DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2013/25

The Cretaceous of NE Greenland: Integration and Implications of the Nanok-1 Core Well

Report Supplement to Nanok-1 Core Well and The Cretaceous of NE Greenland Data Packages

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

G E U S

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

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1. Executive Summary

This report supplement presents a summary of selected results of the Nanok-1 core data package and “The Cretaceous of North-East Greenland” report series. The report supplement aims to integrate the data derived from the time-equivalent intervals reported in these reports and to discuss their implications for the Upper Cretaceous petroleum geology of the neighboring offshore basins. The supplement is delivered to the participating sponsoring companies of the analytical programs of both the Nanok-1 core well (Appendix B4) and The Cretaceous of NE Greenland (Appendix J1).

The Nanok-1 core penetrated the Upper Cenomanian – Lower Campanian interval of the Fosdalen Formation (note the redefined usage after Bjerager et al., 2012) at Knudshoved, east coast of Hold with Hope. Tectonostratigraphically, the succession corresponds to the late post-rift phase, characterized by filling of inherited fault block topography and change from axial N–S oriented sedimentation to east-directed sediment delivery (see Ineson et al., 2012a for wider discussion). In brief, four main aspects in this interval are considered to be of potential importance regarding the regional petroleum geology: 1) Increase in source rock potential during the Cenomanian; 2) Onset of accelerated reduction of accommodation space and inferred increase in sediment bypass during the Late Cenomanian; 3) Turonian uplift event; and 4) the Coniacian–Santonian maximum regression, culmination of sediment by-pass and basin floor fan development.

The main results and implications are summarized in the text below and in Figure 1.

Upper Cretaceous basin development

- During the Cretaceous, the relative sea level (RSL) in NE Greenland probably peaked sometimes between the Latest Albian and the Middle Cenomanian. Overall, Late Cretaceous water depth trends likely show some diachronity in West – East transects in the NE Greenland – Norway shelf due to successive filling of the inherited fault block topography. Consequently, the maximum flooding in offshore basins may have occurred somewhat later during the Cenomanian.
- The Upper Cenomanian section shows the onset of marked reduction in accumulation rate due to decreasing accommodation space in Hold with Hope (Nanok-1 core). This is interpreted to reflect filling of inherited fault block topog-

raphy and onset of increased sediment delivery to offshore basins. The interpretation is supported by comparison with sediment accumulation records from the Vøring and Møre Basins, which demonstrates that, in contrast to the Greenland onshore record, increased sediment accumulation in these deep axial basins started in the Cenomanian (see Ineson et al., 2012a for further discussion).

- The regressive/forced regressive trend that commenced in the Late Cenomanian was punctuated by flooding during the Turonian, which led to re-establishment of transitional basinal conditions in the Nanok-1 core (candidate TST–HST). These deposits commonly show relatively high bioturbation intensities and were probably bottom current influenced. The occurrence of a "deep sea" trace fossil assemblage (*Paleodictyon* sub-ichnofacies) in the Upper Turonian gravity flow deposits at Månedal (Månedal Fm, Traill Ø; see below) suggest that the Turonian flooding and highstand were regional.
- Significant fault reactivation and uplift in the Traill-Ø and GSØ regions in Late Turonian – Coniacian is indicated by the reappearance of fault scarp related slope apron systems (the Månedal Formation). There is no direct evidence for coeval tectonic activity at Hold with Hope. However, a probable Late Turonian tectonic event can be also detected in the Vøring Basin (Brekke et al., 2013). Whether the mainly post-Cenomanian reduction in accommodation space in Hold with Hope (see below) was influenced by uplift is uncertain.
- The Coniacian is mainly interpreted to record a regional sea-level fall and a lowstand phase that continued during the Santonian (LST). A major SB and condensed section with probable hiatal bypass surface(s) were formed between the Late Coniacian and the Middle Santonian (the Nanok Mb) on Hold with Hope. Moreover, the Nanok Mb may correlate with the Vega Sund Fm basin floor fan deposition at Traill Ø, much of which is tentatively referred to the Upper Coniacian; the thermally altered nature of these rocks, however, hinders precise dating.
- The Upper Santonian section records increasing accommodation space and accumulation rate on Hold with Hope. During this time, most of the Østersletten Mb basin floor fan sandstones were deposited (candidate LST/early TST). Probable diachronity in basin floor fan development at Traill-Ø and Hold with Hope may point to a narrower shelf width in Traill-Ø region, and/or a more proximal location to slope at Hold with Hope.

- The Campanian stage represents a return to mudstone-dominated sedimentation and drowning. Lower Campanian deposits are tentatively interpreted to correspond to slope and basinal environments of intermediate water depth (TST/HST).
- Although exact comparison with published sea level curves is not possible due to e.g., biostratigraphic issues, it is believed that the main relative sea level trends in the Upper Cenomanian – Lower Campanian section were controlled by eustasy.

Reservoir

- As discussed above, the NE Greenland margin was characterized by unfilled fault block topography until the Cenomanian. This structural framework acted as a sediment trap and limited the amount of sediments that were transported to offshore basins before that time. The decrease in accumulation rate due to reduction in accommodation space started in the latest Cenomanian and probably demarcated the onset of increased sediment delivery to offshore basins. This trend escalated during the Coniacian–Santonian, when overfilling of the topography coincided with regional relative sea level drop(s). The interval is manifested by major by-pass surface(s) (the Nanok Mb) and sand-rich basin floor fan systems (Vega Sund Fm and the Østersletten Mb) in NE Greenland. Consequently, this period is considered to have the greatest potential for transport of Greenland-derived sand in particular to the Vøring and Møre Basins prior to the Campanian rift phase.

- The lack of Upper Cretaceous outcrops north from Hold with Hope complicates extrapolation of these data to the Danmarkshavn Basin. Considering that the basin is situated proximal to NE Greenland margin, the onset of sediment accumulation and deposition of Greenland-derived sand probably occurred earlier than in the Vøring and Møre Basins. Potential intervals of significance include the Ryazanian–Valanginian, during which a major erosional by-pass surface was formed in Store Koldewey. An additional by-pass surface was developed during the Late Barremian.

Source Rock

- Screening analyses of 1244 outcrop samples from the Cretaceous of North-East Greenland demonstrated that Hydrogen Indices are invariably low in the exposed sections. The Upper Cenomanian – Lower Campanian interval, which is typically poorly exposed in outcrop, was analyzed in the Nanok-1 corewell data package. Although the screening results from the well did not confirm the presence of source rock of economic interest, the data indicated that the Cenomanian section shows downward increasing source rock potential until the thermal destruction due to intrusion at the base of the core. In addition, there are two oil stained intervals in the core that almost certainly have a Cretaceous source. Stable carbon isotopic compositions of mudstone extracts are related to that of the oil shows, but show a less marine-dominated character. Since the lowermost drilled portion of the mudstone succession is not amenable to analyses due to high maturity, this observation adds substance to the concept of increasing marine influence with increasing depth through the mudstone succession intruded by the sill into which the corehole terminated. Biomarkers contain a moderate concentration of bicadinanes (angiosperm input), a feature that has not been previously recorded in North-East Greenland, and generally indicates a source not older than Cretaceous. Considering both the negative evidence derived from regional screening as well as trends seen in the core, the best candidate for the source of the oil stains is considered to be the Middle – lower Upper Cenomanian succession at the base and below the drilled interval. Although the original petroleum potential of this interval is not known due to thermal destruction, it is probable that the interval did not develop into a commercial source rock in the study area. However, considering that the potential source interval predates the major onset of accelerated reduction in accommodation space in proximal fault blocks and the inferred increase in offshore sediment delivery, the Middle – lower Upper Cenomanian section may show increased source potential in the under-filled axial basins in offshore areas.

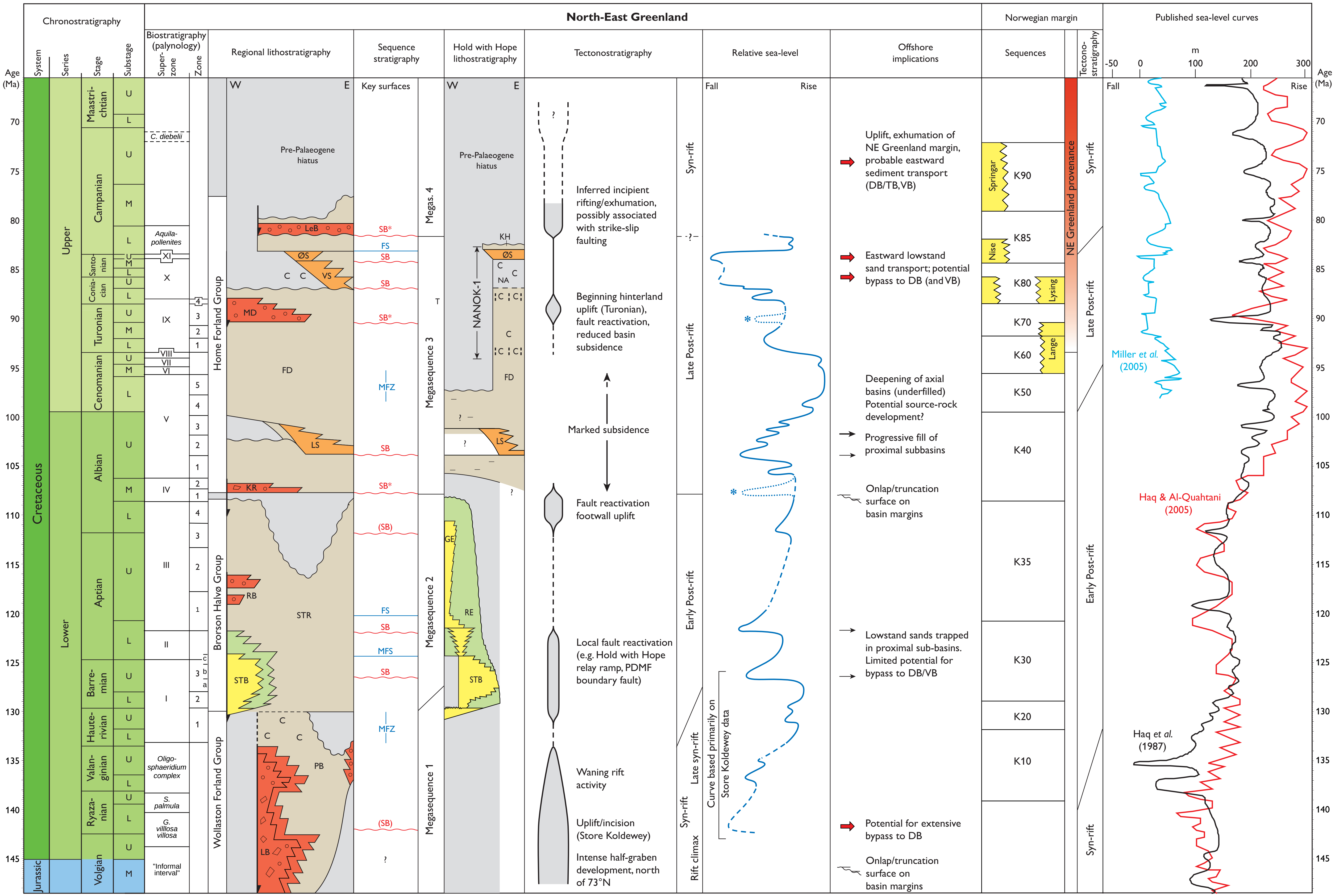

Figure 1. Summary of the bio-, litho-, sequence and tectonostratigraphy of the Cretaceous of North-East Greenland, together with an inferred relative sea-level curve (magnitude of excursions schematic) and interpreted implications of these data for offshore exploration. Data from the Norwegian shelf for comparison are from Vergara *et al*. (2001) and Lien (2005); provenance data from Fonneland *et al*. (2004) and Morton *et al*. (2005). Sequence boundaries and sea-level lowstands marked with asterisks are related to fault activity, often involving tectonic block rotation where contrasting relative sea-level histories are expected across individual tectonic elements (see Gawthorpe *et al.*1994). Formations (Fm) and Members (Mb): **FD**, Fosdalen Fm; **DB**, Danmarkshavn Basin; **GL**, Gulelv Mb; **KH**, Knudshoved Mb; **KR**, Kontakt Ravine Fm; **LB**, Lindemans Bugt Fm; **LeB**, Leitch Bjerg Fm; **LS**, Langsiden Mb; **MD**, Månedal Fm; **NA**, Nanok Mb; **PB**, Palnatokes Bjerg Fm; **RB**, Rold Bjerge Fm; **RE**, Rødelv Mb; **RR**, Rødryggen Mb; **SK** , Sorte Kløft Mb; **STB**, Steensby Bjerg Fm; **STR**, Stratumbjerg Fm; **TB**, Thetis Basin; **VB**, Vøring Basin; **VS**, Vega Sund Fm; **ØS**, Østersletten Mb. Other: **FS**, Flooding surface; **MFS**, Maximum Flooding Surface; **MFZ**, Zone of Maximum Flooding; **SB**, Sequence Boundary,

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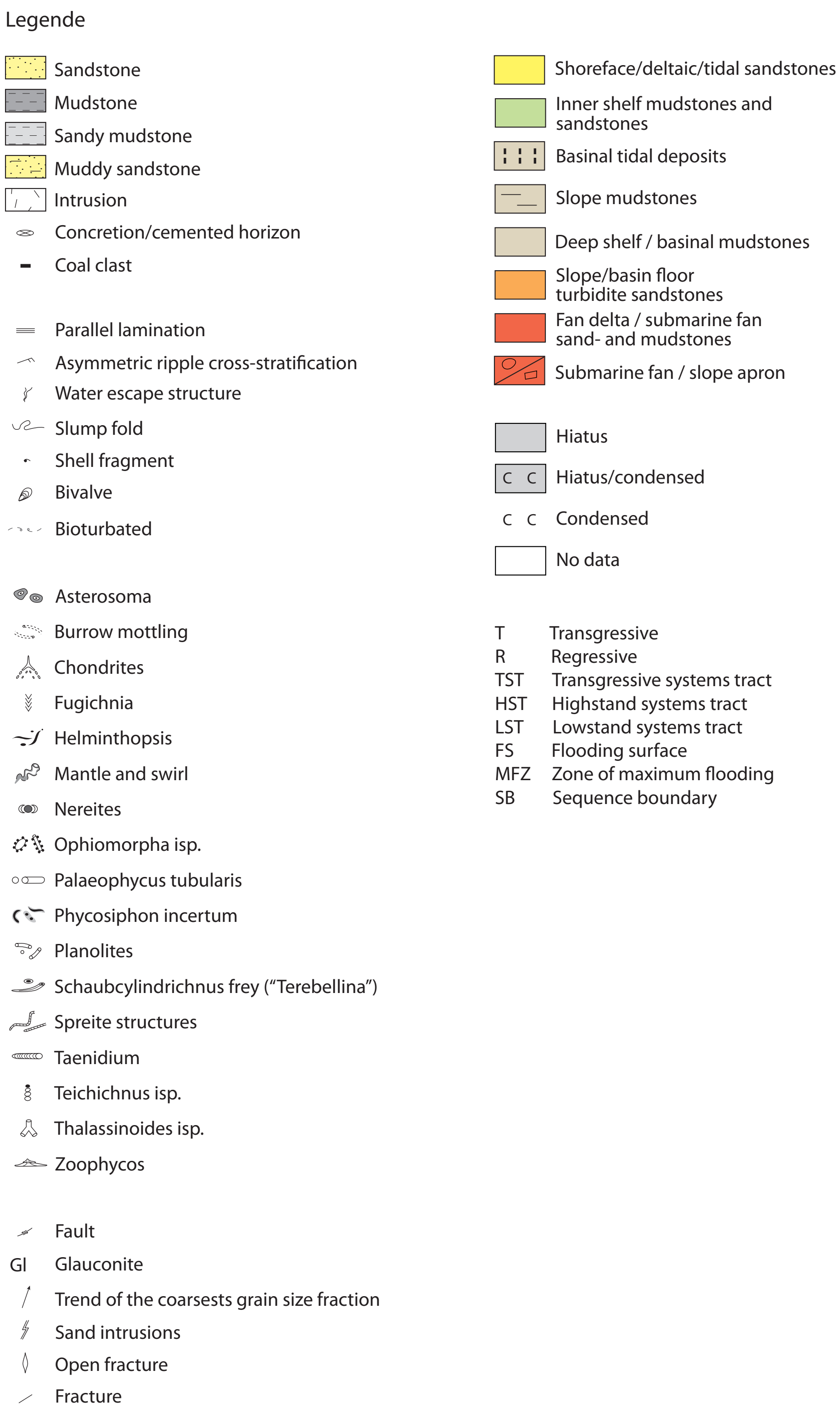

Figure 1 (cont.). Legend to Figs. 1, 3 and 5.

2. Introduction

This report supplement presents a summary of selected results of the Nanok-1 core data package and “The Cretaceous of North-East Greenland” report series. The report supplement aims to integrate the data derived from the time-equivalent intervals reported in these reports and to discuss their implications for the Upper Cretaceous petroleum geology of neighboring offshore basins. The supplement is delivered to the participating sponsoring companies of the specific analytical programs both of the Nanok-1 core well (Appendix B4) and The Cretaceous of NE Greenland (Appendix J1).

The Nanok-1 core penetrated the Upper Cenomanian – Lower Campanian interval of the Fosdalen Formation (note the redefined usage after Bjerager et al., 2012) at Knudshoved, east coast of Hold with Hope. The correlative intervals are typically poorly exposed or missing in NE Greenland (Fig. 2) often complicating regional correlations and the verification of the relative sea level trends observed in the Nanok-1 core. This is particularly the case with the Cenomanian–Turonian section.

In the text below, the Late Cenomanian – Early Campanian basin development is first synthesized chronostratigraphically. This is followed by a summary of the main implications with respect to reservoir and source rock development. For a more detailed account of the depositional evolution and data behind the interpretations, see the original reports listed below:

1) Alsen, P. & Bjerager, M. 2012: The Cretaceous of NE Greenland: Annotated bibliography (Subproject 1). Danmarks og Grønlands Geologiske Undersøgelse Rapport **2012/48.**
2) Nøhr-Hansen, H., Alsen, P., Piasecki, S., Sheldon, E. & Morigi, C. 2012: The Cretaceous of NE Greenland: Integrated biostratigraphy (Subproject 2). Danmarks og Grønlands Geologiske Undersøgelse Rapport **2012/49.**
3) Bjerager, M., Alsen, P., Bojesen-Koefoed, J.A., Fyhn, M.B.W., Hovikoski, J.,Ineson, J.R., Nøhr-Hansen, H., Nielsen, L.H., Piasecki, S. & Vosgerau, H. 2012: The Cretaceous of NE Greenland: Lithostratigraphic subdivision (Subproject 3). Danmarks og Grønlands Geologiske Undersøgelse Rapport **2012/50.**
4) Bojesen-Koefoed, J.A., Alsen, P., Anthonsen, K.L., Bjerager, M., Fyhn, M.B.W., Hovikoski, J., Ineson, J.R., Nøhr-Hansen, H., Nielsen, L.H., Piasecki, S. & Vosgerau, H. 2012: The Cretaceous of NE Greenland: Source rock evaluation

(Subproject 4). Danmarks og Grønlands Geologiske Undersøgelse Rapport **2012/51.**

5) Ineson, J.R., Vosgerau, H., Nøhr-Hansen, H., Weibel, R., Nielsen, L.H., Hovikoski, J. &. Alsen, P. 2012b: The Cretaceous of NE Greenland: Sandstone reservoir analogue (Subproject 5). Danmarks og Grønlands Geologiske Undersøgelse Rapport **2012/52.**
6) Hovikoski, J., Alsen, P., Bjerager, M., Bojesen-Koefoed, J.A., Fyhn, M.B.W., Ineson, J.R., Nøhr-Hansen, H., Nielsen, L.H., Piasecki, S. & Vosgerau, H. 2012a: The Cretaceous of NE Greenland: Sequence stratigraphy (Subproject 6). Danmarks og Grønlands Geologiske Undersøgelse Rapport **2012/53**.
7) Fyhn, M.B.W., Ineson, J.R., Hovikoski, J., Bjerager, M., Vosgerau, H., Bojesen-Koefoed, J.A., Nøhr-Hansen, H., Nielsen, L.H., Piasecki, S. & Alsen, P. 2012: The Cretaceous of NE Greenland: Tectono-stratigraphy and tectonic-stratigraphic scenarios (Subproject 7). Danmarks og Grønlands Geologiske Undersøgelse Rapport **2012/54.**
8) Ineson, J., Alsen, P., Anthosen, K., Bjerager, M., Bojesen-Koefoed, J.A., Fyhn, M.B.W., Hovikoski, J., Morigi, C., Nielsen, L.H., Nøhr-Hansen, H., Piasecki, S., Vosgerau, H., & Weibel., R., 2012a: The Cretaceous of NE Greenland: Integrated Summary. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2012/114**.
9) Hovikoski, J., Alsen, P., Bojesen-Koefoed, J.A., Boserup, J., Fries, K., Green, P., Weibel, R., Hjuler, M., Japsen, P., Kjøller, C., Larsen, L., Lindgren, H., Morigi, C., Nytoft, P., Nøhr-Hansen, H., Olivarius, M., Petersen, H., Pilgaard, A., Sheldon, E., Springer, N., & Therkelsen, J. 2012b: Nanok-1 Core Well, GGU 517004, Hold with Hope, Northeast Greenland – Final Well Report. Contribution to Petroleum Geological Studies, Services, and Data in East and Northeast Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2012/106.**

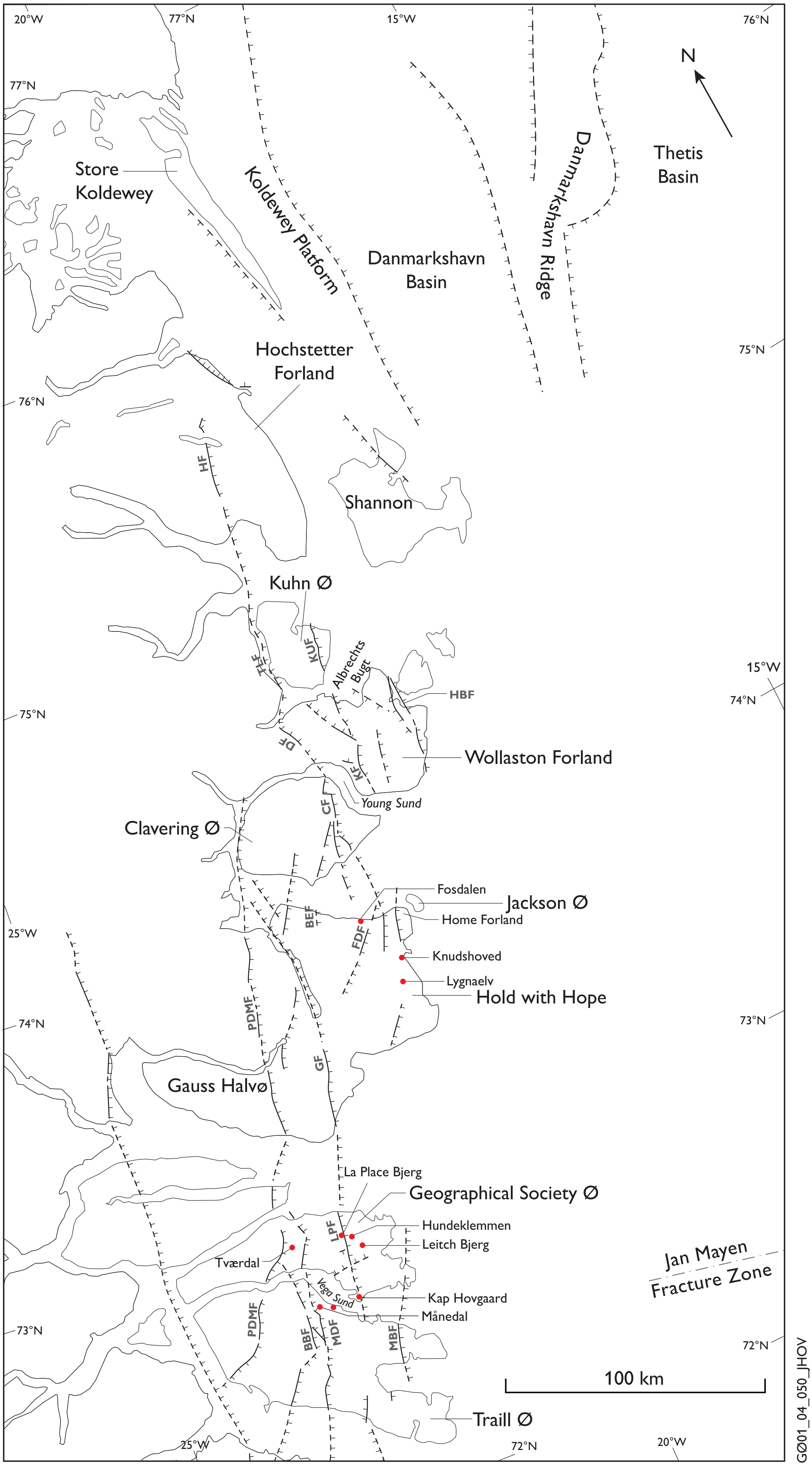

Figure 2. Map of North-East Greenland showing the studied Cenomanian – Lower Campanian outcrops. **BBF** = Bordbjerg Fault, **BEF** = Blå Elv Fault, **CF** = Clavering Fault, **DF** = Dombjerg Fault, **GF** = Gisecki Fault, **HBF** = Hühnerbjerg Fault, **HF** = Hochstetter Fault, **FDF** = Fosdalen Fault, **KUF** = Kuhn Fault, **LPF** = Laplace Bjerg Fault, **MDF** = Månedal Fault, **MBF** = Mols Bjerge Fault, **PDMF** = Post Devonian Main fault, **TLF** = Thomsen Land fault.

3. Synthesis of the Upper Cretaceous Depositional evolution

3.1 Cenomanian

Cenomanian strata are generally poorly represented in NE Greenland. With the exception of the Lower – ?mid Cenomanian deposits in a proximal setting on Geographical Society Ø, Cenomanian strata are restricted to Hold with Hope (Fig. 2). The Cenomanian is interpreted to represent generally a sea-level highstand and shows some evidence for increasing source potential. The Upper Cenomanian shows the onset of decreasing accommodation space at Hold with Hope, which is thought to reflect filled fault block topography (Figs. 3–6).

The Cretaceous relative sea level in NE Greenland probably peaked sometimes between the Uppermost Albian and the Middle Cenomanian. This interpretation is based on the back-stepping pattern and the eventual disappearance of basin floor fan systems (Langesiden Mb) during the latest Albian at Hold with Hope. These deposits were replaced by a poorly exposed mudrock succession of the Early–Middle Cenomanian age. Overall, Late Cretaceous water depth trends likely show some diachronity in West – East transects in the NE Greenland – Norway shelf due to successive filling of the inherited fault block topography. Consequently, the maximum flooding in offshore basins may have occurred somewhat later during the Cenomanian.

The sedimentary facies show that the Upper Cenomanian Fosdalen Formation was deposited in a basinal and/or incipient slope setting in the Nanok-1 core (Fig. 4A). The upper Upper Cenomanian section shows the onset of a marked reduction in accumulation rate due to decreasing accommodation space. This is evidenced by a gradational facies change from basinal/incipient slope sedimentation to tidally-influenced mudstones and sandstones during the latter part of the Upper Cenomanian (Figs. 3 and 4BC). Moreover, this interval is also characterized by recurring, minor hiatal surfaces typified by sideritic/ankeritic layers overlain by glauconite clast-bearing surfaces and firm-ground burrows (*Glossifungites* Ichnofacies; Fig. 4B).

Tides are common in deep-sea environments especially near areas of topography on the sea floor such as the slope (Dykstra, 2012). In particular, tides are important processes in many modern submarine canyons (Shanmugam, 2008 and references there-in). They can be generated by internal waves and/or surface tides, and currently there are no definite criteria to differentiate between these two from the rock record (Shanmugam, 2008; Dykstra, 2012). However, considering the abundant terrestrially derived organic matter, the local disappearance of dinoflagellates as well as trace fossils more common of shallow marine environments, the depositional environment is interpreted to have been intimately sourced by shallow marine tidally-influenced depositional systems.

Although relatively little is known about the relationship between deep sea tides and sea level change, some data suggest that tidal-currents are amplified in deep sea environments during forced regressions.

The marked decrease in accommodation space that started in the latest Cenomanian is interpreted to reflect the filling of inherited fault block topography and the onset of increased sediment delivery to offshore basins (Figs. 5 and 6). The interpretation is supported by comparison of sediment accumulation records from the Vøring and Møre Basins, which demonstrates that, in contrast to the Greenland onshore record, increased sediment accumulation in these deep axial basins started in the Cenomanian (Fig. 6; see Ineson et al., 2012a for further discussion).

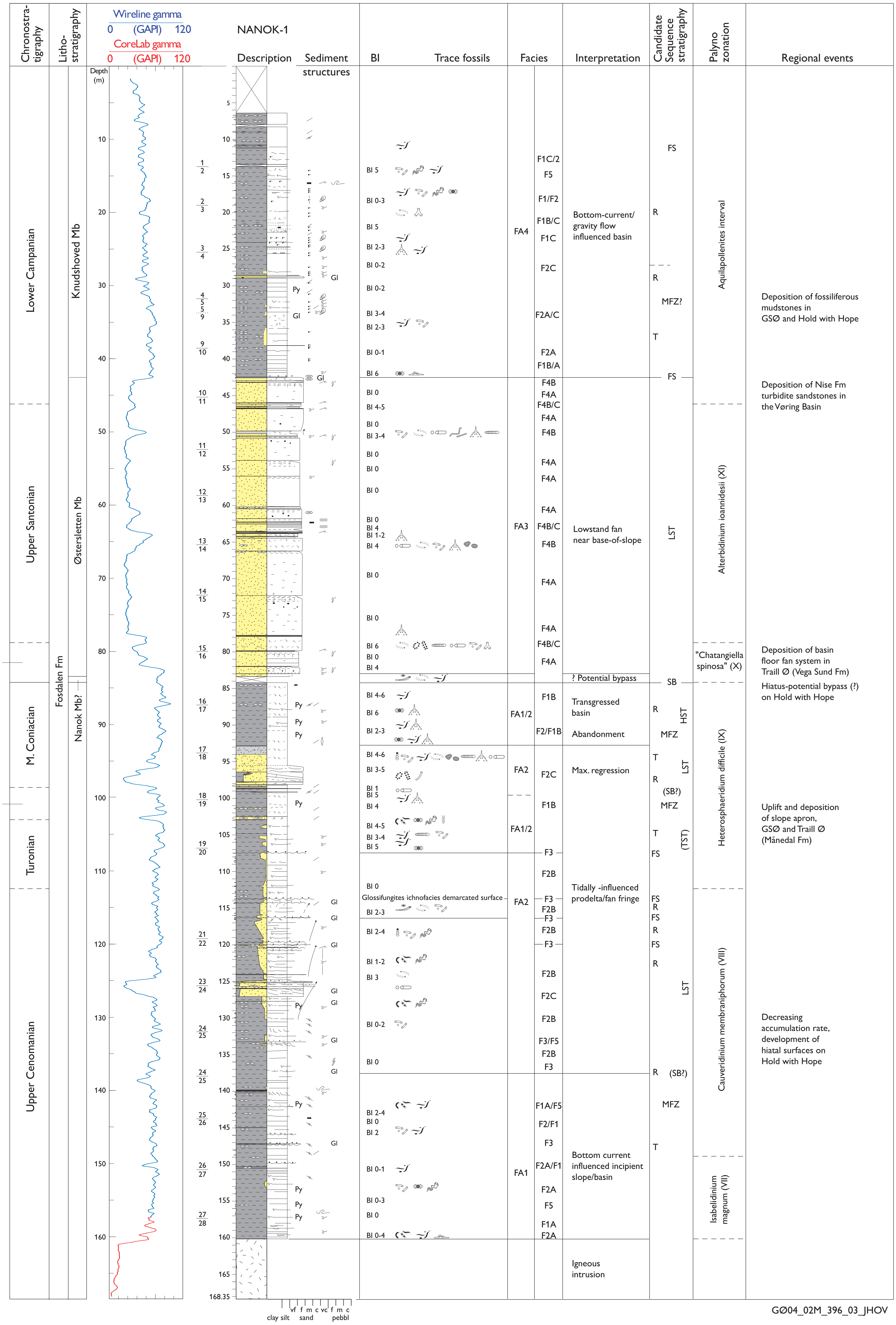

Figure 3. Summary log of the NANOK-1 core well showing main coeval regional events. See Figure 1 for legend

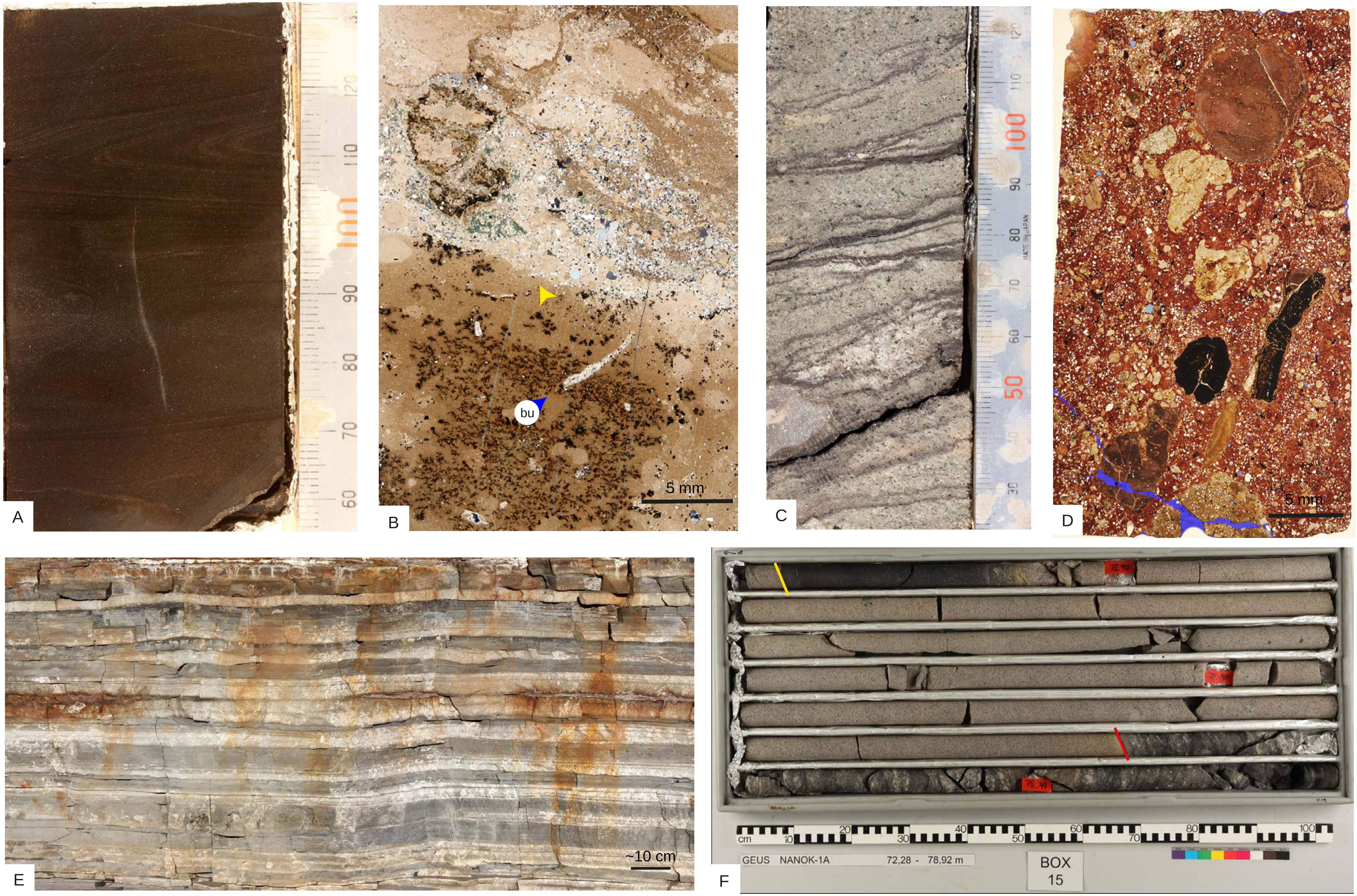

Figure 4. Facies plate illustrating examples from some of the most important phases in the Cenomanian – Lower Campanian depositional evolution. A) Upper Cenomanian slump-folded mudstones from the base of the Nanok-1 core. The Upper Cenomanian interval shows a slight increase in source potential down section until thermal destruction at the base of the core. B) and C) Examples of a hiatal surface and tidal sandstone, respectively, which are interpreted to reflect decreasing accommodation space at Hold with Hope that started during the latest Cenomanian. An unlined, passively-filled burrow (bu) descending from an erosional surface (yellow arrow) is indicated in Fig. 4C. D)–F) Facies examples reflecting the Upper Coniacian–Santonian maximum regression, culmination of sediment by-pass and basin floor fan development. D) Reddish, goethite- and hematite-rich pebbly sandstone from the lower part of the Nanok Mb (outcrop sample). E) Upper Coniacian? Vega Sund Fm. basin floor fan deposits from Traill Ø. F) Upper Santonian gravity flow sandstones of the Østersletten Mb. Red line marks the base of a structureless sandstone bed that grades into carbonaceous sandstone in the top of the bed. Yellow line indicates the top of the bed.

3.2 Turonian

Turonian rocks are present in the Nanok-1 core (Hold with Hope) as well as on GSØ and Traill-Ø. Turonian shows evidence for some stratigraphic condensation and regional flooding (TST-HST). This interval is also characterized by a significant increase in tectonic activity, which is reflected by the appearance of coarse-grained deep sea gravity flow deposition on Traill-Ø and GSØ (the Månedal Fm). There is no direct evidence for coeval tectonic activity on Hold with Hope. However, a probable Late Turonian tectonic event can also be detected in the Vøring Basin (Brekke et al., 2013), suggesting that the tectonic event is regional.

The regressive/forced regressive trend that commenced in the Late Cenomanian was punctuated by flooding during the Turonian, which led to re-establishment of transitional basinal conditions in the Nanok-1 core (candidate TST–HST). These deposits show commonly high bioturbation intensities and were probably bottom current influenced. This flooding event shows some stratigraphic condensation, which is interpreted to relate in part to regionally decreased sediment supply. The occurrence of a "deep sea" trace fossil assemblage (*Paleodictyon* sub-ichnofacies) in the Upper Turonian gravity flow deposits at Månedal (Månedal Fm, Traill Ø; see below) probably suggests that the Turonian flooding and highstand were regional.

The late Turonian – Coniacian shows evidence of significant fault reactivation and uplift in the Traill Ø and GSØ regions by reappearance of fault scarp-related slope apron systems (the Månedal Formation; Surlyk and Noe-Nygaard, 2001). The formation comprise a wide range of facies including boulder conglomerates, pebble-cobble conglomerates, pebbly sandstones, pebbly mudstones and mudstones deposited from various gravity flow processes (Surlyk & Noe-Nygaard, 2001). The Månedal Fm was deposited in a deep sea environment at the Månedal fault as evidenced by the aforementioned occurrence of *Paleodictyon* sub-Ichnofacies. This supports the idea that the fault scarp was situated at the Post Devonian Main Fault during that time rather than at the Månedal Fault (Surlyk & Noe-Nygaard, 2001).

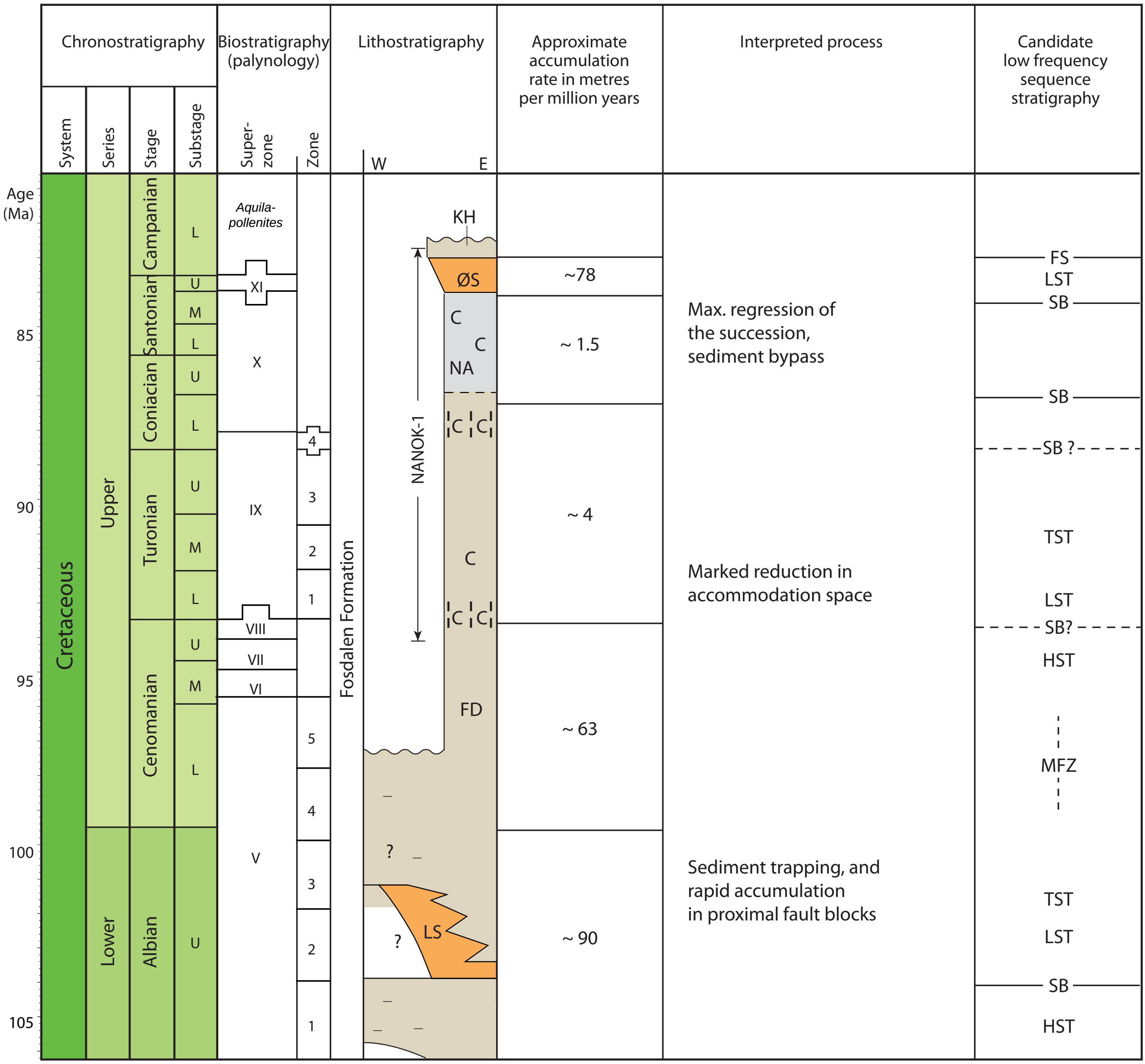

Figure 5. Lithostratigraphic summary log of the Upper Albian – Lower Campanian section at Hold with Hope showing generalized sequence stratigraphic interpretation and approximate accumulation rates per million years. Note that these figures are rough estimations due to e.g., biostratigraphic uncertainties and only aim to illustrate main trends in the accumulation history. For legend, see Fig. 1.

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3.3 Coniacian–Santonian

Coniacian–Santonian deposits crop out on Traill Ø (Vega Sund Fm.), GSØ and Hold with Hope regions (Fosdalen Fm.). The interval represents the time of maximum regression, culmination of sediment by-pass and basin floor fan development (Figs. 5D–F). Consequently, this period is considered to have the greatest potential for transport of Greenland-derived sand in particular to the Vøring and Møre Basins prior to the Campanian rift.

The Coniacian is mainly interpreted to record a regional sea-level fall and a lowstand phase that continued during the Santonian (LST). A candidate conformable, minor SB is recognized in the Middle Coniacian in the Nanok-1 core, above which an abrupt progradation of tidal deposits took place. The regressive development was temporally interrupted by a flooding event during the latter part of the Middle Coniacian, which led to re-establishment of transitional basinal conditions in the Nanok-1 core. However, the lack of correlative intervals elsewhere in NE Greenland hinders distinction between auto- and allocyclic factors in these intervals.

A major SB and condensed section with probable hiatal bypass surface(s) were formed between the Upper Coniacian and Middle Santonian (the Nanok Mb) on Hold with Hope. The reddish, hematite- and goethite-rich lower part of the Nanok Member containing phosphate-rich burrows (see also Kelly et al., 1998) and apatite clasts is interpreted to reflect prolonged exposure to oxygenated bottom currents. In addition to geochemical evidence, the development of sequence boundary at this level is also supported by the stratigraphic position intimately below a gravity-flow sandstone unit. Moreover, the Nanok Mb may correlate with the Vega Sund Fm basin floor fan deposition at Traill-Ø, much of which is tentatively thought to be of Late Coniacian age; the thermally altered nature of these rocks hinders precise dating (see below).

On Traill Ø, the Coniacian–Santonian is represented by the >90-m thick Vega Sund Formation. The outcropping part of the unit forms a generally upward fining succession comprising dominantly sheet sandstones and mudstones that are interpreted as a mixed, sustained- and surge-flow influenced basin floor fan turbidite system. The sustained flow is assigned to hyperpycnal currents (i.e., negatively buoyant sediment suspension generated by a river flood; Mulder et al., 2003). Deposition took place mainly in unchannelized part of fan and fan fringe settings, ~6 km offshore of the alleged shelf edge defining fault (the Månedal fault; see also Surlyk & Noe-Nygaard 2001). The evidence for hyperpycnal deposition includes inversely to normally graded lamina sets, dominance of parallel lamination, gradational bed boundaries, local climbing ripples, and intrabed erosional surfaces, which in concert point to fluctuating, long-duration flow. The fine-grained fan fringe comprises a range of bed types including massive mud beds, thin sand turbidites, thin muddy debris flow beds and cm- to dm-scale bioturbated light grey mudstones (“hemiturbidites” of Stow and Wetzel, 1990). The evidence of both local flow concentration (debris flow beds) and long-lived buoyant plumes (relatively thick bioturbated beds) may point to reversing buoyancy in fan fringe settings; hyperpycnal currents may lose their negative buoyancy if particle concentration decreases due to deposition and/or saline water does not sufficiently intersperse into the flow in marine environments (e.g., Mulder, 2011). In these cases, buoyancy reversal may occur, in particular, in the distal part of the hyperpycnally-influenced depositional system leading to the above-mentioned long-lived hypopycnal plume (“hemiturbidite”) and residual concentrated flow (Pritchard and Gladstone, 2009).

The fan fringe shows locally similarities with shelfal prodeltas by containing synaeresis cracks as well as *Teichichnus, fugichnia* and *Planolites* dominated trace fossil fabric in the event bed intervals.

The precise dating of the Vega Sund Fm is hindered by the thermally altered nature of the deposits. A record of poorly preserved dinoflagellate specimens of *Spinidinium echinoideum* and *Heterosphaeridium difficile* may suggest a late Coniacian age or slightly younger for the middle part of the succession, and may correlate with the "*Chatangiella spinosa*” (X) Zone (age of the Nanok Mb). However, the zone fossil "*Chatangiella spinosa*” has not been recorded. Similarly, a very poorly preserved fragment of *Heterosphaeridium difficile* from the upper part of the exposure may suggest a pre late Santonian age. The absence of the pollen genus *Aquilapollenites* is in line with the interpretation by suggesting a pre Campanian age.

The Upper Santonian records increasing accommodation space and accumulation rate on Hold with Hope. During this time, most of the Østersletten Mb basin-floor fan sandstones were deposited. In addition to the sedimentary facies, pervasive coal particles and locally decreasing dinoflagellate diversity are in line with a LST/early TST phase during this time. The probable diachronity in basin floor-fan development at Traill-Ø and

Hold with Hope may point to narrower shelf width in Traill-Ø region, and/or more proximal location to slope at Hold with Hope.

3.4 Campanian

Campanian deposits outcrop on Hold with Hope, GSØ and Traill Ø, locally forming more than 300 m-thick successions. In general, the Campanian records drowning that followed the Coniacian–Santonian lowstand and early transgressive systems tract, and a return to mudstone-dominated sedimentation. A significant exception to this is potentially the ?Lower Campanian Leitch Bjerg Fm that comprises coarse-grained submarine fan deposits similar to those of the Wollaston Forland Group (Surlyk, 1978). This could suggest renewed fault activity in the region and possibly the initiation of a new rift episode (see discussion in Ineson et al., 2012a). The age of the unit, however, requires confirmation in the future.

Overall, the Campanian is poorly exposed and commonly no detailed sedimentological observations can be collected. The deposits show common slumps, sporadic cm-to dm-scale sandstone beds with incipient boumas in a generally mudstone-dominated succession. Post-depositional trace fossils (*Planolites*, burrow mottling) and *Zoophycos* are common. No *Nereites* Ichnofacies was observed. These deposits are tentatively interpreted to correspond to slope and basinal environments (GSØ) of intermediate water depth (TST/HST). This interval in the Nanok-1 core shows common bottom current influence.

The new Leitch Bjerg Fm (Bjerager et al., 2012) comprises a possible Lower Campanian coarse clastic submarine slope apron/submarine fan succession, 125 m-thick. Two isolated lensoidal/small channelized conglomerates, up to a few meters-thick, with mud-supported and clast-supported textures are imbedded in the lower mudstone-dominated interval. It is overlain by three overall fining upward channelized units, 48 m, 35 m and 22 m thick, respectively. They consist of clast-supported pebble conglomerates with well-rounded crystalline clasts and few outsized boulders, massive sandstone with intraformational mudclasts, graded sandstone beds and plane-bedded sandstones and mudstones, deposited by various gravity flow processes. The top is marked by an unconformity and overlain by a thick sandstone-dominated Paleocene succession. The age of the unit, however, requires confirmation in the future.

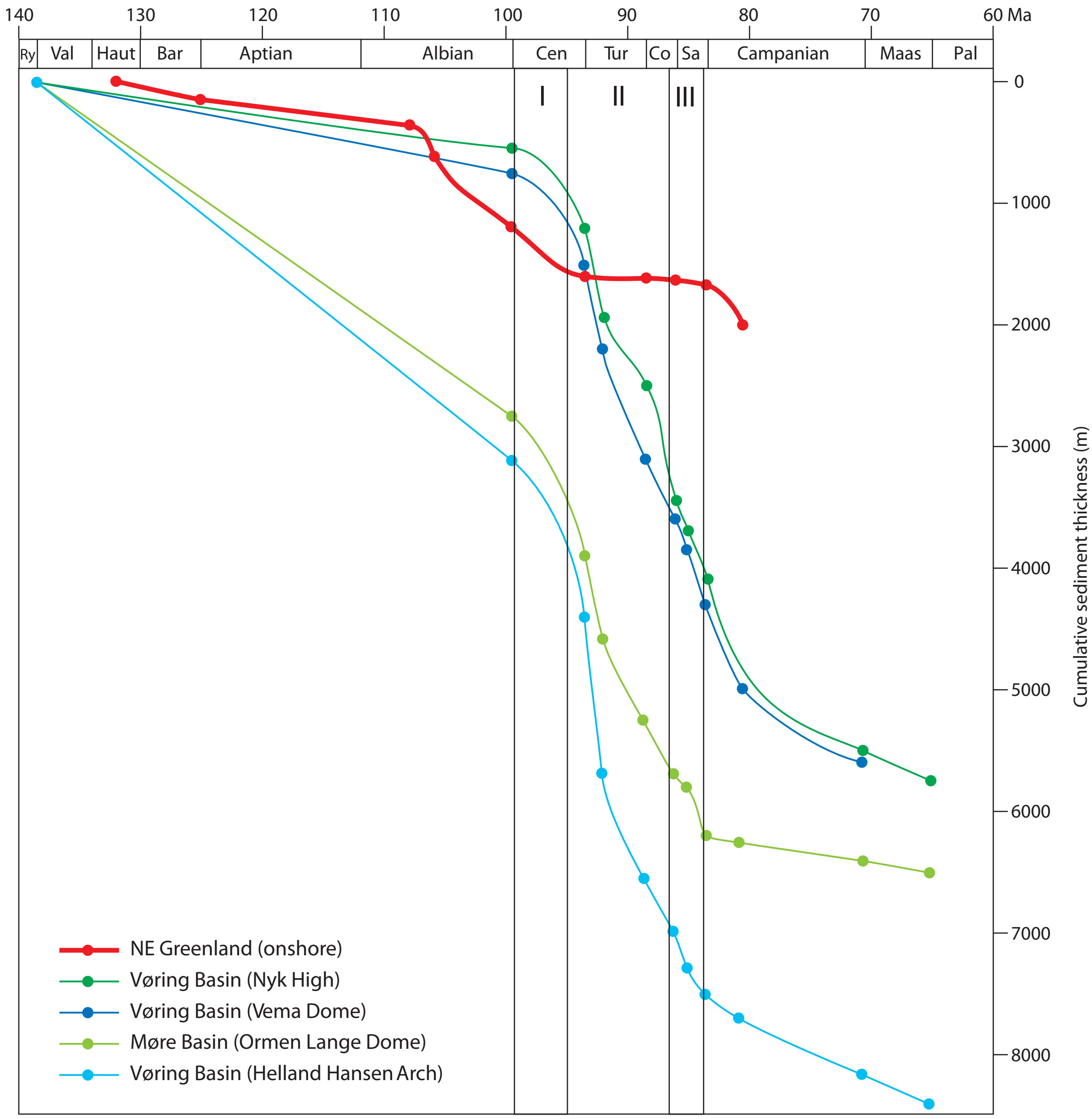

Figure 6. Cumulative Cretaceous sediment thickness (compacted) from key wells in the Vøring and Møre Basins on the Norwegian shelf compared with a generalized, composite curve from East Greenland (see Ineson et al., 2012a for further discussion). The Norwegian shelf data are from Færseth & Lien (2002), re-plotted to the same timescale. Main implications derived from the Nanok-1 well and coeval outcrops are indicated in time-windows I-III. I) Potential increase in source potential in offshore basins. II) Onset of accelerated reduction of accommodation space at NE Greenland margin and inferred increase in sediment bypass. III) Maximum regression, culmination of sediment by-pass and basin floor fan development.

4. Reservoir

As discussed above, the NE Greenland margin was characterized by an unfilled fault block topography until the Cenomanian. This structural framework acted as a sediment trap and limited the amount of sediments that were transported to offshore basins before that time (Figs. 5 and 6). The decrease in accumulation rate due to a reduction in accommodation space started in the Cenomanian and probably demarcated the onset of increased sediment delivery to offshore basins. This trend escalated during the Coniacian–Santonian, when overfilling of the proximal depocenters coincided with regional relative sea level drop(s). The interval is manifested by major by-pass surface(s) (the Nanok Mb) and sand-rich basin floor fan systems (Vega Sund Fm and the Østersletten Mb) in North-East Greenland. Consequently, this period is considered to have the greatest potential for transport of Greenland-derived sand in particular to the Vøring and Møre Basins prior to the Campanian rift phase.

The lack of Upper Cretaceous outcrops north of Hold with Hope complicates extrapolation of these data to the Danmarkshavn Basin. Considering that the basin was situated proximal to the North-East Greenland margin, the onset of sediment accumulation and deposition of Greenland-derived sand probably occurred earlier than in the Vøring and Møre Basins. Potential intervals of significance include the Ryazanian–Valanginian, during which a major erosional by-pass surface was formed on Store Koldewey. An additional by-pass surface was developed during the Late Barremian.

For the understanding of the Mesozoic depositional history of the northern basins (e.g., Danmarkshavn and SW Barents Sea Basins) an area of major importance is the Wandel Sea Basin in eastern North Greenland. This area documents a few km-thick, Upper Jurassic – Upper Cretaceous succession, forms the northern extent of the Koldewey Platform and was situated immediately NW of the SW Barents Sea prior to the Eocene break-up. These deposits and their implications will be addressed in an upcoming project that will be announced in the autumn of 2013.

4.1 Reservoir Quality

The reservoir quality of the Østersletten Mb sandstones was assessed in the Nanok-1 core data package. The unit comprises approximately 40 m of sandstones considered to be of reasonably good reservoir quality. The net/gross ratio is estimated to be 81–

88% based on a 15% porosity cut-off value. The average porosity of the reservoir quality sandstone is 21–22%, and the average permeability ranges between 50–150 mD.

The Østersletten Mb sandstones are interpreted to be part of a small-scale sand-dominated fan near base of slope. The paucity of clay, even in beds that show preserved tops, and the inferred proximal locus of sand accumulation may suggest a low sediment transport efficiency system (cf., Richards et al., 1998). This would further point to decreasing net/gross ratio towards the basin and a possibly relatively abrupt mid fan – basin floor gradation.

Sedimentological evidence and the tectonostratigraphic position of both the Vega Sund Fm and the Østersletten Mb suggest a filled rift-topography and mainly east-directed flow, which may have promoted development of east-oriented radial fan development rather than e.g., an elongate axial geometry. However, if these systems reached underfilled offshore basins, they would likely show topographic confinement.

Both of the fan systems are interpreted to show recurring evidence for river-flood origin for turbidite emplacement. As discussed above, the Vega Sund Fm especially shows evidence of widespread fine-grained hyperpycnal deposition. Some recent studies have also suggested that the structureless sandstone facies that characterize the Østersletten Mb, could also be generated by hyperpycnal currents influenced by lofting (reversing buoyancy, e.g., Stevenson and Peakall, 2010). Even though further research on turbidite flow processes is needed to decide whether the structureless sandstones are related to collapse induced high density turbidites or hyperpycnal currents, at least interbedded facies point to probable direct riverine influence on sedimentation.

Understanding the flow initiation, nature of sediment transport, and depositional processes are not trivial issues from a reservoir perspective since they may contain unique information about the controls of the depositional systems, such as climate, relative sea level, source area and basin morphology. Hyperpycnal sediment transport to the deep sea in particular is thought to be bolstered by a rather specific set of controlling parameters including uplifted source areas, lowstand settings where rivers drain straight to canyon heads, small to medium scale rivers, and narrow shelfs that hinder rivers from merging into larger river systems (e.g., Mulder et al., 2003). The last mentioned factor suggests that hyperpycnal-prone settings may contain a larger number of fluvial point sources and may merge into ramp-like coalescing or closely spaced basin floor fans (see Bourget et al., 2010 for a modern example). Individual fan systems, on the other hand, can be relatively small due to feeder channel size.

5. Source Rock

Screening analyses of 1244 outcrop samples from the Cretaceous of North-East Greenland demonstrated that Hydrogen Indices are invariably low in the exposed sections. The Cenomanian – Campanian interval, which is typically poorly exposed in outcrop, was analyzed in the Nanok-1 corewell data package. Although the screening results from the well did not confirm the presence of source rock of economic interest, the data indicated that the Cenomanian section shows downward increasing source rock potential until the thermal destruction due to the igneous intrusion at the base of the core. In addition, there are two oil stained intervals in the core that almost certainly have a Cretaceous source: Stable Carbon isotopic compositions of mudstone extracts are related to that of the oil shows, but show a less marine-dominated character. Since the lowermost drilled portion of the mudstone succession is not amenable to analyses due to high maturity, this observation adds substance to the concept of increasing marine influence with increasing depth through the mudstone succession intruded by the sill in which the corehole terminated. Biomarkers contain a moderate concentration of bicadinanes (angiosperm input), a feature that has not been previously recorded in North-East Greenland, and generally indicates a source not older than Cretaceous. Considering both the negative evidence derived from regional screening as well as trends seen in the core, the best candidate for the source of the migrated oil in the oil stained intervals is considered to be the Middle – lower Upper Cenomanian succession at the base and below the drilled interval. Although the original petroleum potential of this interval is not known due to thermal destruction, it is probable that the interval did not develop into a commercial source rock in the study area. However, considering that the potential source interval predates the major onset of accelerated reduction in accommodation space in proximal fault blocks and the inferred increase in offshore sediment delivery (Fig. 5), the Middle – lower Upper Cenomanian section may show increased source potential in the underfilled axial basins in offshore areas.

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