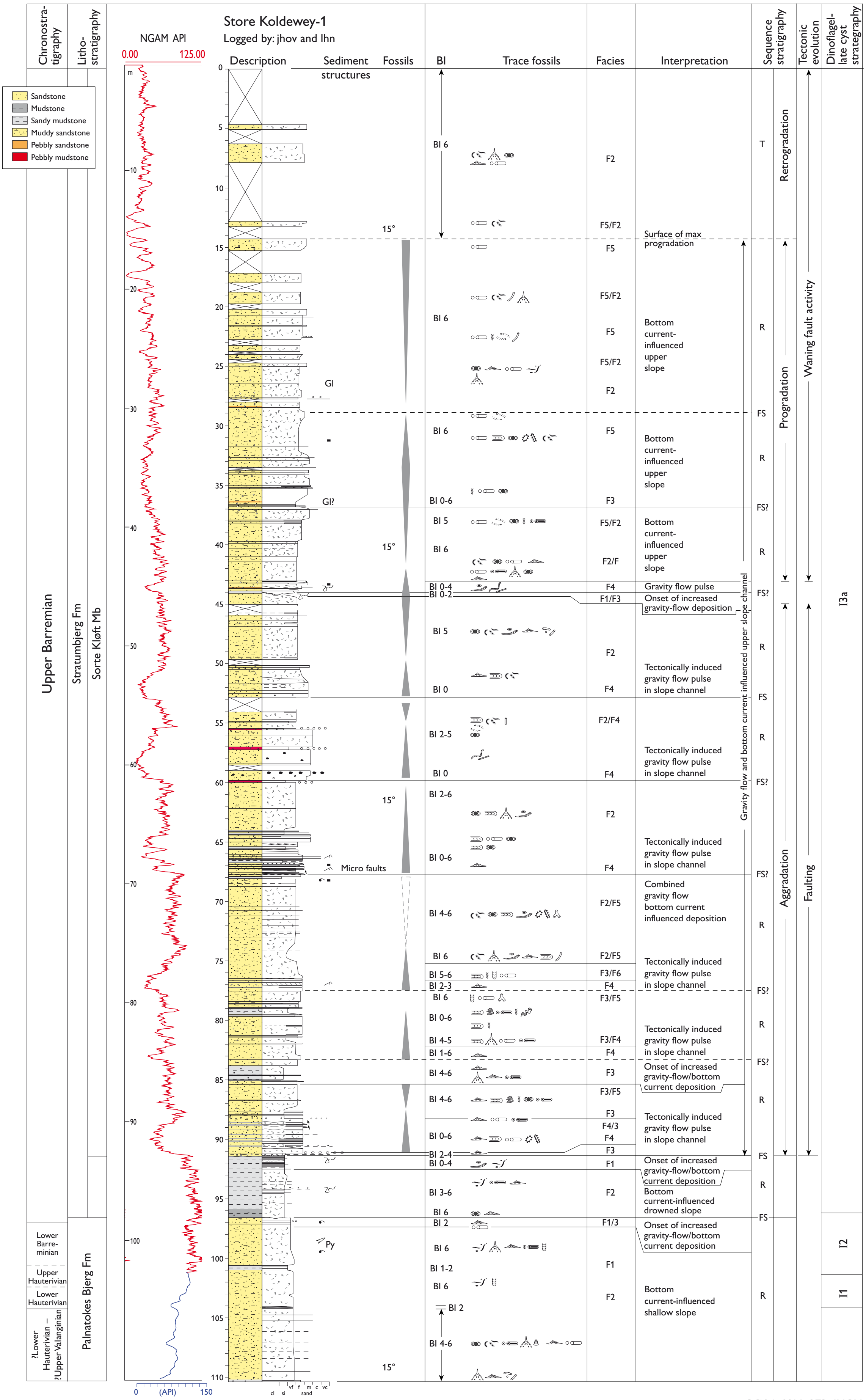

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Fig. 8 *Sedimentological log of the Store Koldewey-1 well.*

The base of the Upper Barremian Stratumbjerg Formation (dinoflagellate zone I3A) record a temporal shift in depocenter from the southern to northern part of the island. In the north, a more than 90 m-thick, fine-to medium-grained sandstone unit interpreted as an upper slope channel was deposited (the Sorte Kløft Mb). Contemporaneous strata in the south are represented by hiatal conglomerates and *Glossifungites* Ichnofacies demarcated surfaces, which are interpreted to reflect sediment by-pass and a period of increased bottom current velocity. These deposits are further overlain by a ~70 m thick slope mudstone succession (dinoflagellate zone I3B).

Aptian, grey micaceous fine-grained sand form the youngest preserved Mesozoic deposits on the island. The distribution of the Aptian is limited and the thickness probably range from 6 – 8 m to a few tens of meters, although exposure quality rarely allows a precise thickness estimate. Where best exposed, the thin succession is monotonous and without sedimentary structures, indicating severe bioturbation and oxidation of the organic content. Marine deposition is confirmed by the content of abundant dinoflagellates and ammonites.

Thick (up to ca. 100 m) marine Lower Pleistocene deposits belonging to the Store Koldewey Formation unconformable overlie the basement and the Mesozoic succession. The Pleistocene is composed by grey micaceous fine-grained sand, locally with thin beds of coarse grained material or plant remains. The unit is strongly bioturbated and barely any sedimentary structures can be recognized. Scattered mollusks, very few foraminifers and some dinoflagellates suggest a marine origin of the succession.

Store Koldewey-1 well

The Store Koldewey-1 (GGU 517002) was drilled in the Sorte Kløft Area to a TD-depth of ca. 110 m with ca. 90% core retrieval of excellent quality (Fig. 2). The well transected 96.5 m of Upper Barremian upper slope channel, fine- to medium-grained sandstones assigned to the newly defined Sorte Kløft Member of the Stratumbjerg Formation (Fig. 8). The Koldewey-1 well floored in the deepest part of the Palnatokes Bjerg Formation after having penetrated 13.9 meters of mud- and sandstones belonging to the Upper Valanginian – Lower Barremian formation.

The core hole has a diameter of 56 mm and the obtained core has a diameter of 42 mm. Gamma and temperature logs were obtained. Logging results are incorporated in the GIS version. Wire line logging was suspended in the lower 17 meters of the core hole due to technical problems elaborated below. Instead, the lower 28.5 meters of the core was analysed in GEUS' laboratories using gamma ray and density scanners. Laboratory measurements were subsequently integrated with the wire line gamma log (Fig. 8).

The Store Koldewey-1 core hole was drilled using a Sandvik DE 130 drill rig and freshwater circulation with only salt added to prevent freezing of the core hole. Circulating drilling fluids thawed the permafrost surrounding the casing, and the poorly consolidated sandy sediments along the casing were washed out. This eventually caused the casing to loosen impeding further drilling. The Store Koldewey-1well was plugged and abandoned, and further drilling was suspended due to time constraints imposed by the tight logistic framework after a number of unsuccessful attempts to save the well hole.

Source rock potential

Total Carbon (TC)/Total Organic Carbon (TOC)/Total Sulphur (TS)/Rock-Eval screening pyrolysis data are available for a total of 263 samples from Store Koldewey. In addition, vitrinite reflectance (R_o) data from a total of 18 samples plus headspace gas composition data from 3 canned core-pieces are available. The samples range in age from the Bathonian to the Pleistocene and include outcrop samples as well as samples from the Store Koldewey-1 corehole and represent eight different formations.

Except for two loose block samples of peculiar resinite-rich coals of the Muslingebjerg Formation (Bathonian – Callovian) no samples qualify as potential petroleum source rocks. In particular, the lack of petroleum potential observed in the Bernbjerg (Kimmeridgian – Volgian) and Lindemans Bugt (Ryazanian) Formations is noteworthy. These units are known as rich, oil-prone petroleum source rocks elsewhere in North-East Greenland, but on Store Koldewey, they seem to be developed in a relatively shallow-water nearshore facies, in keeping with sedimentological evidence that suggests the presence of a Late Jurassic – Early Cretaceous coastline close to Store Koldewey. Due to the absence of petroleum potential in essentially all of the analysed samples, production of biological marker and stable carbon isotope data was considered futile.

Vitrinite reflectance data cover deposits varying in age from the Callovian to the Aptian. Two samples show marked suppression of vitrinite reflection, and a similar effect is suspected in two additional samples. Excluding these samples all units show essentially similar level of thermal maturity, corresponding to R_o close to 0.50%, irrespective of stratigraphic position.

Only one out of three canned core samples from the Store Koldewey-1 corehole showed the presence of notable proportions of hydrocarbons in the headspace gas. Based on the combined evidence from gas composition and stable isotopic signature (carbon and hydrogen), the hydrocarbons were identified as microbial gas, consisting of nearly pure methane.

Biostratigraphy

Aproximately 400 integrated micro- and macrofossil biostratigraphic analysis bring the understanding of the Mesozoic on Store Koldewey to a much higher level: the succession is demonstrated to be sedimentologically highly complex and differently developed in four structurally separated depositional areas.

The datings allow the recognition of lithostratigraphic units of which a number are new established for the Store Koldewey area. The distribution of the Middle Jurassic is extended throughout the sedimentary basin, whereas the Upper Jurassic is still restricted to the northern area. Marine Ryazanian and Valanginian is now demonstrated from south to north. The Hauterivian and Barremian is identified for the first time, but with Hauterivian restricted to the southern area, whereas the Barremian, previously thought to be Aptian, dominates the Cretaceous succession throughout the study area. The Aptian is shown to be restricted to sporadic occurrences. The Pleistocene caps the Mesozoic in all depositional areas. Overall the succession appears to form a complete Middle Jurassic – Lower Cretaceous succession, but locally the biostratigraphy demonstrate major hiati, unconformities and sedimentary gaps.

The biostratigraphic subdivision of lithostratigraphic units on Store Koldewey now provides a much better means of age assessment of units recorded in offshore seismic data. Each fossil group has its advantages. Microfossil groups include dinoflagellate cysts, spores and pollen, foraminifers and nannofossils. The dinoflagellate cyst stratigraphy forms a rigid stratigraphic framework which will be highly applicable for dating the Mesozoic succession in any future exploration wells on the North-East Greenland shelf. The Store Koldewey succession has provided new data that has improved the Lower Cretaceous palynostratigraphy. Macrofossils include ammonites, belemnites and bivalves and are the only means of dating the more coarse-grained intervals and also provide a means of calibration of the palynostratigraphy.

Burial and uplift

Vitrinite reflectance measurements from Cretaceous and Jurassic sediments on Store Koldewey lie in the range of ca. 0.50% (R_o varying from 0.43% to 0.58%). This corresponds to maximum palaeo-burial temperatures of ca. 80°C and thus documents a deeper burial of the sediments and a subsequent uplift in the order of 1.5 – 2.5 km.

The landscape on Store Koldewey indicates at least three uplift pulses following deposition of the Cretaceous on the island. Two peneplans can be recognized of which the oldest suggests 1000 – 2000 meters uplift and erosion that probably mainly took place during mid-Tertiary time. A younger peneplan suggest further 400 – 500 meters uplift likely during the Neogene. Finally, Lower Pleistocene marine sediments on top of the youngest peneplan in between 100 – 160 meters of altitude suggest a slight recent uplift of the island.

Apatite Fission Track Analysis (AFTA) of most basement samples from Store Koldewey indicate that they cooled below the partial annealing temperature of ca. 100°C during Late Carboniferous to Early Permian time corresponding to a burial depth less than approximately 3 – 4 km below past surface level. Middle Jurassic sediments capping the basement further documents that a present erosion level was attained at that time. Rifting around the end of the Jurassic resulted in renewed uplift suggested by the distinct base-Cretaceous unconformity evident in large parts of the island. At least a few hundred meters of erosion took place in many places at the end of the Jurassic indicating the magnitude of the uplift. Subsequent burial with up to 1.5 – 2.5 km of sediments took place on the island as indicated by the measured organic maturity of sediments. AFTA data suggest that the island attained its maximum burial during the mid-Cretaceous, although evidence for this has not been reported from the offshore basins. This indicates that this event could have been local in extent or restricted to the onshore. However, further analysis is required to test, validate and better constrain this cooling event. AFTA data further indicate ca. 1 – 2 km of Middle to Late Tertiary uplift and denudation of the island in accordance with the depositional pattern and uplift style reported from the offshore area (Hamann *et al*. 2005).

Implications for the offshore geology and petroleum potential

Findings of the present study have a number of potential implications to the prediction of the offshore geology and the related petroleum potential. The Caledonian basement development outlined above and in further detail in the GIS compilation suggests a protracted Caledonian Orogeny in the area lasting throughout the entire Devonian period and continuing long into the Carboniferous. This seems very different from the Caledonian development documented elsewhere; and Devonian rifting and basin formation e.g. in part of the Danmarkshavn Basin may be difficult to reconcile with nearby large-scale compressional mountain building (Fig. 3). The oldest post-Caledonian sediments onshore northern North-East Greenland are Visean (mid-Carboniferous) in age, which may therefore also apply for much of the offshore basin areas.

The time interval, represented by the depositional gab in between the Carboniferous and the Middle Jurassic in the area from Store Koldewey and to the north, denotes one or more periods of uplift and erosion. Much of the sediments sourced by the uplift and bypassing the study area during this/these periods are expected to have been deposited farther to the east e.g. in the Danmarkshavn Basin. This may have introduced relatively proximal (and thus coarse grained) sediments into central parts of the Danmarkshavn Basin during some of the period. The presence of a coarse-grained, Middle Jurassic, fluvial system with an overall eastwards trending transport direction on Store Koldewey documents this relationship (Fig. 9).

Middle Jurassic coals associated with this fluvial depositional system have been demonstrated elsewhere along the Greenland margin and together with the presence of near-coeval coal successions on the conjugated Norwegian margin may suggest a more widespread distribution of this facies. Buried adequately these coals may potentially act as oil and gas source rocks in the offshore area.

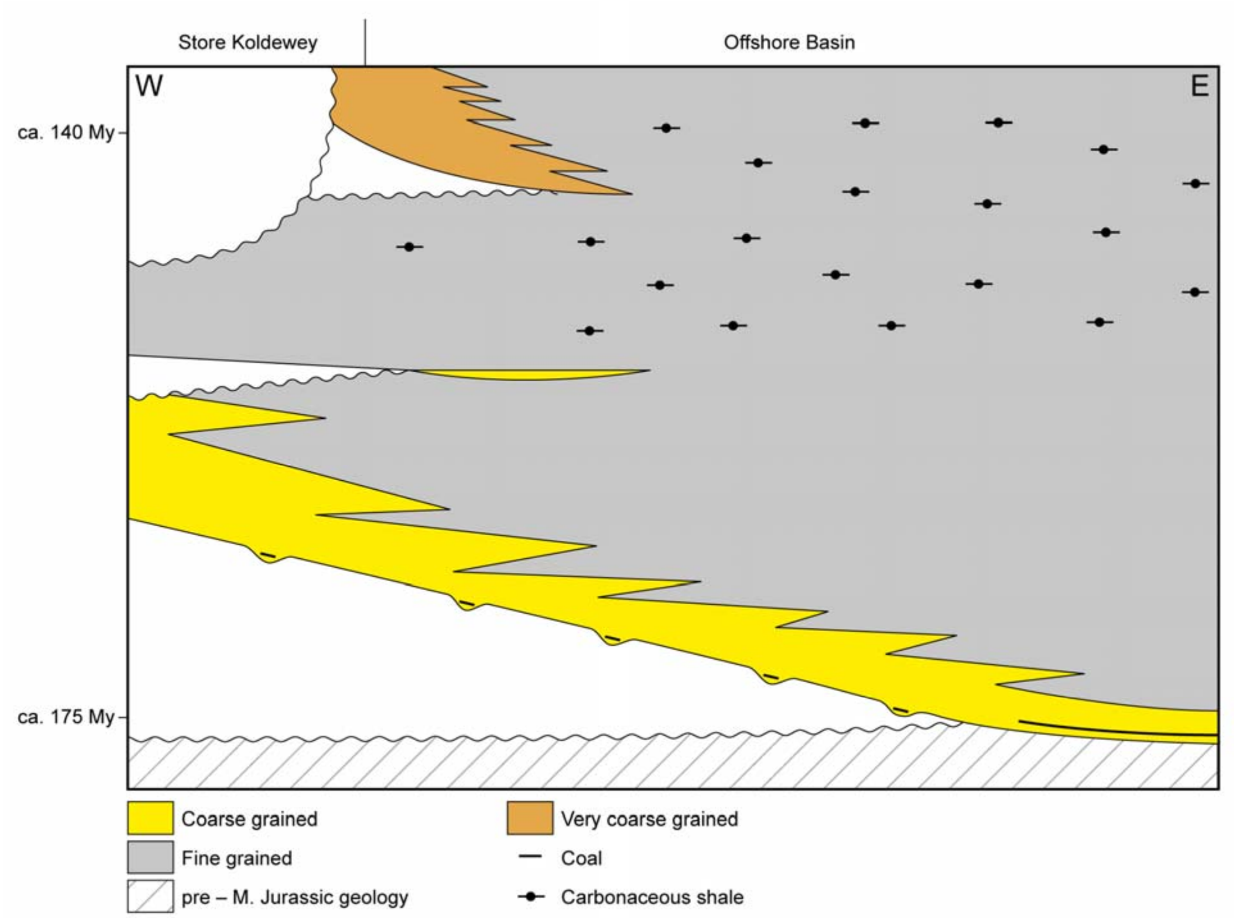

Fig. 9 *Conceptual chronostratigraphic chart from Store Koldewey towards the Danmarkshavn Basin. The chart illustrates the possibility of time transgressive development of facies on Store Koldewey and in the central basin areas and further indicates the likeliness of differently developed lithostratigraphically comparable source rock intervals varying with both time and space.*

By and large, the Jurassic and Cretaceous stratigraphy of Store Koldewey bear a distinct resemblance to that of North-East Greenland farther to the south and to the conjugated Norwegian margin. This suggests a very regional distribution of the associated depositional systems. It therefore seems reasonable to assume that the Jurassic and Cretaceous stratigraphy in the offshore basins few tens of kilometres east of Store Koldewey in many ways resemble that of the island. The depositional facies may be time transgressive, but comparable facies are likely to occur regionally (Fig. 9). In this way, Lower – Middle Jurassic deltaic and fluvial sandstones and coals are likely to have been deposited in part of the greater Danmarkshavn Basin given the overall depositional development during the Jurassic and the presence of similar Middle Jurassic deposits on Store Koldewey (Fig. 9).

The studied Upper Jurassic to Lower Cretaceous succession on Store Koldewey seems to have been deposited in a relatively near-shore environment not far from the exposed Greenlandic craton. The primary palaeo-coastline was situated west of the island and the deposits are strongly affected by its proximal setting. Hence, the examined Upper Jurassic to lowermost Cretaceous succession has no source rock potential. This implies that the coeval successions farther east e.g. in the Danmarkshavn Basin was deposited farther from the primary palaeo-coast and are thus more prone to possess a substantial source rock potential similar to the Upper Jurassic–lowermost Cretaceous elsewhere in North-East Greenland and along the conjugated Atlantic margin.

The overall tectonic framework of Middle – Late Jurassic and Early Cretaceous deposition on Store Koldewey is compatible with that observed farther south in North-East Greenland and to a large extent also along the Norwegian margin. Mesozoic deposition commenced during the Middle Jurassic following a protracted uplift period both on Store Koldewey and farther to the south. Similarly, the end Jurassic/Early Cretaceous rift climax is evidenced both on Store Koldewey and regionally farther south as well as on the conjugated North Atlantic margin. It therefore seems likely that comparable tectonic events might have affected the coeval development in the area offshore Store Koldewey. Strong uplift and erosion may also have affected part of the offshore basins (along structural highs in particular) during the Middle Jurassic and near the end of the Jurassic. This would likely have resulted in the formation of distinct regional unconformities and coarse grained low-stand deposition along uplift areas, both potentially recognizable in seismic data. It is therefore conceivable that an intra-Middle Jurassic unconformity and a near-base Cretaceous unconformity exist in the offshore area, which may help determine the otherwise poorly constrained offshore stratigraphy using seismic data. Bracketing this interval is considered particularly important as the succession is expected to contain both reservoir and source rocks.

A significant late-stage uplift affecting the Danmarkshavn and Thetis Basins, the Danmarkshavn Ridge and the Koldewey Platform was recognized by Hamann *et al*. (2005). Similar to the Barents Sea area, the uplift and erosion offshore Store Koldewey is likely to have had pronounced implications for the area's petroleum potential. None the less, the exact magnitude, style and timing of the uplift and erosion are relatively unconfined so far. It is obvious from seismic data that erosion increases shoreward, and that much of the erosion took place during the Tertiary (Hamann *et al*. 2005).

The Store Koldewey geology provides critical information to the understanding of this uplift. Mesozoic sediments on the island show essentially the same level of thermal maturity, corresponding to R_o close to 0.50%. This is compatible with 1.5 to 2.5 km of burial pending on the palaeo-geothermal gradient and palaeo-surface temperature. It is expected that the offshore area suffered less net-uplift decreasing towards the east.

AFTA data and landscape analysis document the pulsed nature of the uplift and subsidence. At least three uplift/erosion phases can be distinguished following deposition of the youngest Mesozoic strata on Store Koldewey, but the denudation history of the island is expected to have been more complicated than this. The same likely applies to the offshore basins where pulsed uplift, erosion and subsidence phases probably resulted in the present sub-cropping stratigraphy observed from seismic data.

Preliminary AFTA data as interpreted in this study suggest a maximum burial and onset of uplift on Store Koldewey sometimes around the Cenomanian to Turonian. This - somewhat surprising suggestion - is not compatible with the interpretation of offshore seismic data that clearly document thick and continuous Cretaceous and Tertiary successions below the youngest unconformity in the offshore realm (Hamann *et al*. 2005). Consequently, further analysis of the uplift history is absolutely necessary to satisfyingly solve this controversy.

Seismic data indicate a thin sedimentary veneer burying the most recent offshore uplift unconformity (Hamann *et al*. 2005). The Lower Pleistocene burying the Mesozoic on Store Koldewey (Fig. 10) is a likely analogue to this offshore veneer found across the entire Koldewey Platform, the Danmarkshavn Basin and the Danmarkshavn Ridge and much of the Thetis Basin. This suggests an earliest Pleistocene age of the offshore change from uplift and erosion to subsidence and deposition.

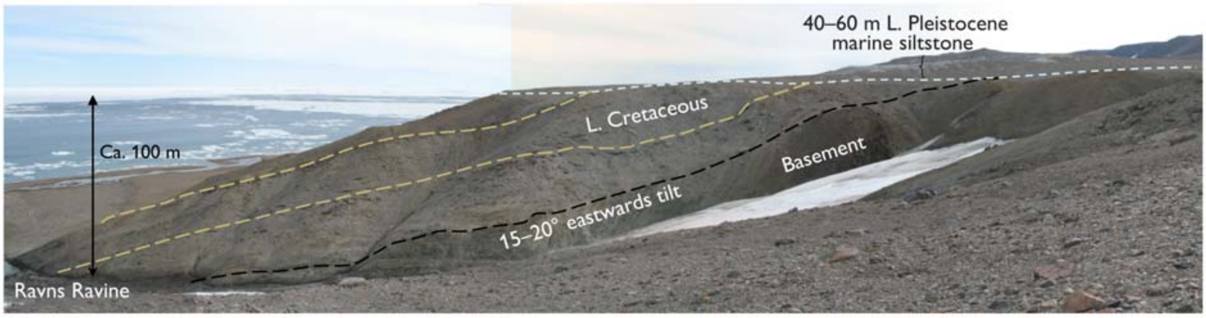

Fig. 10 *Cretaceous strata in Ravns Ravine directly overly the basement and is capped by sub-horizontal Lower Pleistocene strata. This pattern is comparable to that observed seismically offshore, suggesting the age of the oldest sediments overlying the associated unconformity offshore.*

Recommendations to future studies

The present Store Koldewey study has answered a series of questions regarding the geological development of the region. On the other hand, the study points on a number of issues that need future attention beneficial to the prediction of the offshore geology and petroleum potential.

Upper Jurassic core drilling and on- to offshore seismic tying

Despite the effort, the Upper Jurassic Bernbjerg Formation was not reached by the core well during the current project. This was the result of: 1) a poorly constrained Cretaceous stratigraphic outline of the area prior to drilling, including locally developed thick sand filled channels incised into the Jurassic, and 2) technical challenges basically imposed by drilling this thick, loose Cretaceous sand succession. A cored section through the Bernbjerg Formation on the island therefore remains to be drilled, which would otherwise provide a unique opportunity to studying and quantifying the Upper Jurassic source rock equivalent in the area. Based on the gained experience, it will be possible to better avoid and tackle the imposed challenges in a core well targeting the Upper Jurassic source rock equivalent on Store Koldewey.

GEUS' North-East Greenland drilling campaign have explicitly demonstrated the need for core drillings when assessing potential source rocks. Source rock samples from outcrops tend to have a significantly lower petroleum generative potential compared with similar core material due to surface weathering. Outcrop samples are therefore not representative for the true source rock quality, and core material should be used instead to assess source rock potential.

For the offshore exploration to benefit optimally from such a stratigraphic well, it would be attractive to tie the core hole seismically to the existing offshore seismic grid. Optimally, this would allow accurate picking and identification of the main potential source rock interval in the offshore area and further provide directly applicable, important stratigraphic information for this critical stratigraphic interval.

Acoustic properties of Jurassic and Cretaceous sandstones

Hamann *et al*. (2005) reported the presence of a number of DHIs (Direct Hydrocarbon Indicators) in the offshore area. Successful AVO (Amplitude Versus Offset) analyses is standard procedure when assessing such DHIs, but require precise and correct assessment of the acoustic properties of the potential reservoir rock hosting e.g. the hydrocarbons. This is mostly standard knowledge in basins with a mature exploration history where information on the acoustic properties of subsurface rocks are obtained through drilling material (cores/plugs), wire-line logging and 3-D seismic data.

This is obviously not currently the case offshore North-East Greenland. As a substitute for this, a study of the acoustic properties of Jurassic and Cretaceous sandstones onshore Store Koldewey could be carried out. The maximum burial depth of these sandstones is fairly well constrained making them well suited for such a study.

Filling in the biostratigraphic gaps

Store Koldewey contains a relatively rich Lower Cretaceous ammonite fauna, especially within the Barremian and Aptian; intervals that in other parts of North-East Greenland are almost completely barren of ammonites. This offers an excellent opportunity to strengthen the biostratigraphic resolution of these intervals by using ammonites and belemnites to calibrate the palynostratigraphy.

Furthermore, it seems realistic to improve the general age-wise understanding of the Store Koldewey stratigraphy by better constraining the deposits biostratigraphically. The main aim of this effort is to more accurately correlate and compare the Store Koldewey stratigraphy with the existing stratigraphy of North-East Greenland to the south and with that in the offshore basins and the Norwegian shelf farther east.

One obvious benefit of an improved biostratigraphic resolution of the Store Koldewey stratigraphy is that it introduces the opportunity of better studying and understanding differences and similarities in the regional tectonic and lithostratigraphic development. For instance, more precise dating of the Lindemans Bugt Formation on Store Koldewey would help clarify whether or not end-Jurassic rifting on the island occurred slightly staggered compared with farther to the south. Furthermore, more precise dating of the lowermost Jurassic on the island would also help determine whether or not the Middle Jurassic inundation of the area occurred delayed from that observed farther south in North-East Greenland.

Further structural analyses of Store Koldewey

Focus on the present study was on the depositional outline of the Mesozoic present on Store Koldewey. As part of the study, the structural style within and along these sedimentary compartments was noted. However, the complexity and the scattered exposures were not treated exhaustively and a number of open questions remain on the structural development of the island.

A future study could focus in greater detail on the structural outline of Store Koldewey. The benefits from such an analysis are obvious, as the outcome would be applicable to understanding the structural style and development in the offshore area where only limited data exist. This would allow for more robust offshore structural models.

Advanced uplift study of the area immediately facing the offshore basins

The existing uplift studies of North-East Greenland document a number of uplift events interpreted to affect the entire North-East Greenland. The studies were based exclusively on regional landscape analysis combined with modelling of AFTA data of samples collected across all of East Greenland and in the southern part of North-East Greenland.

However, different phases of uplift affected different parts of the East Greenland margin as indicated e.g. by comparing the offshore seismic transects published by Hamann *et al.* (2005) with public domain data from farther to the south along the margin. This emphasizes the need for more specific information on the uplift phases particularly affecting the offshore coming license areas in order to asses the immediate implications for the potential petroleum systems in these areas.

This may be implemented most efficiently by focussing a future uplift study along the easternmost part of onshore Greenland from ca. 75.5°N – ca. 79°N; this is the area facing the offered license areas. Furthermore, the study should incorporate different techniques in order to get a suitable independent quality control of data. These methods could include detailed landscape analysis and AFTA similar to the previous uplift studies, complemented by e.g. apatite and zircon U/(Th-He) analyses. The latter techniques supplement the AFTA method well and are attractive due to their sensitivity to even relatively low-temperature fluctuation expected to occur within the upper ca. 3 km of the crust.

Furthermore, denudation assessment in the same area using zircon fission track analysis and ^{39}Ar-^{40}Ar dating of basement rocks would address aspects of the slightly older uplift history. These techniques are sensitive to cooling from higher temperatures compared e.g. with AFTA, and therefore might help resolve the question of whether offshore basin development initiated during Carboniferous or Devonian time; and thus whether or not

Devonian deposits (potentially including lacustrine source rocks as seen elsewhere in East Greenland) are to be expected regionally offshore.

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