DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2017/40

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Contents

Executive summary

The purpose of the project ”Source rock evaluation, Nuussuaq Basin” is to provide new data on the marine mudstones of the Upper Cretaceous Itilli Formation, as a potential source rock in the Nuussuaq Basin. The backbone of the project is the Albian to Early Turonian non-marine to marine succession adjacent to the Ikorfat fault zone on the north coast of Nuussuaq. To a large extent, the project is based on new data from samples and digital images collected during a fieldtrip in July 2016:

1) Numerous images were taken from helicopter. Together with aerial photos they form the basis for a new detailed geological map, a vertical cross-section and a conceptual model for the structural development of the Ikorfat fault zone area on the north coast of Nuussuaq.

2) Several sedimentological sections of the Kome, Slibestensfjeldet and Itilli formations were measured

3) Seventy-five hand specimens were collected for palynological, isotopic and organic geochemical analyses. The samples represent the Lower Cretaceous Kome-, Slibestensfjeldet-, and Atane formations, and the steeply dipping, Upper Cretaceous mudstone succession of the Itilli Formation in the Ikorfat fault zone area. All the Itilli Formation mudstones in northern Nuussuaq, from Ikorfat and westwards, are referred to the Umiivik Member.

Results

- The new photogrammetrical cross-section indicates a fault east of the Ikorfat gneiss high with syn-sedimentary subsidence during the deposition of the Slibestensfjeldet Formation.

- The new detailed geological map from the Ikorfat fault zone indicates a fault boundary between the westernmost outcrop of the Ravn Kløft Member and the Itilli Formation.

- The youngest movements along the Ikorfat fault post-dates the Paleocene volcanic Vaigat Formation. This shows that the Ikorfat Fault zone was active at least from the Albian to the Palaeogene.

- Palynological data from the sections Ikorfat 2016-1, -2 and Ikorfat 2016-5 in the Ikorfat fault zone demonstrate that marine mudstones of late Cenomanian and Turonian ages are present. This marine transgression has been predicted, but hitherto not demonstrated in the Nuussuaq Basin.

- The new sedimentological logs of the Kome, Slibestensfjeldet and Itilli formations show a succession of depositional environments: Floodplain to shallow lake (the Kome Formation), deep water brackish embayment, which became shallower upwards due to progradation of nearshore deposits (the Slibestensfjeldet Formation), fluvial to estuarine deposition within an incised valley (the Ravn Kløft Member of the Atane Formation), and finally a marine transgression and deposition of marine mudstones (the Itilli Formation).

- A conceptual model has been proposed for the structural development of the Ikorfat fault zone with focus on the eastern fault block (the footwall block) during the Cretaceous.
- Data on palynology and stable Carbon isotopes across the Cenomanian-Turonian boundary in the Itilli Formation, indicate that the succession is coeval with the Oceanic Anoxic Event 2 (OAE2).

- Pyrolysis data on the Umiivik Member at Ikorfat show that the succession generally is dominated by inert terrestrial organic matter and does not constitute a source rock. However, a source rock potential may exist in more distal depositional environments west and north of the Ikorfat fault zone, as indicated by the re-calculated analyses from the Umiivik-1 borehole. The timing of hydrocarbon generation is uncertain.

- The re-assessment of the original petroleum potential from the Umviivik-1 borehole at Svartenhuk Halvø indicates that potential source rocks, equivalent to the Kanguk Formation, may be present in the Nuussuaq Basin.

- The events identified in the Ikorfat fault zone are schematically correlated with the tectonostratigraphic sequences, TSS 1–TSS 9, of the Nuussuaq Basin (Dam et al. 2009: fig. 11) and tentatively correlated with the closest seismic lines recorded offshore north of the Ikorfat area.

Introduction

The Oceanic Anoxic Event 2 (OAE-2) is of late Cenomanian—Turonian age, and is globally recognized as a period characterized by deposition of organic-rich mudstones (Jarvis et al. 2011). In the Arctic, dark grey to black mudstones are known from various formations. In Arctic Canada, the Kanguk Formation from the Sverdrup Basin contains hydrocarbon source-rock facies, which have been correlated to the OAE-2 (Núñez-Betelu et al. 1994 a, b; Lenniger et al. 2014). In the Nuussuaq Basin, West Greenland, traces of oil originating from five different source-rocks have been discovered (Bojesen-Koefoed et al. 1999). One of these, the Itilli oil type, is interpreted as originating from marine mid-Cretaceous mudstones. This oil type has similarities with Cenomanian—Turonian oil types from the Cretaceous Western Interior Seaway in the USA (Bojesen-Koefoed et al. 2004).

The Nuussuaq Basin is a rift basin with a post-rift phase of subsidence during the late Cenomanian or Early Turonian to the early Campanian (TSS 2 of Dam et al. 2009). The early part of this phase of subsidence is characterized by a marine transgression and deposition of the Itilli Formation, which is the focus of the present study. A similar transition from non-marine to marine environments is recorded in the Baffin Bay Basin and the Sverdrup Basin, Arctic Canada (Nøhr-Hansen et al. in prep; MacRae et al. 1996).

Upper Cenomanian – Lower Turonian marine strata are poorly known in the Nuussuaq Basin. Previously, strata of late Cenomanian age have only been indicated from two restricted areas on the north coast of Disko and the south coast of Nuussuaq (Pedersen & Nøhr-Hansen 2014), whereas strata of Turonian age were predicted to occur in the lower part of the Umiivik-1 borehole (Dam et al. 1998b). The establishment of the Cenomanian–Turonian boundary in marine sediments at Ikorfat is important for palaeogeographic interpretations and modelling of the distribution of potential source rocks.

The Ikorfat fault zone has been identified as an important structure in the Nuussuaq Basin (Chalmers et al. 1999, Marcussen et al. 2003, Sørensen et al. 2017). The sedimentary succession at Ikorfat comprises the fluvial Kome Formation, the brackish Slibestensfjeldet Formation and the marine Itilli Formation, as shown from new data presented below (Figs 1, 2).

The new information from digital photogrammetry, sedimentology and palynology adds to the understanding of the tectonic development of the Ikorfat fault zone, which separates Lower Cretaceous sediments to the east from uppermost Cretaceous and Paleocene sediments to the west. Neither of these areas, however, include exposures of Cenomanian–Turonian strata. Their preservation within the fault zone may add to the structural interpretation of the seismic data offshore Nuussuaq.

The purpose of this study is to date the Cretaceous sediments palynologically, to correlate the sedimentary succession to other parts of the Baffin Bay area on basis of palynology and stable Carbon isotopes, and to contribute to the interpretation of the structural development of the Ikorfat fault zone.

Geological Setting

Plate tectonics

Oakey & Chalmers (2012) focused on three stages of plate motion between North America and Greenland since the Paleocene: The separation between North America and Greenland + Eurasia during the Paleocene, the continued separation between North America and Greenland plus separation between Eurasia and Greenland during the Eocene, and finally the continued separation between Eurasia and Greenland since the Oligocene.

The Nuussuaq Basin is situated within a complex of rift basins and transfer systems that linked extension and seafloor spreading in the Labrador Sea to the Baffin Bay (Chalmers et al. 1999; Chalmers & Pulvertaft 2001; Oakey & Chalmers 2012; Gregersen et al. 2013; Nøhr-Hansen et al. 2016).

Structural elements in the Nuussuaq Basin

In the Nuussuaq Basin, the early main boundary faults are dominantly NW—SE striking in the northernmost parts on Ubekendt Ejland and Svartenhuk Halvø. On Nuussuaq and Disko, both N—S and NW—SE trends are mapped (Chalmers et al. 1999; Dam et al. 2009; Fig. 3).

The **Ikorfat and Saqqaqdalen faults** together form a major NW—SE striking fault system. The Ikorfat Fault is exposed on the north side of Nuussuaq (Fig. 3) and the Saqqaqdalen Fault on the south side. Together with the Kuuk Fault, they are interpreted as part of the boundary fault system. Chalmers et al. (1999) interpreted them as formed during the Campanian phase of extension and estimated the displacement of the Ikorfat fault to have been in excess of 1275 m during the pre-Maastrichtian phases(s) of faulting. The faults remained active into the Paleocene as the volcanic

Vaigat Formation is displaced at the Ikorfat fault (Pedersen et al. 1996, 2006). The net post-Vaigat Formation downthrow of the Ikorfat fault is 510 m (Chalmers et al. 1999).

The **Kuugannguaq—Qunnilik (K—Q) Fault** is a major structure within the Nuussuaq Basin and is the most prominent N—S striking fault that can be mapped (Fig. 3). Downthrow of the Tunoqqu Surface (marker horizon within the volcanic Vaigat Formation, discussed below) is as much as 700 m to the west across this fault Nuussuaq, but less further south on Disko (Chalmers et al. 1999). A significant fault east of the K–Q Fault was termed Fault P (Chalmers et al. 1999). It is observed as a 700 m displacement of the Vaigat Formation east of Nuuk Killeq at the south coast of Nuussuaq (Pedersen et al. 1993).

The **Itilli Fault** is the only well-defined regional structure that strikes NE—SW across the northwestern part of Nuussuaq and the southeast corner of Hareøen (Fig. 3). The fault is interpreted as a sinistral strike-slip feature that formed the northeastern continuation of the Ungava fault zone. The Itilli Fault is considered to be a young feature that formed after seafloor spreading and volcanism began. Eocene basalts occur only west of the Itilli Fault, which may have about a kilometre of downthrow to the northwest (Chalmers et al. 1999).

The Nuussuaq Basin.

Precambrian crystalline rocks underlie the Mesozoic and Cenozoic basins of West Greenland. In the Nuussuaq Basin, the Precambrian rocks are unconformably overlain by the siliciclastic, pre- and early syn-volcanic sedimentary Nuussuaq Group, which was divided into eight tectonostratigraphic sequences (TSS 1 to TSS8) by Dam et al. (2009, Fig. 4). The basin was formed during two major phases of extension, the first in the Early Cretaceous (TSS 1) and the second in the Late Cretaceous (TSS 3), separated by a quiescent period of thermal subsidence (TSS 2). The Lower Cretaceous deposits in the Nuussuaq Basin are referred to the Kome-, Slibestensfjeldet-, Upernivik Næs-, and

Atane formations (Pedersen & Nøhr-Hansen 2014). Late Cretaceous thermal subsidence resulted in deposition of the Kangeq Sequence off Greenland and the Itilli Formation as well as the Qilakitsoq Member of the Atane Formation in the Nuussuaq Basin. Renewed tectonism is identified by an early Campanian unconformity in the Nuussuaq Basin (Dam et al. 2000). Three major tectonic episodes, involving major extension and creation of fault-blocks, are recognized in the latest Maastrichtian – earliest Paleocene, each associated with incision of valley systems and development of submarine canyons, TSS 4 to TSS 6 (Fig. 4). The arrival of the Icelandic plume beneath Greenland in the Paleocene resulted in eruption of volcanic rocks that covered the basin (TSS 7, TSS 8, Dam et al. 1998a; Dam et al. 2009, Nelson et al. 2015, Larsen et al. 2016). The West Greenland Basalt Group (Clarke & Pedersen 1976) comprises five formations of Paleocene–Eocene age, of which the Vaigat Formation is important in the Ikorfat area (Pedersen 1985, Larsen et al. 2016). The unconformity between the sedimentary deposits and the overlying volcanic rocks increases in duration eastwards in the basin (Dam et al. 2009: fig. 16). The oldest volcanic rocks of the Vaigat Formation erupted during Chron C27N (Larsen et al. 2016), which is also the oldest undisputed magnetic anomaly in the Labrador Sea (Chalmers & Pulvertaft 2001). In addition, Oakey & Chalmers (2012) interpreted the oldest magnetic anomaly in the Baffin Bay as C27N. Thus, there is a close association between the onset of volcanism in the Nuussuaq Basin and the initiation of seafloor spreading between Greenland and Canada. The Eocene was marked by large-scale flood volcanism in the region, but the rocks are only preserved northwest of the Itilli Fault (Nelson et al. 2015; Larsen et al. 2016). The Eocene volcanic rocks probably covered most of the Nuussuaq Basin, but have since been eroded during subsequent post-breakup uplift events that form the present day high topography of the region (Green et al. 2013).

Compression and inversion

Compressional folds are observed in seismic profiles from the Vaigat and in the Uummannaq Fjord (Chalmers et al. 1999; Marcussen et al. 2002). An inversion zone has been mapped by Sørensen (2011), based on a photogrammetric map of a well-defined volcanic horizon (the Tunoqqu Surface), which is the top of a thin volcanic marker horizon, the Tunoqqu Member of the Vaigat Formation (Pedersen 1985, Pedersen et al. 2017). This top surface was originally sub-horizontal. Around the Qunnilik valley, the surface has been uplifted and faulted into many small blocks by numerous faults, so that it now forms an asymmetric anticline with a steeper dipping western limb and a gently dipping eastern limb (Sørensen 2011; Sørensen et al. 2017; Fig. 3). This structure is interpreted as the result of inversion, which must post-date the deposition of the Naujánguit Member, and probably pre-date the movement along the Itilli fault zone. The inversion may therefore have taken place in the latest Paleocene (Sørensen et al. 2017). This is coincident in time with the inferred formation of inversion structures in the Nuussuaq basin offshore western Disko (Gregersen & Bidstrup 2008).

The Melville Bay area

The Melville Bay area (northeastern Baffin Bay Basin) is known from seismic surveys, which outline three basins (the Melville Bay Graben, the Kivioq Basin and the Upernavik Basin), which are separated by the Melville Bay Ridge and the Kivioq Ridge and are bounded southwards by the Upernavik Escarpment (Gregersen et al. 2013). Eight major depositional units A–H are distinguished. Unit H comprises Precambrian and Lower Palaeozoic rocks, the Cretaceous, Paleocene and Eocene deposits constitute units G, F, and E; and unit A includes the Pliocene and Quaternary deposits (Gregersen et al. 2013: fig. 4). Recently, a number of fully cored boreholes were drilled, primarily in the Kap York Basin, by a consortium of oil companies (Nøhr-Hansen et al. in prep.). The cores document the presence of Neoproterozoic to Turonian sediments overlain by Quaternary deposits. The Lower Cretaceous is mainly non-marine to marginally marine, and the oldest open marine deposits (with marine dinocysts) are late Cenomanian (Nøhr-Hansen et al. in prep).

Seismic Survey

Seismic interpretation is not the main scope of this study, which merely aims at providing a broad correlation from the onshore geology to the limited offshore seismic data. In order to get a proper stratigraphic control from the onshore to the offshore a dedicated study is needed. A seismic survey acquired in 2000 (GEUS2000) resulted in 67 seismic lines north, west and south of the Nuussuaq peninsula. Two of the seismic sections (GEUS00-16 and GEUS00-17) are of particular interest to this study, as they are positioned only a few kilometres offshore and are sub-parallel to the coastline at Ikorfat (Fig. 5A, B). The sections cover a much broader area than the sampling sites and the most easterly and westerly parts are omitted. About two thirds of the length of the sections are shown in the interpretation and cover the distance from west of the GANT#1 onshore well to east of the Ikorfat fault zone (Fig. 5A). The vertical exaggeration of the seismic profiles is c. 1:5. Hence, the apparent dip of the reflectors are exaggerated in Figures 5F, G. The sections GEUS00-16 and GEUS00-17, north of the Ikorfat fault zone, are broadly interpreted and correlated to the onshore geology based on a simplified geological cross-section (Fig. 5D).

The seismic signals suggests that the lowest yellow line marks the boundary to the acoustic basement, although acoustic noise and possibly multiples hamper interpretation of this part of the profile. The Ikorfat fault zone is interpreted to be to 5 km wide (Fig. 5F, G; Fig. 6). A more detailed interpretation of the tectonic development of the Ikorfat fault zone would require additional seismic data. Figure 6 shows a close up of the seismic interpretation.

The seismic sections indicate that a package of eastward dipping sedimentary strata reaches the sea floor immediate east of the Ikorfat fault zone. It has not been possible to correlate the seismic reflectors to the onshore profile at formation or member level. It is suggested that the lowermost interpreted reflector (outlined in yellow) corresponds to the base of the Kome Formation that lies unconformably on top of the basement (as observed onshore northern Nuussuaq). The uppermost interpreted reflector may correspond to the upper part of the preserved Itilli Formation. West of the Ikorfat fault zone there are a number of sills (bright amplitudes) which may be related to the sill geologically mapped onshore at Serfat (see Fig. 5B, E). The thick succession of sub-horizontal lava flows, which form the top of the stratigraphic succession at Ikorfat, is not seen in the seismic sections due to the deep level of erosion in the fjords.

Material and methods

In the summer 2016, forty-five silty to sandy mudstones samples were collected from a 535 m thick succession east of the Ikorfat fault zone. The samples represent the upper part of the Kome Formation, most of the Slibestensfjeldet Formation, possibly the Atane Formation and the lowermost part of the Itilli Formation and thirty silty mud-stones samples were collected from a 298 m thick succession of the Itilli Formation within the Ikorfat fault zone.

All the samples have been studied for:

- Palynomorphs in order to date the succession.
- Isotope composition of the bulk kerogen in order to establish a $\delta\ C^{13}_{org}$ carbon isotope stratigraphy.
- TC/TOC/TS and subjected to Rock-Eval type screening pyrolysis in order to evaluate the source rock potential.

Results

The sedimentary succession in northern Nuussuaq

The Lower Cretaceous in northern Nuussuaq is referred to the Kome Formation, the Slibestensfjeldet Formation and the Atane Formation (Ravn Kløft Member and Kingittoq Member) (TSS 1, Fig. 4). Precambrian basement, overlain by the fluvial Kome Formation is exposed locally between Kuuk (east) and the Ikorfat fault zone, which defines the western boundary of the gneiss promontory at Ikorfat (Figs 1, 7).

The Kome Formation

The Kome Formation drapes the Precambrian basement at Ikorfat and is displaced along a fault, which was active during deposition of the Slibestensfjeldet Formation (Fig. 8). The formation is less than 100 m thick above the gneiss (Fig. 8). In this area section 2016-3 was sampled. Fine-grained sandstones interbedded with silty mudstones with comminuted plant debris dominate the formation (Fig. 9). Thin coal beds, 5–15 cm thick, occur in the lower part of the succession, and rootlets are observed locally. Three sandstone facies are present. 1: Lenses and 5–10 cm thick homogeneous beds of fine-grained sandstone, locally with coal-clasts, are interbedded in mudstone. 2: Tabular sandstones, 20–100 cm thick, with parallel lamination, ripple cross-lamination and flaser-bedding. Locally the sandstone is homogeneous. The base of the sandstones may show current-generated sole-marks. The sandstones occur as isolated beds or form the lower part of short upwards-coarsening (CU) successions. 3: Channelized, trough cross-bedded fine to medium-grained sandstones, generally less than 1 m thick, occur either as isolated sandstone bodies interbedded in the mudstones or as the top of the short CU-successions.

These sedimentary facies indicate deposition in a floodplain with small, possibly ephemeral streams, swamps where the accumulation of plant debris now forms thin coal beds, and shallow lakes, where the streams built short CU successions during progradation of mouth-bars. Thicker fluvial sandstones, 2–4 m, occur in the Kuuk area (Pulvertaft 1979). The upper boundary of the Kome Formation is placed at a coal bed (Midtgaard 1996b; Dam et al. 2009). This bed is indistinct at Ikorfat, and the boundary between the Kome and the Slibestensfjeldet formations is inconspicuous.

The Slibestensfjeldet Formation

The Slibestensfjeldet Formation overlies the Kome Formation and is exposed between Slibestensfjeldet (east) and Ikorfat to the west (Dam et al. 2009: fig. 22). The formation is c. 80 m thick at Slibestensfjeldet, and is here dominated by fine-grained sandstones with wave-generated bedforms, similar to those characteristic of inner-shelf and lower-shoreface marine environments (Midtgaard 1996a). Later studies have shown that the water-body was fresh to brackish (Pedersen & Nøhr-Hansen 2014; present study). At Kussinikassaq, a short distance east of Ikorfat, the Slibestensfjeldet Formation is dominated by mudstones and is c. 200 m thick (Dam et al. 2009). The photogeological section in Figure 8 indicates an apparent thickness of c. 300 m at Kussinikassaq, but this is due to a projection effect because the strata are dipping gently to the north. Above the basement at Ikorfat the Slibestensfjeldet Formation is c. 150 m thick according to the photogrammetric section (Fig. 8).

The basal 8–10 m of the Slibestensfjeldet Formation forms a CU-succession, which is dominated by tabular sandstone with parallel lamination and wave-ripple cross-stratification (Fig. 10). These structures suggest that the floodplain of the Kome Formation developed into a shallow lake at the transition to the Slibestensfjeldet Formation. Samples were collected in section 2016-4. New data, presented below, indicate that the Kome and Slibestensfjeldet formations are Albian.

The lower part of the Slibestensfjeldet Formation is dominated by dark grey, silty mudstones with a moderate fissility. The transition from the sandstones below to the mudstones is sharp, and is interpreted as a drowning surface. The mudstone includes 5–10 cm thick beds of very fine to fine-grained sandstone, cemented by a yellow-weathering mineral (Fig. 11). Higher up in the mudstone succession the number and thickness of the sandstone beds increases. The upper part of the Slibestensfjeldet is distinctly upwards coarsening (Fig. 12). The muddy siltstone contain thin sand-streaks and beds of fine-grained, parallel laminated sandstone, locally with wave-ripple cross-lamination. Towards the top of the formation, the sandstone becomes medium-grained and cross-bedded. Midtgaard (1996b) reported a Gilbert delta type in the top of the formation.

In a small gully, informally called "Skredkløft", the sandstones from the upper part of the Slibestensfjeldet Formation are seen to be redeposited as part of slides. The overlying slide involved coarser sandstones, which may represent fluvial sandstones from the Ravn Kløft Member (Figs 13, 13a). This is further discussed in section 5.5.

Ravn Kløft Member and Kingittoq Member of the Atane Formation

The Slibestensfjeldet is truncated by an erosional surface, overlain by fluvial sandstones of the Ravn Kløft Member of the Atane Formation. This boundary is well-exposed in the gullies Kussinikassaq and Angiarsuit, east of Ikorfat (Fig. 12). In the central parts of the member the fluvial facies are interbedded with deltaic and tidal estuarine deposits. The uppermost unit comprises amalgamated fluvial multi-storey sandstone sheets (Midtgaard 1996b; Dam et al. 2009). The Ravn Kløft Member may constitute the fill of a large valley. The member was not sampled in 2016, and the biostratigraphy is based on a low number of samples (Dam et al. 2009, Pedersen & Nøhr-Hansen 2014). The Ravn Kløft Member is conformably overlain by interbedded mudstones and sandstones, interpreted as delta plain deposits of the Kingittoq Member of the Atane Formation (Midtgaard 1996b; Dam et al. 2009). The western boundary of the two members may be a fault, discussed in the paragraph on structural geology below (Figs 7, 8).

The Itilli Formation

The Itilli Formation at Ikorfat is dominated by grey mudstones, with range from dark-grey paper-shales to medium-grey silty mudstone adjacent to fine-grained sandstone beds. The formation was previously known only from a small outcrop of Maastrichtian strata in the Ikorfat fault zone (Birkelund 1965; Kennedy et al. 1999; Fig. 14).

Field observations, supported by photogrammetrical data, indicate that the lower boundary of the Itilli Formation in the Ikorfat area may be present in the top of section Ikorfat-2016-4 (Fig. 11). The lower boundary appears to be a drowning surface (Fig. 2). This overlies the deformed strata (upper part of the Slibestensfjeldet Formation, and probably parts of the Ravn Kløft Member) in "Skredkløft". The palynological samples from the upper part of Ikorfat-2016-4 indicate a gradual change from a brackish to a marine environment (see below). A series of up to 30 cm thick sandstone beds occur in the top of section Ikorfat-2016-1 (Fig. 15). Some of these are poorly sorted medium- to coarse-grained sandstones with load-casts and clearly erosive basal surfaces. Other beds consist of fine-grained sandstone with parallel lamination and ripple cross-lamination in places. The sandstones are interpreted as deposited from sediment gravity flows (Fig. 15).

In the outcrops at Ikorfat, the most remarkable feature of the formation is the occurrence of redeposited mega-clasts of sandstone. In the northern part of the outcrop a white, coarse-grained sandstone clast is seen (Fig. 16). It is c. 5x 10 m in the outcrop and its third dimension is unknown. Apparently the sandstone was deposited as part of a channel and was transported as part of a mudslide. Further south, the mudstones include clasts, which represent parts of more than 10 m thick sandstone beds (Fig. 17). These clasts were probably transported by a slide, and deformation structures suggest that they were weakly cemented prior to the time of transportation.

The mudstones in the Ikorfat Fault Zone are referred to the Umiivik Member of the Itilli Formation. This member is interpreted as deposition from turbidites and fall-out from suspension in a base-of slope and basin floor fan environment (Dam et al. 1998b, 2009), and is known from various outcrops (Birkelund 1965; Nøhr-Hansen 1996; Pedersen & Nøhr-Hansen 2014). The Umiivik Member has its type section in the Umiivik-1 well at Svartenhuk, where it is interpreted to include most of the Upper Cretaceous (Dam et al. 1998b, 2009). The Umiivik Member is exposed along the north coast of Nuussuaq between Ikorfat and Niaqornat, but here the exposed strata are Campanian to early Maastrichtian (Fig. 14). The new results suggest that a complete succession of the Umiivik Member may be present in the subsurface west of Ikorfat. Mudstones in a source-rock facies may occur in parts of the Umiivik Member, which are not known at present.

The sedimentary succession west of the Itilli fault zone

West of the Ikorfat fault zone the outcrops are dominated by upper Cretaceous to Paleocene marine mudstones of the Itilli Formation (Umiivik Member) and the Kangilia Formation (Annertuneq Conglomerate Member and overlying Kangilia Formation), which are exposed between Serfat and Niaqornat (Fig. 14). Marine syn-volcanic mudstones of the Eqalulik Formation are present, although often poorly exposed, below the volcanic Vaigat Formation along the north coast of Nuussuaq from Niaqornat and eastwards across the Ikorfat fault zone and further east (Figs 7, 8, 14).

Palyno- and chrono-stratigraphy

A total of 19 palyno-events have been identified in the Ikorfat fault zone representing the youngest or last occurrence (LO), oldest or first occurrence (FO) of a taxon or peak occurrences, so-called acmes (Figs 18–19). The events have, when possible, been correlated with the palyno-events previously described for the Albian to Turonian strata of the Nuussuaq Basin, West Greenland (Pedersen & Nøhr-Hansen 2014). Stratigraphic marker species are illustrated on Figure 20. The timescale of Gradstein et al. (2012) has been followed.

Palynology of the Albien –Cenomanian Ikorfat 2016-3 & -4 sections east of the Ikorfat fault zone

Forty-five silty to sandy mudstones samples were collected from a 535 m thick succession east of the Ikorfat fault zone succession in the summer of 2016. The samples represent the upper part of the Kome Formation, most of the Slibestensfjeldet Formation, possibly the Atane Formation and the lowermost part of the Itilli Formation

The organic material from the 12 samples representing the upper part of the Kome Formation is dominated by coal particles, tracheids, physical degraded terrestrial organic material and barren or very poorly recognisable miospores and dinocysts (Fig. 18).

The presence of few poorly preserved specimens of *Hurlandsia rugara, Pseudoceratium interiorense* and *Vesperopsis nebulosa* in the lowermost samples, the FO of *Wuroia* spp. and the FO of common *Pseudoceratium interiorense* in the upper part of the Kome Formation support a middle Albian age for the uppermost Kome Formation as suggested by Pedersen & Nøhr-Hansen (2014). The lower part of the Kome Formation exposed at Majorallattarfik (fig. 21 in Dam et al. 2009) was tentatively dated as late Aptian, early Albian, or middle Albian based on a very sparse content of miospores (Pedersen & Nøhr-Hansen 2014).

Twenty-three closely spaced samples from the lower part of the Slibestensfjeldet Formation (Fig. 11) consist of a low diversity assemblage of brackish water indicator species characterised by common to abundant *P. interiorense* and by the FO and LO of *Nyktericysta tripenta.* In the present study *Hurlandsia rugara, N. tripenta* and *P. interiorense* all seems to have LO in the uppermost Slibestensfjeldet Formation. However in the previous study by Pedersen & Nøhr-Hansen (2014) *Nyktericysta tripenta* (as *Balmula tripenta*) and *P. interiorense* was shown to range into the lower part of Ravn Kløft Member (lower part of the Atane Formation) at type section locality.

Three samples from the upper part of the Slibestensfjeldet Formation are almost barren of palynomorphs.

The Atane Formation is characterised by common *Rugubivesiculites rugusus* pollen, the brackish water dinocyst indicators *Nyktericysta* aff. *arachnion, Vesperopsis* aff. *pseudo-vitrea* and *Wuroia corrugata* and a few specimens of the acritarch genus *Limbicysta*. A similar assemblage was previous reported from the Atane Formation in the upper part of the FP93-3-1 borehole and from the Kamaffiaraq section, northern Disko (Pedersen & Nøhr-Hansen 2014), as well as from the upper Albian/Lower Cenomanian Baston Ridge and Strand Fiord formations of at Axel Heiberg Island, arctic Canada (MacRae et al. 1996). The two formations represent an overall regression from dominantly marine to dominantly terrestrial deposition overlain by the marine Kanguk Formation (MacRae et al. 1996; Schröder-Adams et al. 2014).

The FO of the dinocyst species *Nyktericysta davisii* has been recorded as a palyno-event for the uppermost Slibestensfjeldet Formation at the type locality at Kussini-kassaq and for the lowermost part of Ravns Kløft Member (Pedersen & Nøhr-Hansen 2014). The absence of *Nyktericysta davisii* in the Ikorfat section indicate that the upper part of Slibestensfjeldet Formation is missing here, and support the observations in the field and in the photogrammetry that Ravns Kløft Member is not preserved in section 2016-4.

Four samples possibly representing the lower part of the Itilli Formation east of the Ikorfat fault zone all yielded common *Rugubivesiculites rugusus* pollen. The influx of *Euryduniym, Florentinia, Odontochitina, Oligosphaeridium* and *Xenascus* species in the lower part of the Itilli Formation indicate a transition to more marine water conditions. The FO of *Xenascus ceratioides* indicate an Albian or younger age. The presence of *Eurydinium* aff. *ingramii, Odontochitina* cf. *rhakodes* and a *Nyktericysta davisii* specimen with long horns may indicate an Early Cenomanian age. A similar transition have been recorded from the upper part of the Kamaffiaraq section, northern Disko (Pedersen & Nøhr-Hansen 2014).

Palynology of the Cenomanian–Turonian Ikorfat 2016-1, -2 & -5 sections within the Ikorfat fault zone

The lowermost sample from the c. 300 m thick succession of grey mudstones of the Itilli Formation within the Ikorfat fault zone (Figs 15, 21) is also dominated by coal particles, tracheids and physically degraded terrestrial organic material. The presence of common *Systematophora cretacea* and a single *Spiniferites* sp. are the only marine indicators (Fig. 19). According to Davey (1979) and Prössl (1990) the presence of *S. cretacea* suggests a late Albian or possible Early Cenomanian age.

The diversity and numbers of marine dinocyst specimens increase upward within the next six samples dated as late Cenomanian based on the FO and common occurrences of *Isabelidinium magnum, Surculosphaeridium longifurcatum* and the *Cyclonephelium compactum/membraniphorum* complex. *Isabelidinium magnum* has a FO in the late Cenomanian (Costa & Davey 1992). The *C. compactum/membraniphorum* complex has a FO in the latest Cenomanian and appear as common to abundant across the Cenomanian–Turonian Oceanic Anoxic Event 2 (OAE2) boundary event Figure 22 (Marshall & Batten 1988; Pearce et al. 2009; Olde et al. 2015; van Helmond et al. 2016).

The upper Cenomanian–Lower Turonian transition at Ikorfat is characterised by a low diverse dinocyst assemblage and by a *Rugubivesiculites rugosus* acme. The base of the Turonian is tentatively picked by the FO of *Heterosphaeridium difficile* at 405m, followed by the FO of *Chatangiella* species and *Odontochitina* cf. *rhakodes* at 425m. The FO of *H. difficile* and LO of *O. rhakodes* indicate an Early Turonian age according to Costa & Davey (1992), Pearce et al. (2003) and Fensome et al. (2008) respectively. The numbers of *Rugubivesiculites rugosus* decrease in the upper part of the succession whereas the dinocyst diversity increase, the assemblage is dominated by *Chatangiella* species and *Trithyrodinium suspectum*. The presence of *Palaeoperidinium eurypylum* at the top of the section may indicate an age no younger than Early Turonian (Costa & Davey 1992). An Early Turonian age for the top of the section may also be indicated by the FO of *Senoniasphaera* cf. *rotundata* and by the presence of relatively few *H. dificille* specimens, *H. dificille* is often very abundant in the middle Turonian (Bailey, D. and BioStrat, 2017 http://www.biostrat.org.uk/index.html#).

The palynological assemblage from the Itilli Formation succession within the Ikorfat fault zone correlates with similar assemblages of late Cenomanian–Early Turonian age from the organic-rich "paper" shale of the lower part of the Kanguk Formation on Axel Heiberg Island, Arctic Canada Figure 18 (Núñez-Betelu et al. 1994a, b; Lenniger et al. 2014; Fig. 1b), and from the north-east Baffin Bay coreholes (Nøhr-Hansen et al. in prep.)

δ^{13}C bulk organic curves

The δ^{13}C bulk organic profile across the Cenomanian-Turonian boundary in the Itilli Formation, at Ikorfat, mirrors a positive organic carbon excursion, with a maximum coinciding with the FO of common species of the *Cyclonephelium compactum/membraniphorum* complex (Fig. 23). The organic carbon values decrease upwards in the succession below the FO of *Heterosphaeridium difficile* (Fig. 19 and Fig. 23). Similar excursion pattern below the FO of *H. difficile* have been recorded from the Kanguk Formation at Axel Heiberg Island Canada and from the Global Boundary Stratotype Section Point at Pueblo, Colorado, USA (Lenniger et al. 2014, Fig. 23), whereas the *C. compactum/membraniphorum* complex has been recorded common to abundant from the start and across the Cenomanian–Turonian Oceanic Anoxic Event 2 (OAE2) boundary event in Europe and USA (van Helmond et al. 2016, Fig. 22).

Source Rock potential

A total of 75 samples, representing two composite profiles: Ikorfat 2016-3, -4 (45 samples) and Ikorfat 2016-1, -2, -5 (30 samples) were analysed for petroleum potential (Figs 24–25). Total Carbon (TC, wt-%), Total Organic Carbon (TOC, wt-%) and Total Sulphur (TS, wt-%) were determined by combustion in a LECO CS-200 induction furnace.

Petroleum potential was determined by Rock-Eval-type pyrolysis using a Source Rock Analyzer (SRA) instrument.

The Ikorfat 2016-3, -4 profile shows near-identical values of total carbon (TC) and total organic carbon (TOC) ranging from slightly less than 1 wt-% to nearly 27 wt-%, and the deposits thus contain very little mineral-bound carbon. The source-rock pyrolysis analysis registers parameters such as total sulphur (TS), S1 (the amount of bitumen present in the sample), S2 (the amount of bitumen and gas generated from kerogen), and T_{max} (the temperature of maximum generation of hydrocarbons during S2). In the samples from sections 2016-3 and 2016-4, TS is invariably very low, and the S1 yield is < 0.31 mg/g. The S2 pyrolysis yield is generally < 7 mg/g, with a single sample showing approx. 40 mg/g, which results in consistently low values of the Hydrogen Index (HI), 3–152. Although a few stray values are recorded, T_{max} is close to 435 °C on average and the Production Index (PI) is low (Figs 24–25).

The sections Ikorfat 2016-1, 2016-2, and 2016-5 in general show almost identical values of total carbon (TC) and total organic carbon (TOC), ranging from slightly more than 1 wt-% to nearly 5 wt-%, with an overall upwards decreasing trend. Total sulphur (TS) is variable. Low values (<0.60 wt-%) are found at the base of the profile, whereas the interval approx. 340-425 m, which straddles the Cenomanian – Turonian transition, shows variable, but generally somewhat higher values (approx. 1–5 wt-%) with a trend very similar to that of the stable carbon isotopic data. From approx. 425m to the top of the profile S1 yields are consistently very low (< 0.13 mg/g), as are S2 pyrolysis yields (< 3.06 mg/g), which results in consistently low values of the Hydrogen Index (HI), 5–95. Although a few stray values are recorded, T_{max} is close to 435 °C on average and the Production Index (PI) is low, <0.12 (Figs 24–25).

Discussion of source rock potential

The Lower Cretaceous deposits, sections Ikorfat 2016-3, and 2016-4 are a succession of thermally immature/early mature mudstones, containing fairly high proportions of terrestrial type III/IV kerogen with little or no potential for generation of petroleum (Figs 24–25). The very low contents of sulphur suggest deposition in fresh- to brackish-water environments with little if any marine influence, which is also indicated by the presence of coal-like deposits with TOC close to 27 wt-% near the base of the profile. An increasing trend in TS, initiated in the upper portion of the succession at the transition to the Cenomanian may point to increasingly marine depositional conditions. The Upper Cretaceous deposits, sections Ikorfat 2016-1, 2016-2, and 2016-5 represent a succession of thermally immature/early mature mudstones, containing fairly high proportions of terrestrial type III/IV kerogen with little or no potential for generation of petroleum (Figs 24–25). The moderate to high levels of sulphur are conformable with a marine or marginal marine depositional environment; in particular the interval straddling the Cenomanian-Turonian transition is enriched in sulphur. However, the enrichment is not accompanied by a corresponding increase in petroleum potential, probably due to an inherently inert nature of the kerogen.

Developments of enhanced petroleum generation potential in deposits of Cenomanian-Turonian age is frequent and known worldwide (eg. Jarvis et al. 2011; Kuhnt et al. 1990), albeit contingent on local depositional conditions, which at the Ikorfat locality clearly were unfavourable. From the greater Baffin Bay area highly prolific petroleum source rocks of Cenomanian – Turonian age are known from the Kanguk Formation on Ellesmere Island, Canada (Núñez-Betelu 1993; Núñez-Betelu et al. 1994 a, b), and on Svartenhuk Halvø, some 80 kilometres North of the Ikorfat location, the Umiivik-1 fully cored borehole penetrated approx. 1200 m marine mudstones, the upper c. 540 m of which are dated to the Late Turonian – Coniacian (Dam et al. 1998b). The deposits are pervasively intruded by doleritic intrusions, three of which are very thick and have heated the host formation to render biostratigraphic dating impossible and petroleum geochemical analysis very difficult in the deeper part of the drilled succession. Hence, post oil-window maturity (i.e. vitrinite reflectance Ro>1.3%) prevails at depth greater than approximately 450m, and palynomorphs are generally destroyed. However, still it seems reasonable to assume the borehole penetrates into the Cenomanian. The Umiivik-1 sedimentary succession represents the distal part of a major turbidite complex, probably the northwards extension of the complex known from further south in western and northern Nuussuaq, see Dam and Sønderholm (1994) for details. There is a general upwards coarsening/thickening and increase in density of bioturbation throughout the entire succession.

Source-rock potential of the Itilli Formation in the Umiivik-1 borehole

Based on sedimentological evidence, the lowermost part of the sedimentary succession in Umiivik-1, approx. 1050 – 1200m, was generally deposited under some level of oxygen restriction, and the presence of an original petroleum source potential in this interval is indicated by the fact that the cores were saturated with wet hydrocarbon gases that even caused audible fracturing of the rocks when the cores were retrieved. This was not observed in overlying parts of the succession, despite very high levels of thermal maturity. Moreover, unpublished C-isotopic data may perhaps suggest the interval mentioned may correlate to the Cenomanian – Turonian isotopic excursion observed in the Ikorfat 2016-1, -2, -5 profile. Hence, accepting that the interval approx. 1050 – 1200 m in the Umiivik-1 borehole wholly or partly corresponds to the interval approx. 340 – 490 m in the Ikorfat 2016-1, -2, -5 profile (defined by the $\delta^{13}C$ excursion), recalculation of the original petroleum potential of the lowermost part of the Umiivik-1 succession may give an indication of the development of petroleum potential along the axis of the turbidite system. This can be done according to the procedure of Peters et al. (2005) followed by calculation of the "source potential index" ("SPI") of Demaison and Huizinga (1991, 1994) as: ***SPI = Thickness of unit * (mean S1 + mean S2) * rock density / 1000***.

The SPI conveniently combines source rock thickness and richness into one parameter which can be used for easy comparison of units, provided that these are at the same level of thermal maturity. The SPI thus represents the total amount of petroleum (in Tonnes) that ultimately may be generated from column of source rock with a height corresponding to the thickness of the unit and an area of one square metre. Since the Ikorfat section is thermally immature, no recalculation is needed, whereas virtually all original petroleum generation potential is exhausted in the Umiivik-1 succession, which is thus recalculated. Calculation of SPI is done assuming a thickness of 150m for both successions and the results are listed in Table 1.

Input data:	TOC* (wt-%)	S1* (kg/T)	S2* (Kg/T)	HI*	PI*
Ikorfat	2,6	0,01	0,49	19	0,01
Umiivik	2,4	1,1	0,3	12	0,82
Recalculated data:	Thickness (m)	TOC (wt-%)	S1+S2 (Kg/T)	HI	SPI (T/m^2)
Ikorfat	150	2,6	0,5	19	0,2
Umiivik	150	3,4	4	400	5,3

Table 1. Estimation of original petroleum potential and SPI, for details of calculation see Peters et al. (2005), Demaison & Huizinga (1991, 1994). TOC*, S1*, S2*, HI*, PI*: measured average values for interval.

Bearing in mind the uncertainty arising from the assumptions made in order to do the recalculation and SPI-assessment, the results hint at increasing petroleum potential in more distal localities of deposition during the Cenomanian – Turonian, as also shown by the very high petroleum potential displayed by the shales of the lower part of the Kanguk Formation on Ellesmere Island. This observation may have important implications for exploration in the greater Baffin Bay area, contingent on the detailed basin evolution during the interval.

Structural geology

The first phase of rifting (TSS 1) is characterized by deposition of non-marine, Lower Cretaceous deposits belonging to the Kome Formation, the Slibestensfjeldet Formation, and parts of the Atane Formation (the Ravn Kløft Member and the Kingittoq Member) (Dam et al. 2009). Their ages are interpreted as Albian—middle Cenomanian (Dam et al. 2009; Pedersen & Nøhr-Hansen 2014, and new data in the present report (Fig. 4 and Fig. 18).

The first indication of extension at Ikorfat, after deposition of the Kome Formation, is the syn-sedimentary fault on the eastern side of the gneiss promontory (Fig. 8). This fault is not directly observed in the field but is inferred as an explanation for the c. 200 m difference in altitude of the basal mudstones of the Slibestensfjeldet Formation from Kussinikassaq to the gully with section Ikorfat-2016-3. (Fig. 26 Diagram A, B).

After the deposition of the Slibestensfjeldet Formation the area must have been subject to a phase of relative base-level fall, which generated the erosional unconformity at the base of the Ravn Kløft Member. The base-level fall may have been caused either by uplift (a response to movement of larger fault blocks?) or fall of the water table in the large body of water where the Slibestensfjeldet Formation was deposited. This water body was large enough to generate sedimentary facies similar to those of lower shoreface and inner shelf marine environments. The fluvial and estuarine deposits were deposited during slowly rising base-level. The boundary between the Ravn Kløft Member and the Kingittoq Member is interpreted as a drowning surface, and the Kingittoq Member may have been deposited during an early phase of base-level rise, prior to deposition of the Itilli Formation.

The second indication of extension in the vicinity of the Ikorfat fault zone is represented by the slides, which displaced the upper part of the Slibestensfjeldet Formation and probably the Ravn Kløft Member (Figs 13, 13a). Increased subsidence west of Ikorfat generated a set of rotated extensional fault blocks above a decollement surface, which was probably located c. 40—50 m above the base of the Slibestensfjeldet Formation. The north-facing slope of the Skredkløft gully shows that large blocks of sandstone were transported in a matrix of mudstone (Figs 13, 13a). The initial slide seems to involve only the upper part of the Slibestensfjeldet Formation, and the sandstones appear to have been transported on a layer of mudstone without significant fragmentation. The following, overlying, slide contains blocks of white sandstone in a matrix of mudstone. These sandstones are coarser-grained and more fragmented. One example suggests that the sandstone clast moved with sufficient energy to deform an underlying thin sandstone bed (Figs 13, 13a).

At the top of Skredkløft, the boundary between the deformed sandstones and the overlying beds of the Itilli Formation is fairly well exposed. This succession was sampled in the upper part of section Ikorfat-2016-4 (Figs 11, 18). This suggests that the slides formed during the initial phase of TSS 2, in the early to middle Cenomanian. (Fig. 26 Diagram B–D).

A younger phase of extension initiated extensional fault blocks above a new decollement surface, and resulted in movement of large sandstone clasts. These are exposed in the steeply dipping beds in the southern end of the exposure in the fault zone (Figs 16, 17). These slides formed in the Late Cretaceous during TSS 2. Later downwards drag on the fault block west of the Ikorfat fault zone could explain the steep dip (60° to vertical) of the strata (Fig. 26 Diagram E). A small outcrop of the Itilli Formation with a Maastrichtian ammonite fauna is preserved east of the youngest trace of the Ikorfat fault (Birkelund 1965; Kennedy et al. 1999). This block was uplifted during TSS 4–TSS 6, and subsequent erosion has removed any Upper Cretaceous–Paleocene deposits as well as the upper part of the Kingittoq Member on the eastern block. The resulting sub-horizontal surface was transgressed in the Paleocene and overlain by marine, syn-volcanic mudstones of the Eqalulik Formation. These were subsequently overlain by the hyaloclastites of the Vaigat Formation (Fig. 26 Diagram E).

Movements along the Ikorfat Fault during the Paleocene, and later, can be deduced from the volcanic succession (Pedersen et al. 2017). A photogrammetric section shows that the hyaloclastites as well as the lava flows systematically are thicker west of the fault (A.K. Pedersen pers. comm. 2017). This indicates continuous larger subsidence to the west. Possibly, compaction of the fine-grained sediments (Itilli and Kangilia formations) may have contributed to the generation of increased accomodation space west of the fault (A.K. Pedersen pers. comm. 2017). The last movement down-faulted the lava succession west of the fault and this movement must be younger than the volcanic succession (Selandian).

Discussion

Mudstones in source rock facies in the Umiivik Member of the Itilli Formation in the northern part of the Nuussuaq Basin

Sørensen et al. (2017) presented a map showing the inferred distribution of the Itilli Formation based on the known outcrops and the occurrences of hydrocarbons of the Itilli oil type (Fig 27). It is notable that most of the oil seeps are discovered close to fault zones. It was also suggested that the lower Itilli Formation was probably sufficiently buried to have generated oil in large areas west and north-west of the Ikorfat fault based on sediment thicknesses modelled by Chalmers et al. (1999). The Itilli Formation was judged to be source prone in an area of regional extent both offshore and onshore in western Nuussuaq and Svartenhuk Halvø, although the timing of hydrocarbon generation is highly uncertain (Sørensen et al. 2017).

The recalculation of the geochemical parameters of the mudstones in the lower part of the Umiivik-1 well suggest that these mudstones have source-rock potential outside areas of igneous intrusions (paragraph 5.4.1). In contrast, the present study indicates that the Umiivik Member is without source-rock potential in the studied samples, due to the dominance of terrestrial organic matter (Figs 24, 25).

The project is carried out within a fault zone, and consequently the complete stratigraphic section may not be present. In addition, the samples were collected before the complex structures were fully understood. It is therefore possible, that future sampling may reveal levels with larger amounts of marine organic matter.

A significant result of the present study is that the presence of marine, Lower Turonian mudstones has been confirmed. This is an important contribution to the understanding of the palaeogeography of the Nuussuaq Basin, and for future models of the regional source-rock potential.

Correlation Kanguk Formation, May Point, Canadian margin, Umiiivik-1

The terrestrial to brackish water palynological assemblages from the Kome, Slibestensfjeldet and Atane formations west of the Ikorfat fault zone may be correlated with almost similar assemblages recorded from arctic Canada (MacRae et al. 1996) and from core samples from north-east Baffin Bay, W. Greenland. Parts of the Lower Cretaceous succession from north-east Baffin Bay demonstrates source rock potential for generation of petroleum, in contrast to the organic material from the Lower Cretaceous succession at Ikorfat (Nøhr-Hansen et al. in prep.).

Likewise, the marine palynological assemblages from the Itilli Formation east of the Ikorfat fault zone may be correlated with almost similar marine assemblages, recorded from arctic Canada (Núñez-Betelu et al. 1994a,b; Lenniger et al. 2014), and from core samples from north-east Baffin Bay, W. Greenland. (Nøhr-Hansen et al. in prep.) Parts of the Upper Cretaceous succession from arctic Canada and north-east Baffin Bay demonstrates source rock potential for generation of petroleum, in contrast to the organic material from the Upper Cretaceous succession at Ikorfat (Nøhr-Hansen et al. in prep.).

Depositional model

On a basin scale, the Lower Cretaceous of the Nuussuaq Basin has been interpreted as deposited in rift basins (TSS 1 of Dam et al. 2009). The palynological data show that the brackish water embayment, in which parts of the Slibestensfjeldet Formation were deposited, was not restricted to a local rift basin, but was part of a larger body of brackish water (Nøhr-Hansen et al. in prep.). Likewise, the late Cenomanian–Early Turonian marine transgression in the Nuussuaq Basin (basal part of TSS 2) is contemporaneous with a regional marine transgression also recorded in basins further north and west (Nøhr-Hansen et al. in prep.).

In northern Disko a local member of the Itilli Formation, the Kussinerujuk Member, is exposed almost directly south of Kangilia and Annertuneq. The Kussinerujuk Member overlies an erosional unconformity incised into the deltaic Kingittoq Member (Pulvertaft & Chalmers 1990; Dam et al. 2009). It may be speculated that this erosional unconformity from Kussinerujuk and Kamaffiaraq to Asuk is parallel to the Kuugannguaq-Qunnilik fault and was transgressed from the north. This might explain the local occurrence of marine palynomorphs in a restricted part of northern Disko. On the south coast of Nuussuaq the Itilli Formation may be present west of Kingittoq, but it is not observed due to burial below sea level. In southern Nuussuaq, from Kingittoq and eastwards, and northern Disko, from Asuk and eastwards, the Albian and Cenomanian was characterized by deposition of deltaic deposits of the Kingittoq Member.

Conclusions

- The new photogrammetrical cross section indicates a fault east of the Ikorfat gneiss high with syn-sedimentary subsidence during the deposition of the Slibestensfjeldet Formation (Fig. 8).

- The new detailed geological map from the Ikorfat fault zone indicates a fault boundary between the westernmost outcrop of the Ravn Kløft Member and the Itilli Formation (Figs 7, 8).

- The youngest movements along the Ikorfat fault post-dates the Paleocene volcanic Vaigat Formation. This shows that the Ikorfat Fault zone was active at least from the Albian to the Palaeogene (Fig. 5D).

- Palynological data from the sections Ikorfat 2016-1, -2 and Ikorfat 2016-5 in the Ikorfat fault zone demonstrate that marine mudstones of late Cenomanian and Turonian ages are present (Figs 15, 19–21). This marine transgression has been predicted, but hitherto not demonstrated in the Nuussuaq Basin.

- The new sedimentological logs of the Kome, Slibestensfjeldet and Itilli formations show a succession of depositional environments: Floodplain to shallow lake (the Kome Formation; Figs 9– 10), deep water brackish embayment, which became shallower upwards due to progradation of nearshore deposits (the Slibestensfjeldet Formation; Figs 11, 12, 18), fluvial to estuarine deposition within an incised valley (the Ravn Kløft Member of the Atane Formation; Fig. 12), and finally a marine transgression and deposition of marine mudstones (the Itilli Formation; Figs 15–17, 21).

- A conceptual model has been proposed for the structural development of the Ikorfat fault zone with focus on the eastern fault block (the footwall block) during the Cretaceous (Fig. 26).

- Data on palynology and stable Carbon isotopes across the Cenomanian-Turonian boundary in the Itilli Formation, indicate that the succession is coeval with the Oceanic Anoxic Event 2 (OAE2), Figures 22, 23.

- Pyrolysis data on the Umiivik Member at Ikorfat show that the succession generally is dominated by inert terrestrial organic matter and does not constitute a source rock (Figs 24, 25). However, a source rock potential may exist in more distal depositional environments west and north of the Ikorfat fault zone, as indicated by the re-calculated analyses from the Umiivik-1 borehole (Table 1). The timing of hydrocarbon generation is uncertain.

- The re-assessment of the original petroleum potential from the Umviivik-1 borehole at Svartenhuk Halvø indicates that potential source rocks, equivalent to the Kanguk Formation, may be present in the Nuussuaq Basin (Fig. 27).

- The events identified in the Ikorfat fault zone are schematically correlated with the tectonostratigraphic sequences, TSS 1–TSS 9, of the Nuussuaq Basin (Dam et al. 2009: fig. 11) and tentatively correlated with the closest seismic lines recorded offshore north of the Ikorfat area (Figs 4–6).

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Figures

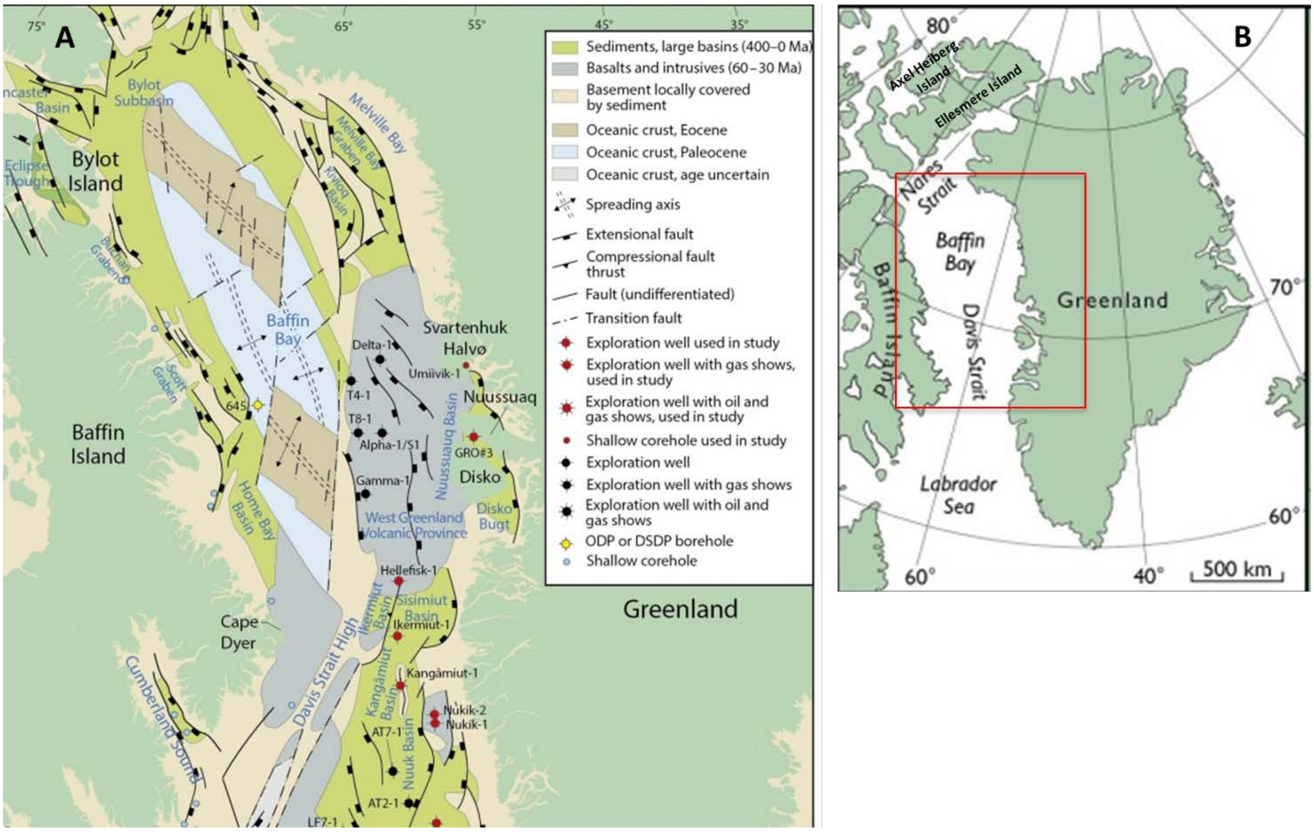


Figure 1. **A**. Geological location map, which shows the plate tectonic setting of the Baffin Bay, the position of the Nuussuaq Basin, and the Melville Bay Graben and Kivioq Basins further north. The area covered by West Greenland Basalt Group, on land and offshore, is indicated. **B**. Location of the area shown in A. The outcrops of the Kanguk Fm in Axel Heiberg Land, northern Canada, are also indicated. From Nøhr-Hansen et al. (2016).

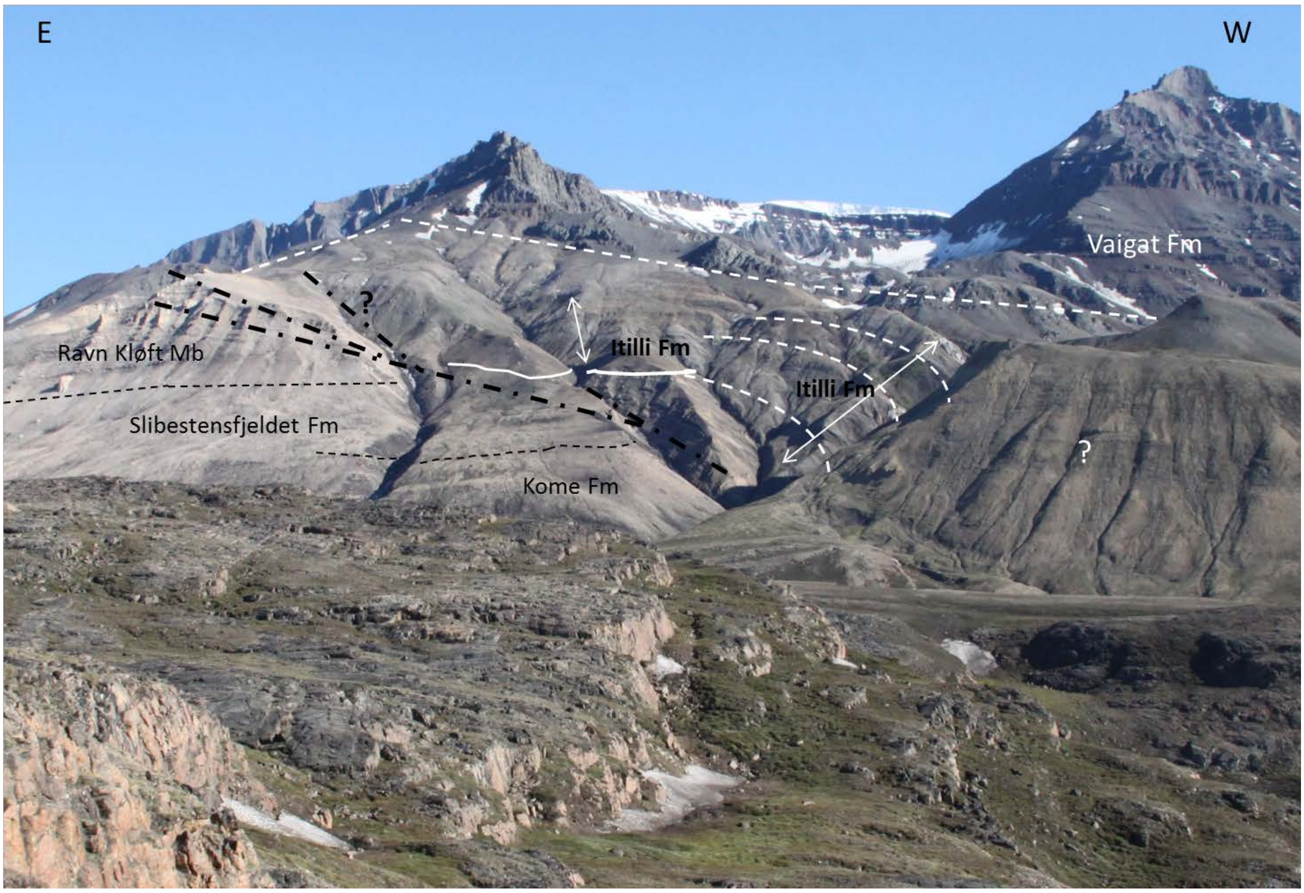


Figure 2. View towards the south from the gneiss high at Ikorfat. The white line indicates the approximate position of the drowning surface at the base of the Itilli Formation at Ikorfat. A number of faults, which were active during the Cretaceous, are indicated. The white dashed lines show very schematically that the dip of the mudstones (Itilli Formation) increase towards the youngest position of the Ikorfat fault. The presence of a number of faults justifies the term Ikorfat fault zone. Photo K.G. Jacobsen.

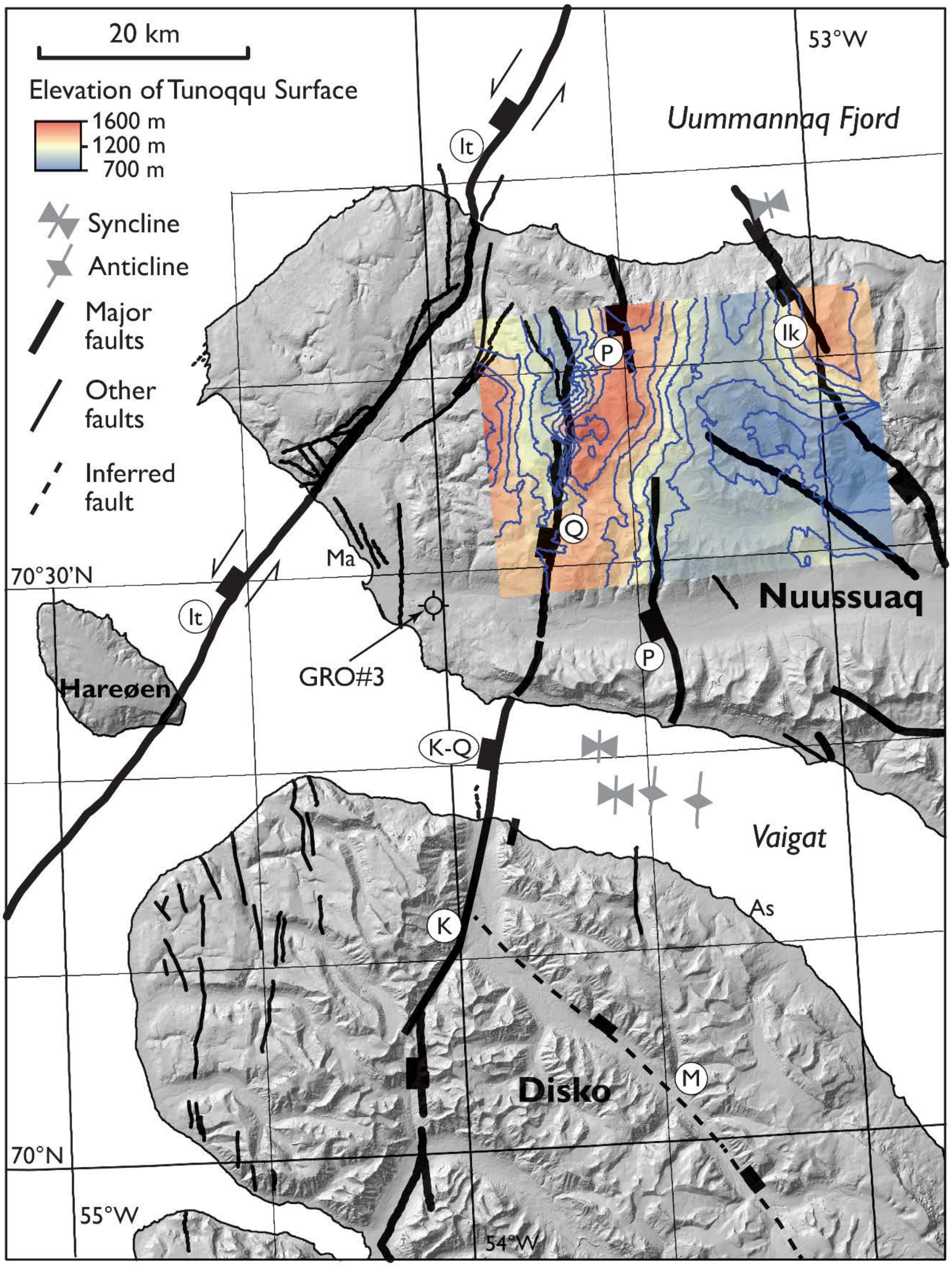


Figure 3. The Tunoqqu surface (dark red in Figure 5D, E) mapped by photogrammetry. The relief of the surface is up to 900 m. As: Asuk locality. Ma: Marraat locality. Ik: Ikorfat Fault. It: Itilli Fault. K–Q: Kuugannguaq–Qunnilik Fault. Faults P and M follow the nomenclature of Chalmers et al. (1999). Figure from Sørensen et al. (2017).

Correlation of events in the Ikorfat fault zone with tectonostratigraphic sequences of the Nuussuaq Basin

TSS	Basin development	Events in the Ikorfat area		Lithostratigraphy N coast of Nuussuaq		Geological age	
TSS 8		??				Eocene	
TSS 7	Subsidence, eruption of large volumes of volcanic rocks	??		Maligât Fm		Paleocene	Selandian
		Hangingwall block downfaulted to the west		Vaigat Fm Subaerial lava flows Hyaloclastite breccias			Late Danian to Thanetian
		Ponding of volcanic rocks west of Ikorfat fault	E				
	Subsidence, marine transgression	Deposition of mud and tuff beds Transgression		Eqalulik Fm Shelf			Late Danian
TSS 6	Renewed uplift and valley incision	Erosion of footwall block east of Ikorfat	D, E	Kangilia Fm	Marine slope		Late Danian
TSS 5	Uplift, valley incision						Danian
TSS4	Subsidence						
	Uplift, valley incision				Annertuneq Cgl. Mb Submarine channel	Latest Maastrichtian	
TSS 3	Subsidence	Marine mudstones with ammonite fauna		Itilli Fm	Umiivik Mb Marine shelf	Maastrichtian to Early Campanian	
	Rifting, angular unconformity	Submarine landslides	C, D				
TSS 2	Thermal subsidence	Deposition of marine mudstones Marine transgression	B, C			Santonian, Coniacian Turonian Late Cenomanian	
TSS 1	Rifting	Delta plain deposits Flooding		Atane	Kingittoq Mb Deltaplain	Early Cenomanian	
		Estuarine deposits Fluvial incision			Ravn Kløft Mb Estuary	Albian	
		Syn-sedimentary subsidence at fault east of Ikorfat Flooding	A, B	Slibestensfjeldet Fm Deep, brackish embayment			
		Deposition on weathered Precambrian rocks		Kome Fm, Floodplain			

Figure 4. Schematic correlation between the tectonostratigraphic sequences, TSS 1–TSS 9, of the Nuussuaq Basin (Dam et al. 2009: fig. 11) with the events identified in the Ikorfat fault zone. For further explanation see text. The letters A—E refer to the diagrams in Figure 26. The Kanglia Formation overlies the Itilli Fm in outcrops 10-15 km east of Ikorfat (Fig. 14). Two important transgressions in the Ikorfat area, at the bases of the Itilli and Eqalulik formations, are outlined in blue.

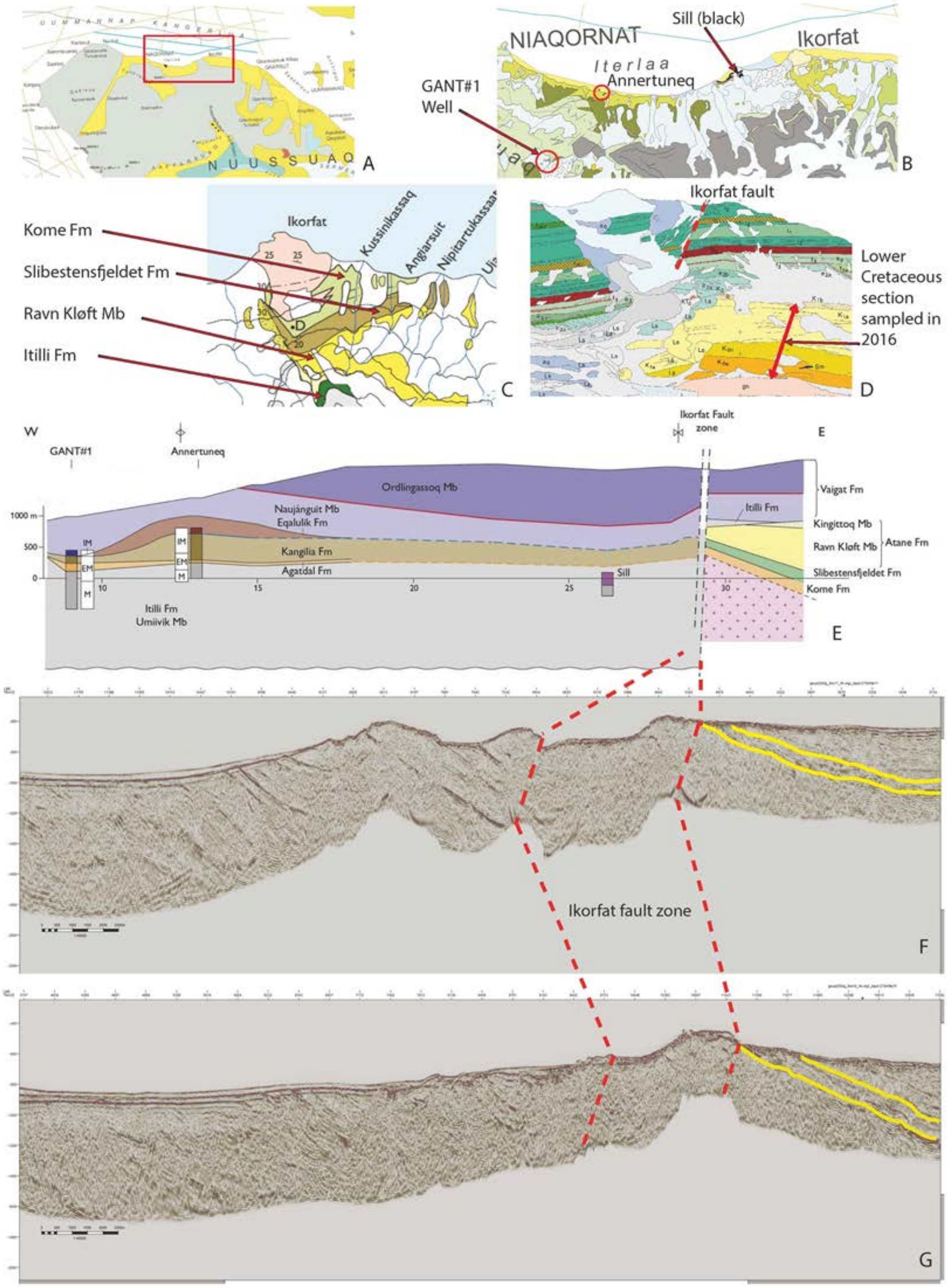


Figure 5. **A**: GEUS2000 seismic survey (sections 16–17 shown in blue). The red frame shows the location of B.

B: Geology of the areas close to Ikorfat. **C**: Geological map of the Ikorfat area, located in B (**B, C** from Dam et al. 2009). **D**: Geological section at the Ikorfat fault (red dashed line), from Pedersen et al. (2006). **E**: Simplified geological cross-section of the geology exposed along the north coast of Nuussuaq (the vertical axis is twice the horizontal). The Tunoqqu surface is the top of the Naujánguit Mb (shown in red). **F, G**: Seismic sections GEUS2000-16 and -17 with inferred correlation of the Ikorfat fault zone. The base of the Lower Cretaceous Kome Fm is the lowest of the reflectors outlined in yellow.

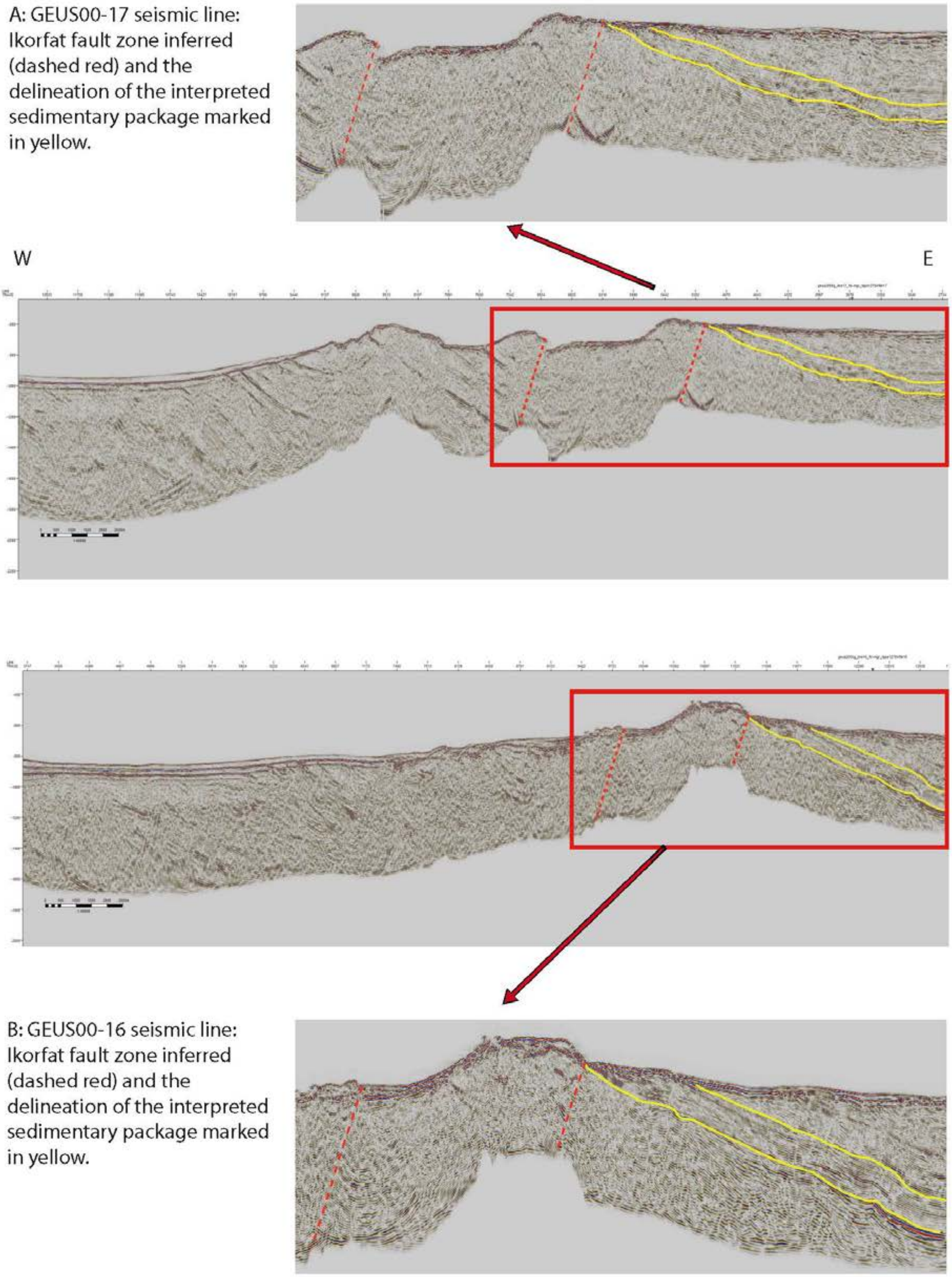


Figure 6 **A**, **B**: Detailed interpretation of the seismic lines GEUS2000-line 16–17. See Figure 5.

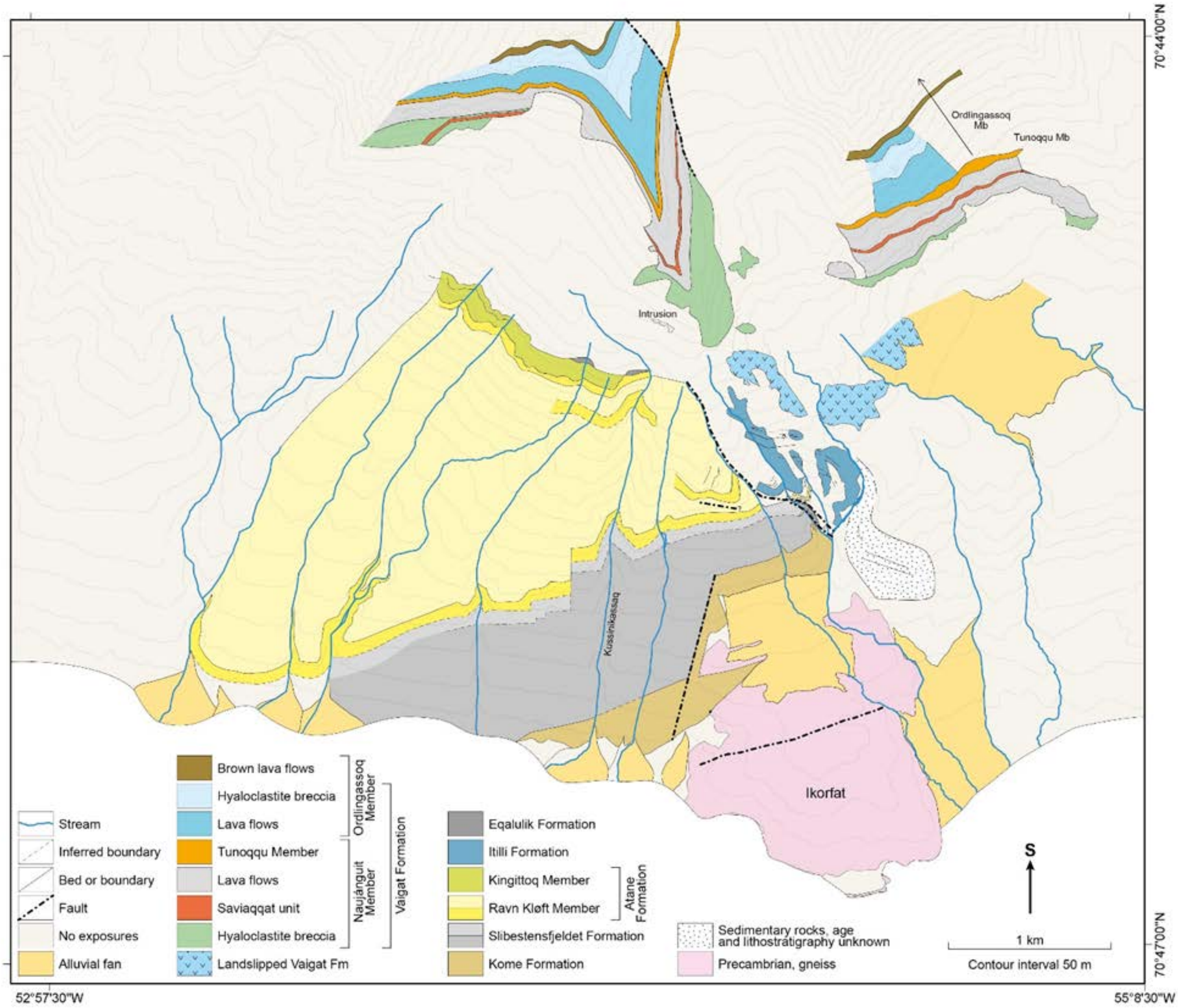


Figure 7. New, detailed geological map of the Ikorfat fault zone based on digital photogrammetry, which replaces the former map in scale 1:100 000 (Rosenkrantz et al. 1974). The map shows that the boundary between the Ravn Kløft Mb (Atane Fm) and the Itilli Fm is interpreted as a fault. The presence of the Itilli Fm is also indicated.

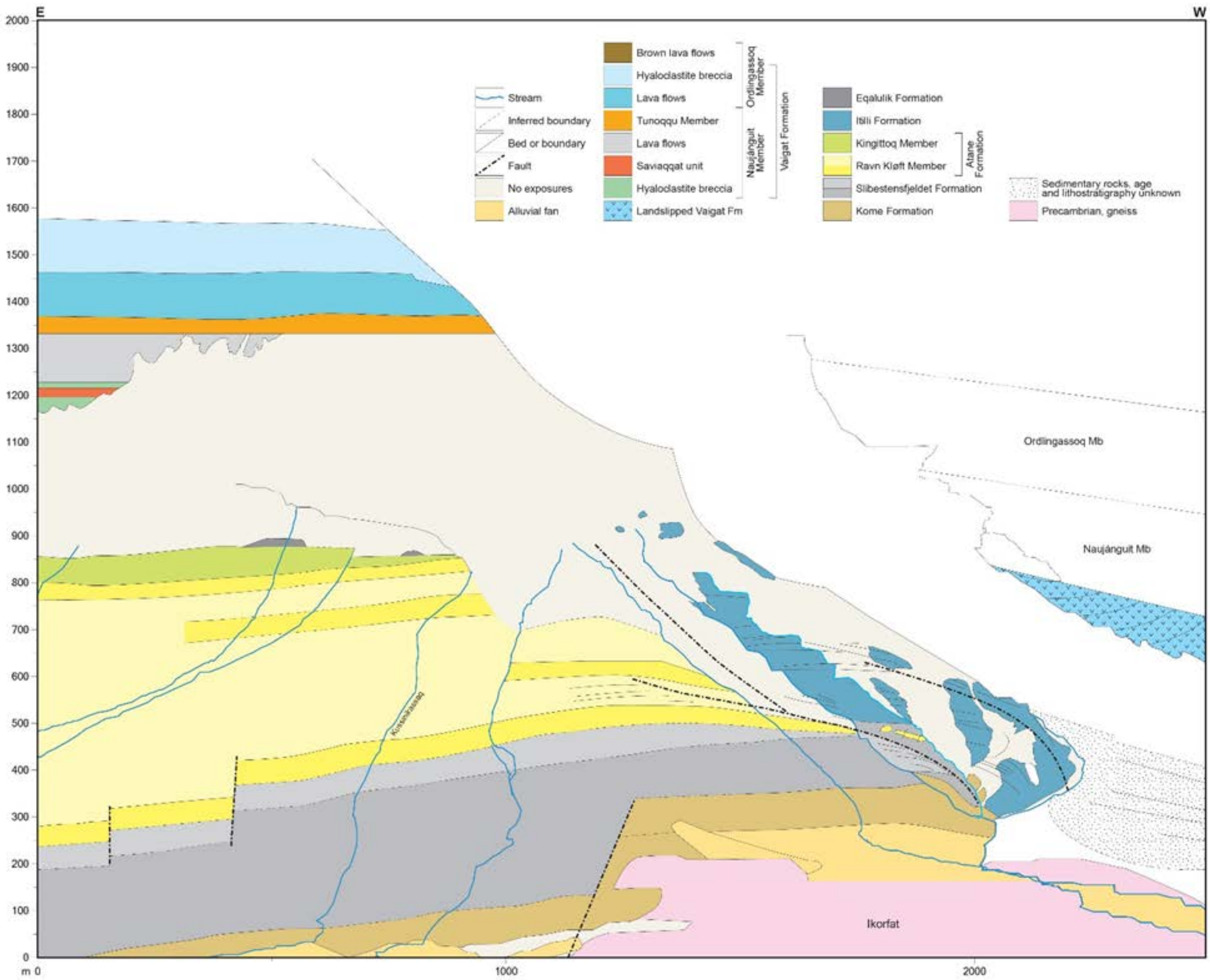


Figure 8. New geological section of the area east of the Ikorfat fault zone, based on digital photogrammetry. The section shows an interpreted syn-sedimentary fault in the Slibestensfjeldet Formation east of Ikorfat, and faults between the Ravn Kløft Member and the Itilli Formation. The steeply dipping beds of the Itilli Formation in the fault zone are indicated. Only the lower part of the volcanic Vaigat Formation is shown. This section is drawn as seen from the Uummannaq Fjord, and is the mirror image of Fig. 5D.

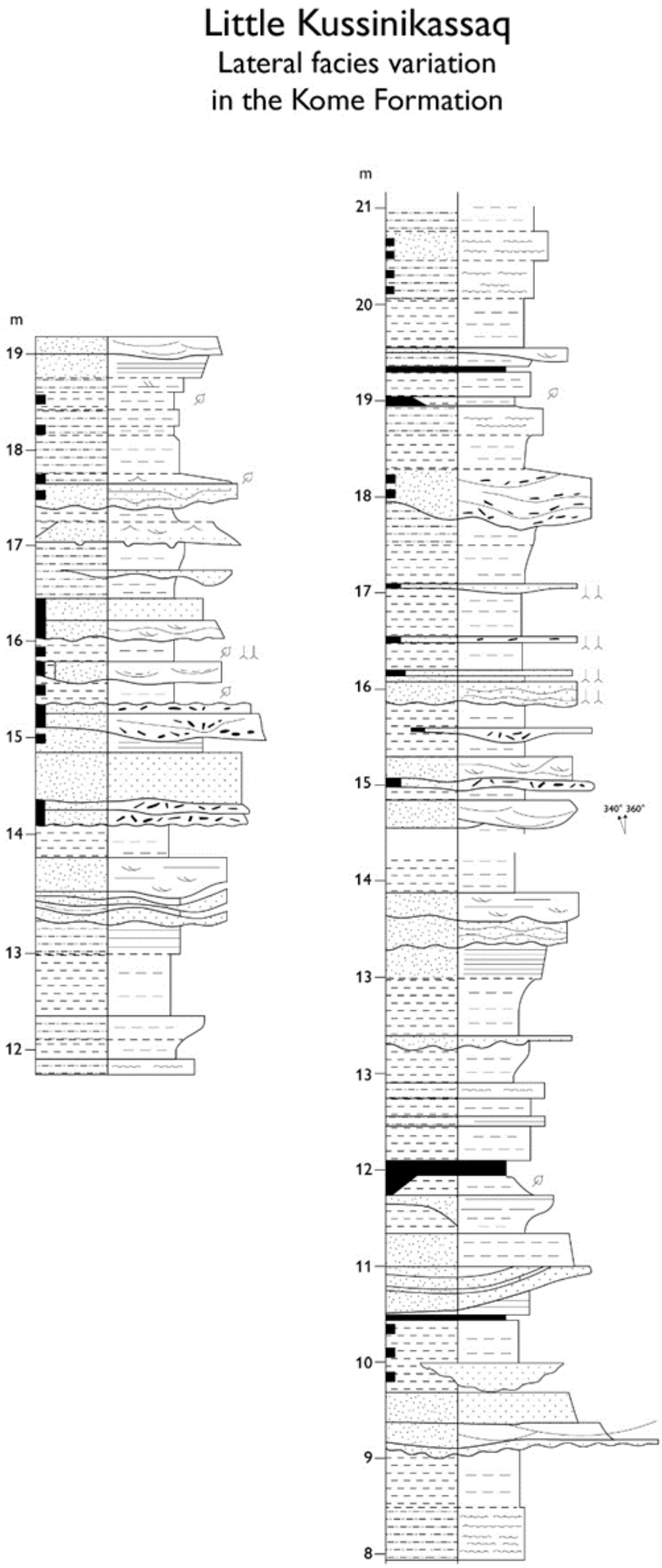


Figure 9. Sedimentological log of part of the Kome Formation in a small gully between Kussinikassaq and the gneiss promontory (informally and unofficially referred to as "Little Kussinikassaq"). Both logs are measured in this gully and illustrate the lateral facies variation within the formation. Note that the coal beds are thin, and that the sandstones varies in thickness laterally.

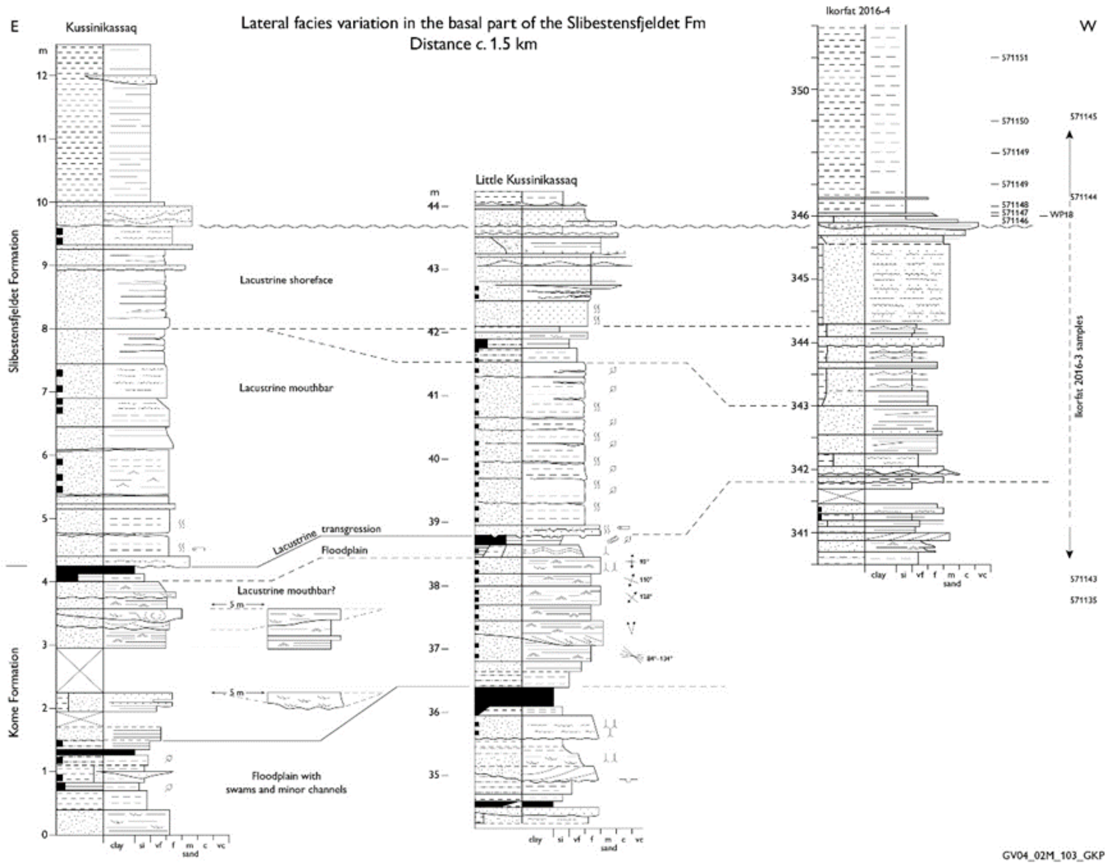


Figure 10. Sedimentological log of the basal part of the Slibestensfjeldet Formation in two gullies east of the basement high and the third (Ikorfat-2016-4) on top of the basement high. The sedimentary facies and the sandstone thicknesses vary a little between the three sections. Note the presence of wave-ripple cross-lamination, which is not observed in the Kome Formation.

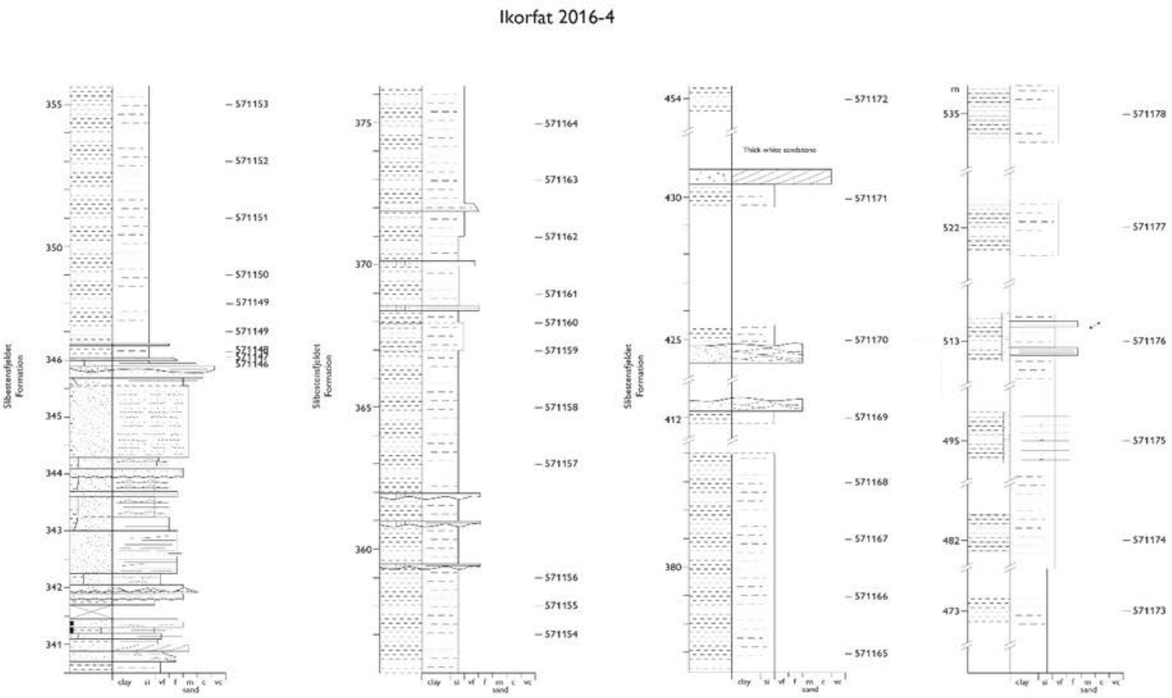


Figure 11. Sedimentological log from section Ikorfat-2016-4. It represents the Slibestensfjeldet Formation and the lowermost part of the Itilli Formation. The Ravn Kløft Member is not present in this section. Above 384 m the logs only shows the lithology and altitude of the samples collected for palynologi and source-rock evaluation. The sandstones in the upper part of the Slibestensfjeldet Formation were poorly exposed in this section and are not shown in the sedimentological log. The lowest possible position of the boundary between the Slibestensfjeldet Fm and the Itilli Fm is at 454 m. The decollement surface indicated in Fig. 26 B–E is probably located around 390 m in the section, but is not conspicuous in the field.

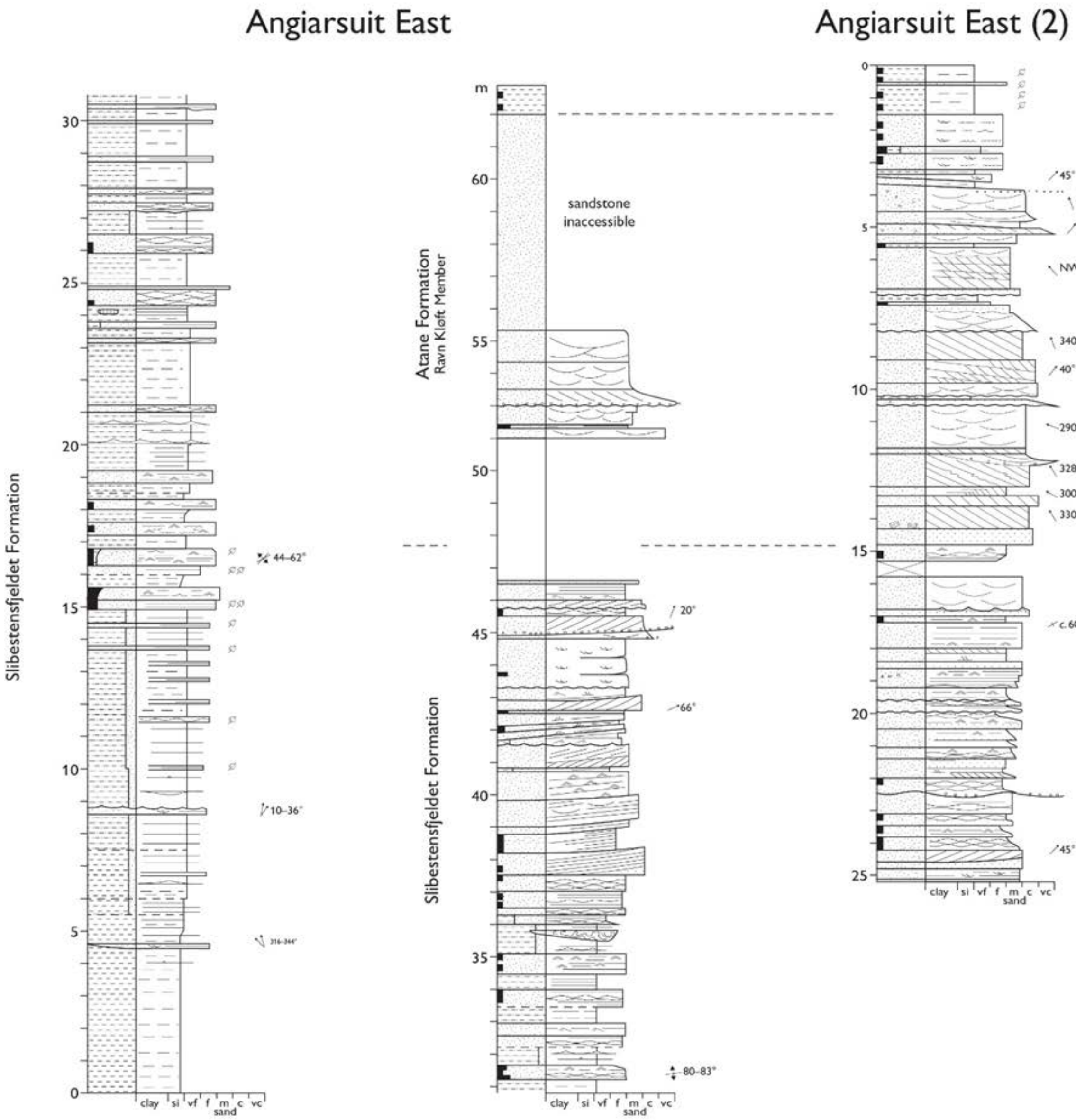


Figure 12. Sedimentological log of the upper part of the Slibestensfjeldet Formation and the basal part of the Ravn Kløft Member. The log is measured at Angiarsuit 1-2 km east of Ikorfat and illustrate the upwards-coarsening succession. The erosive boundary of the basal part of the Ravn Kløft Member was studied in a nearby outcrop. Current directions were towards the north in the fluvial sandstones.

Figure 13. The north-facing slope of the small gully “Skredkløft” at Ikorfat. The sandstones from the upper part of the Slibestensfjeldet Fm are seen to be redeposited as part of slides. The overlying slide involved coarser sandstones, which may represent fluvial sandstones from the Ravn Kløft Mb.

Figure 13a. Details of the strata exposed in the north-facing slope of the gully Skredkløft. The sandstones in the lower part of the photo shows sandstones from the upper part of the Slibestensfjeldet Formation, which were part of an early slide. The blue arrows point to a mud-stone at the base of the overlying slide. White arrows point to a thin load-deformed sandstone bed below the white sandstone clast. Height of section approximately 25 m. Photo K.G. Jacob-sen.

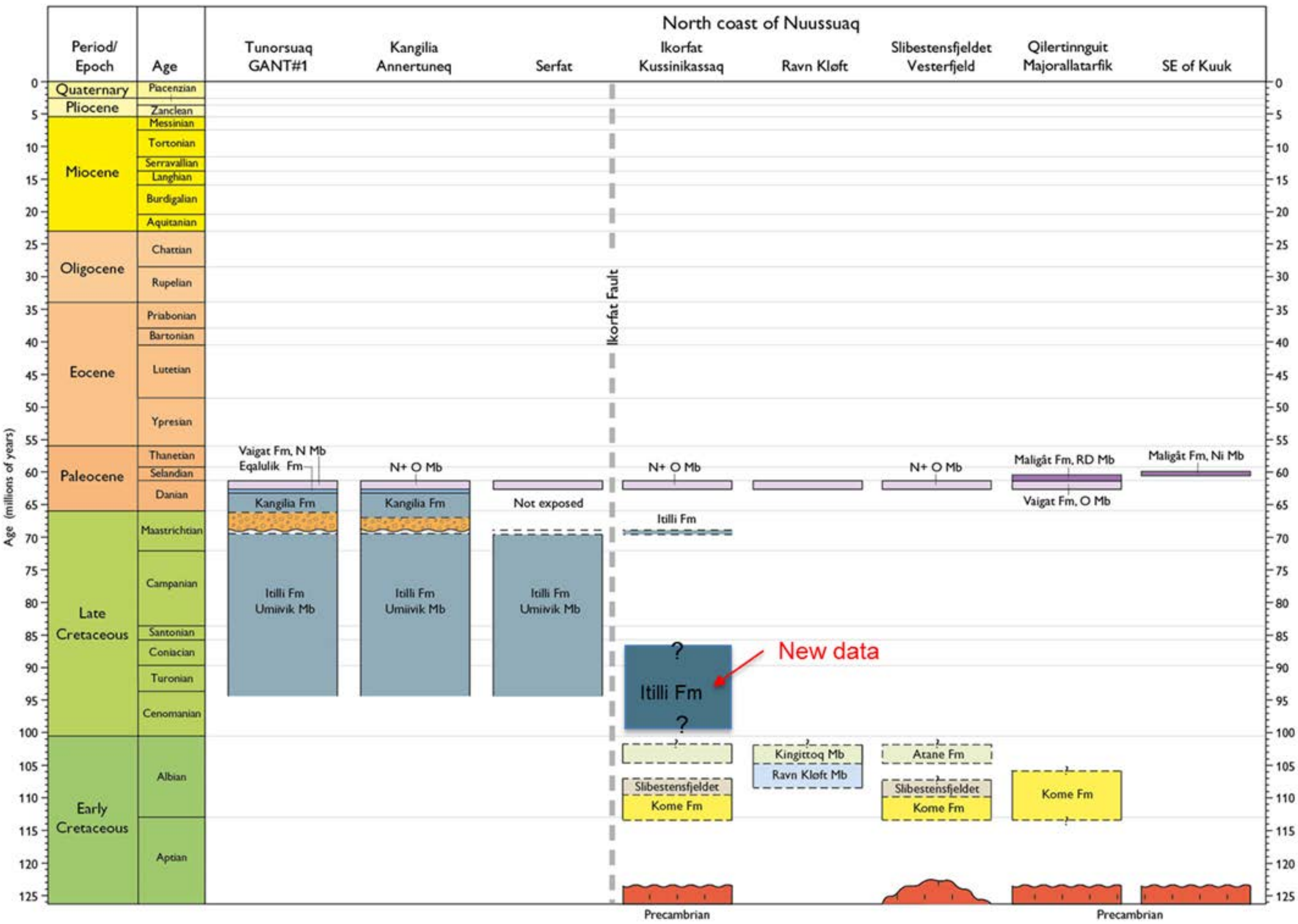
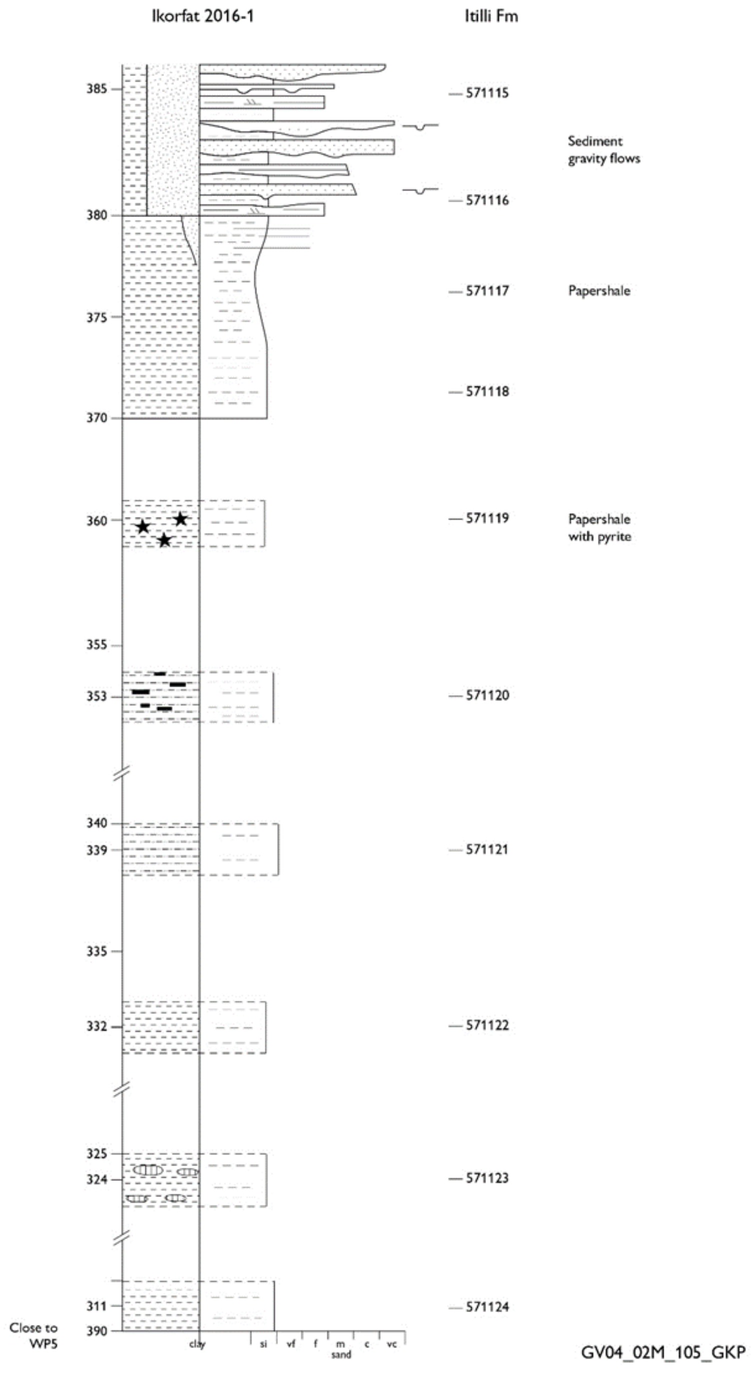


Figure 14. Schematic diagram of the lithostratigraphic units which may be observed along the north coast of Nuussuaq, east of the Itilli valley. The new palynological data from the Ikorfat fault zone suggest that mudstones of the Umiivik Member (of the Itilli Formation) may have been deposited continuously from the late Cenomanian to the Campanian/early Maastrichtian.



Fiure 15. Sedimentological log from section Ikorfat-2016-1. It represents the Itilli Formation, and shows silty mudstones, which locally weathers as paper shales. Yellow-weathering concretions occur in the lower part of the succession. Thick, short black lines indicate comminuted plant debris. Black stars indicate pyrite. The uppermost six metres comprises medium- to coarse-grained sandstones interbedded with silty mudstone. The sandstones are interpreted as deposited from sediment gravity flows.

Figure 16. Mudstones of the Itilli Formation with a redeposited mega-clast of white, coarse-grained sandstone, estimated to be c. 5x 10 m in the outcrop. The third dimension is unknown. The sedimentary structures suggest that the sandstone originally was deposited in a channel. The sandstone was only slightly deformed during transport and re-deposition, and it is suggested that the sandstone was transported as part of a mudslide.

Figure 17. The steeply dipping beds of the Itilli Formation in the outcrop within the fault zone.

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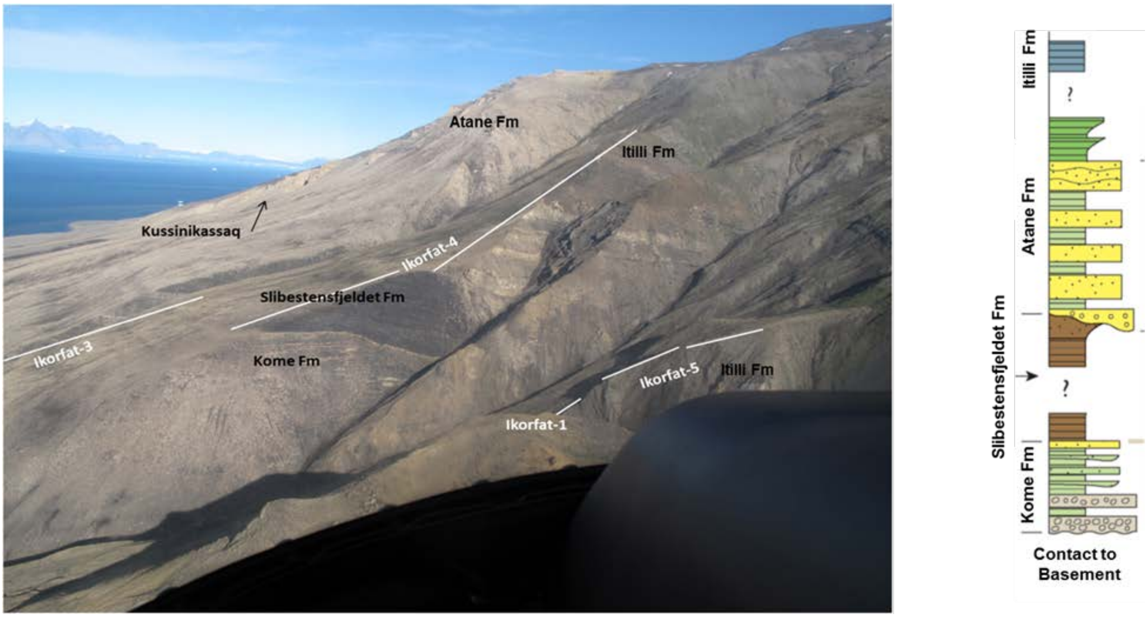


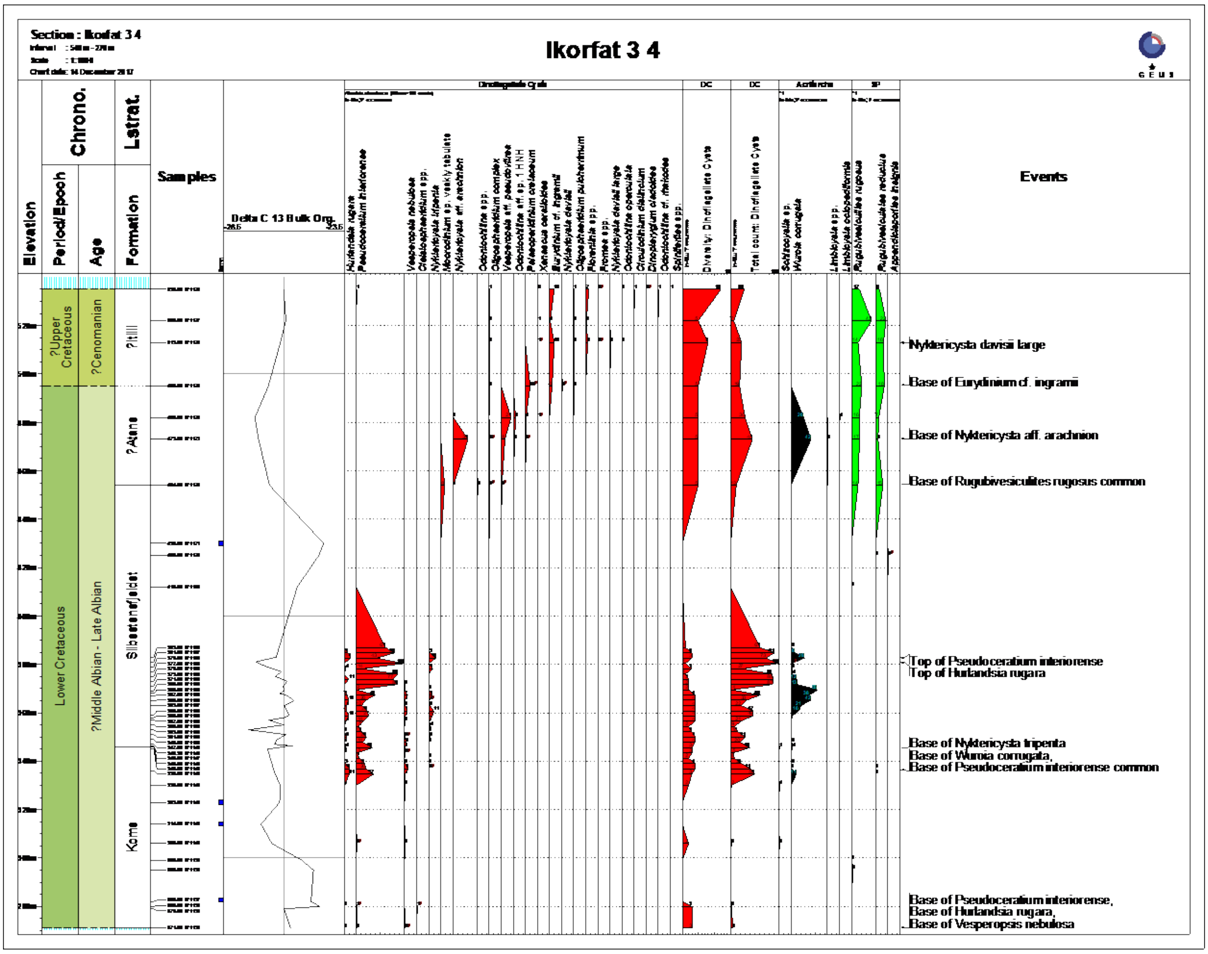
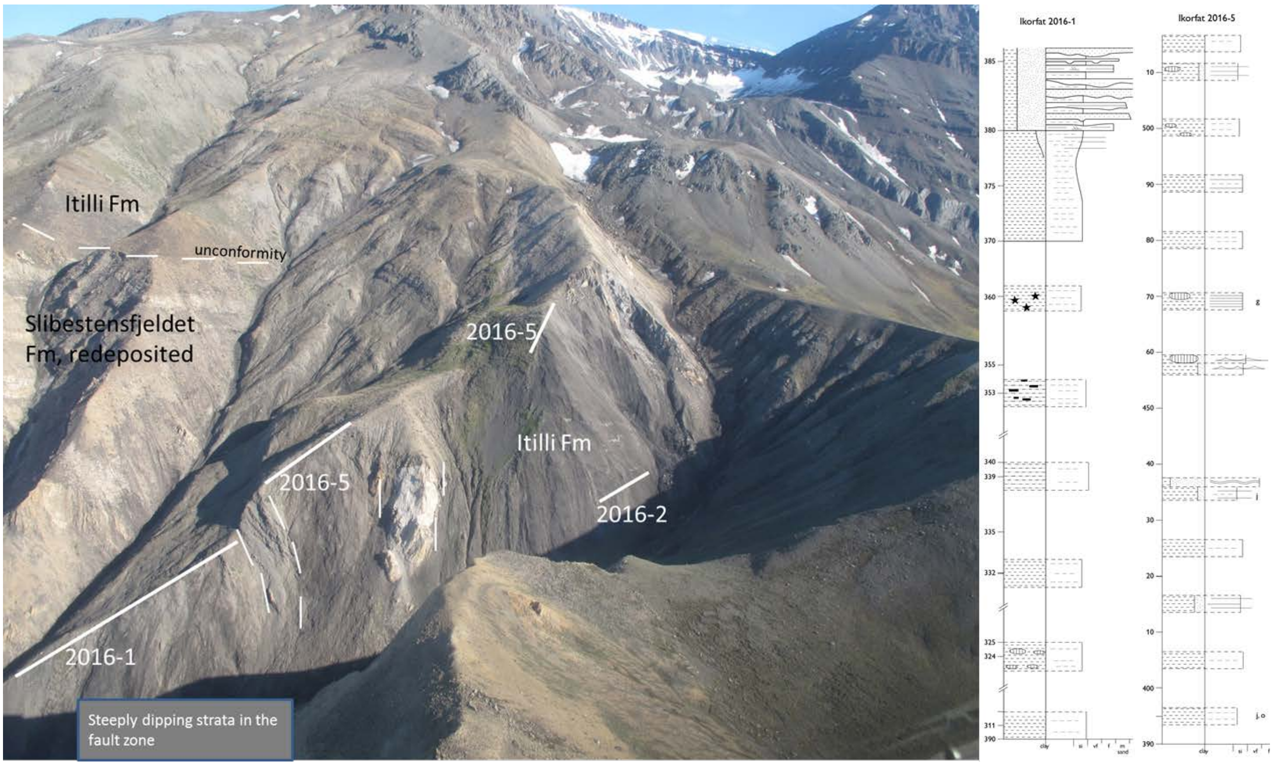


Figure 18. Range chart for the palynomorphs identified in samples from sections Ikorfat-2016-3, -4. Most of the samples represent the Kome and Slibestensfjeldet formations.



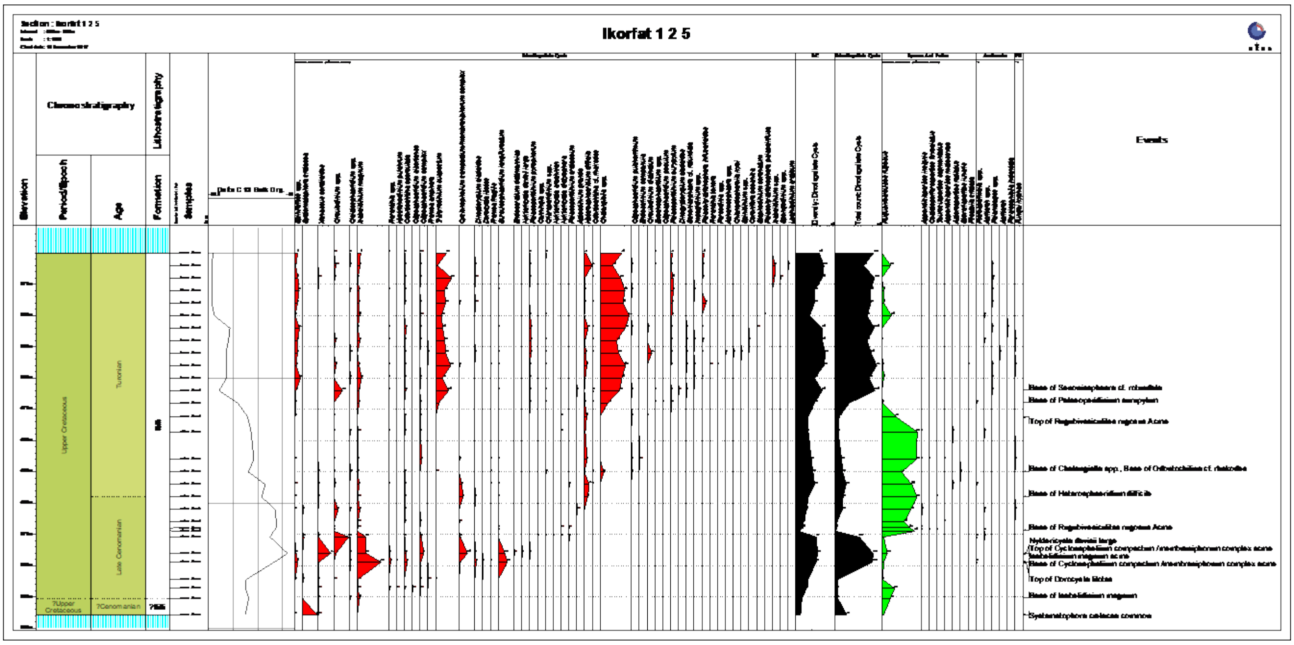


Figure 19. Range chart for the palynomorphs identified in samples from sections Ikorfat-2016-1, -2, -5 all the samples represent the Itilli Formation. The unconformity indicated in the photo at the base of the Itilli Fm is interpreted as a drowning surface (see also Fig. 2).

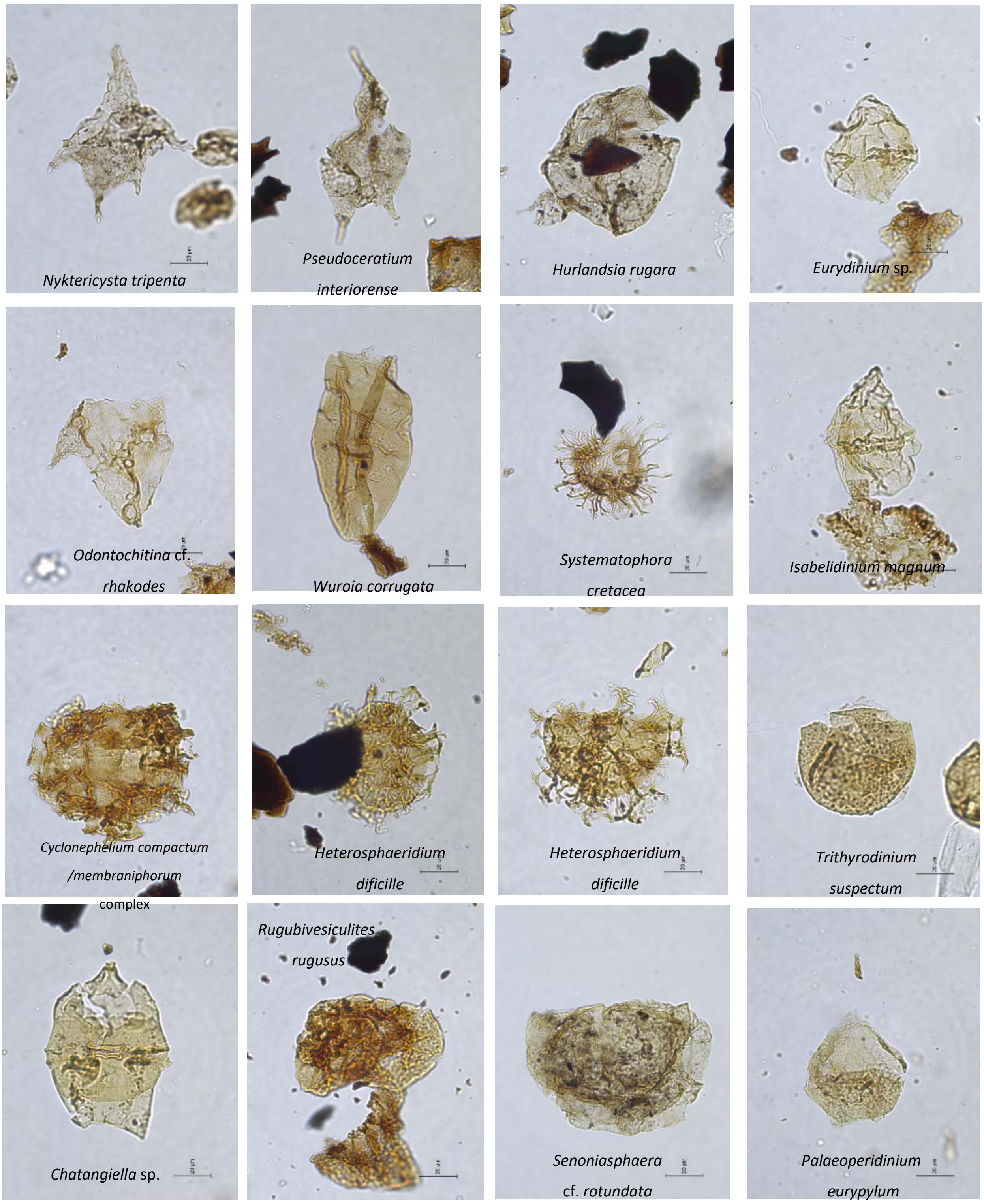


Figure 20. Stratigraphic marker species of dinocysts and pollen.

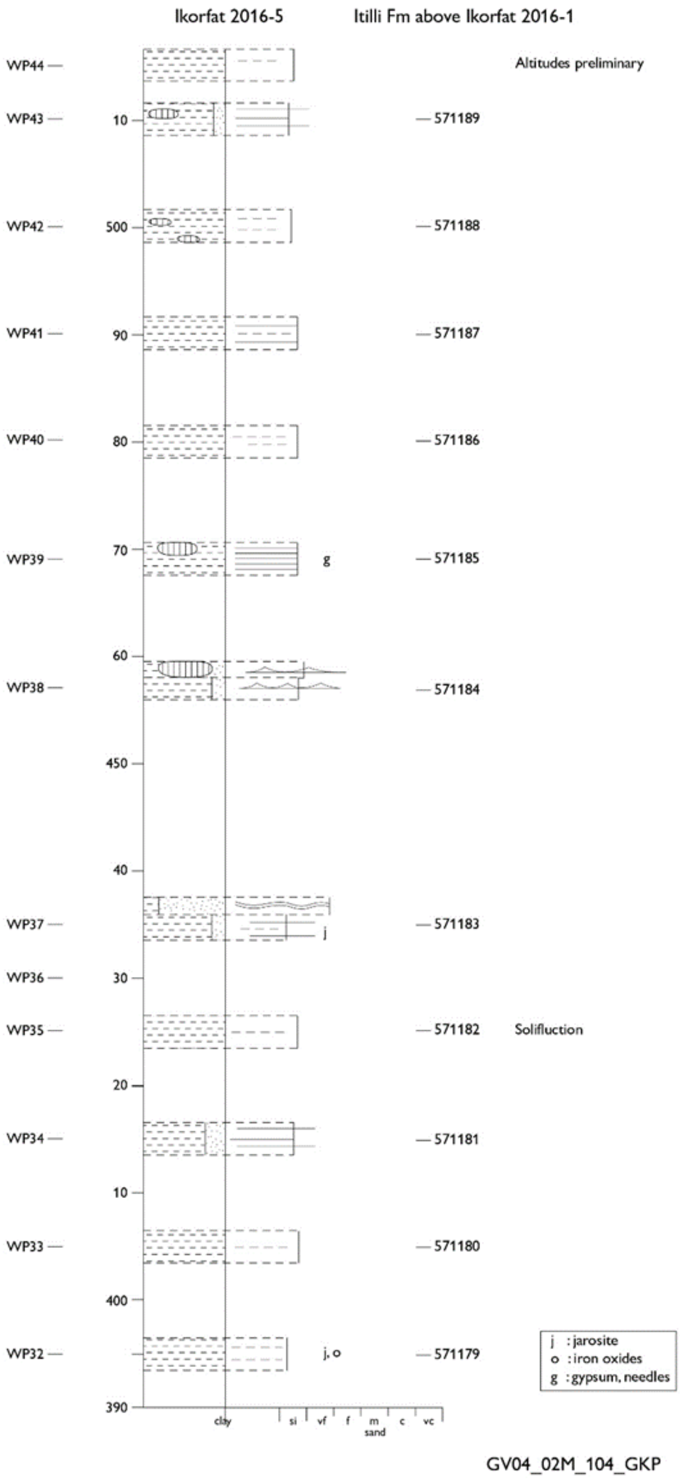


Figure 21. Lithology and altitude of the samples collected in section Ikorfat-2016-5. The section is a continuation of section Ikorfat-2016-1. The upper part of section Ikorfat-2016-5 overlaps with parts of section Ikorfat-2016-2, which is not represented by a log.

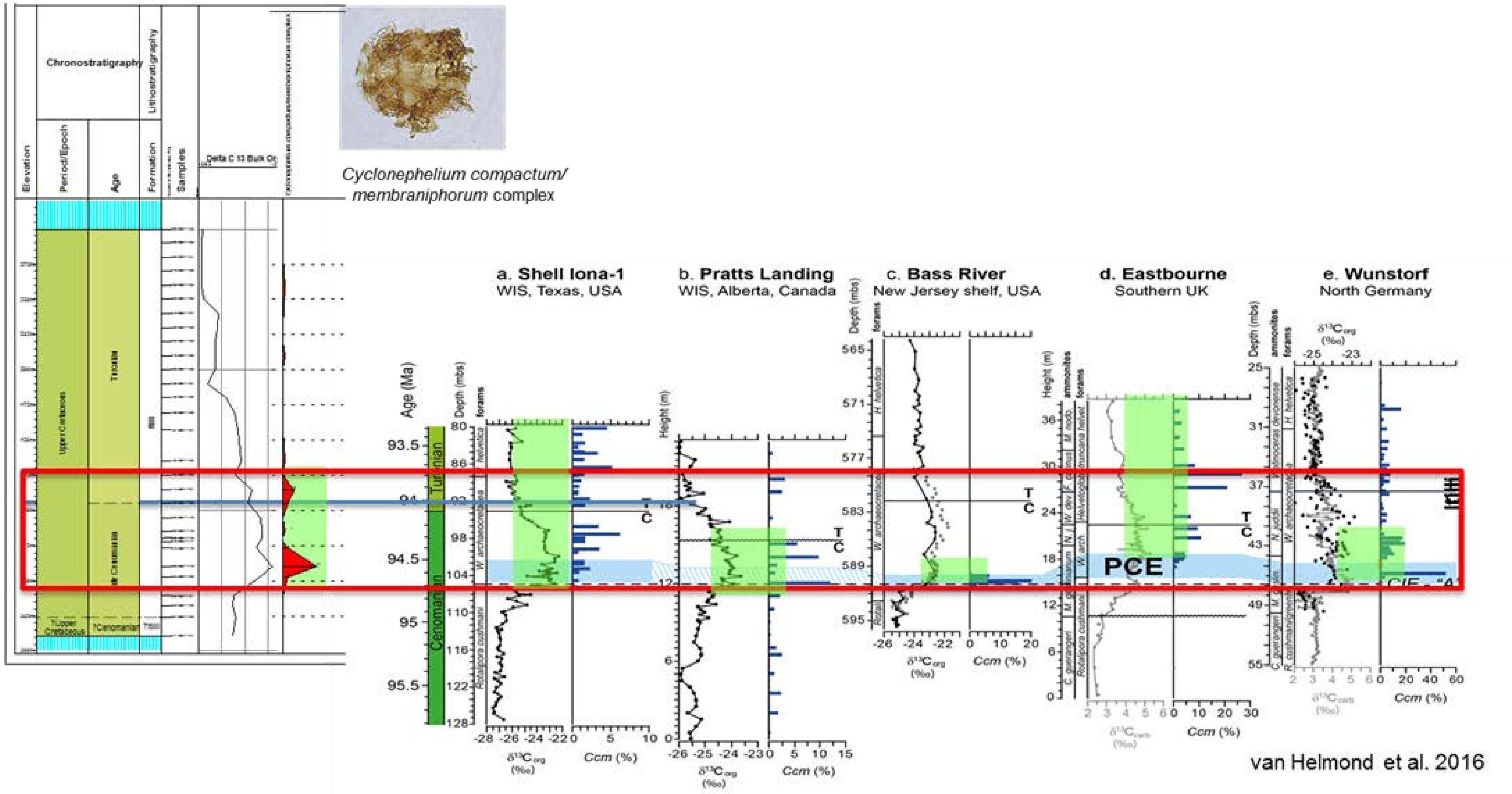


Figure 22. Correlation of the *Cyclonephelium compactum/membraniphorum* complex FO and acme within the Itilli Fm samples dated as late Cenomanian to Early Cenomanian with similar occurrences of the *C. compactum/membraniphorum* complex from the start and across the Cenomanian–Turonian Oceanic Anoxic Event 2 (OAE2) boundary event in Europe and North America.

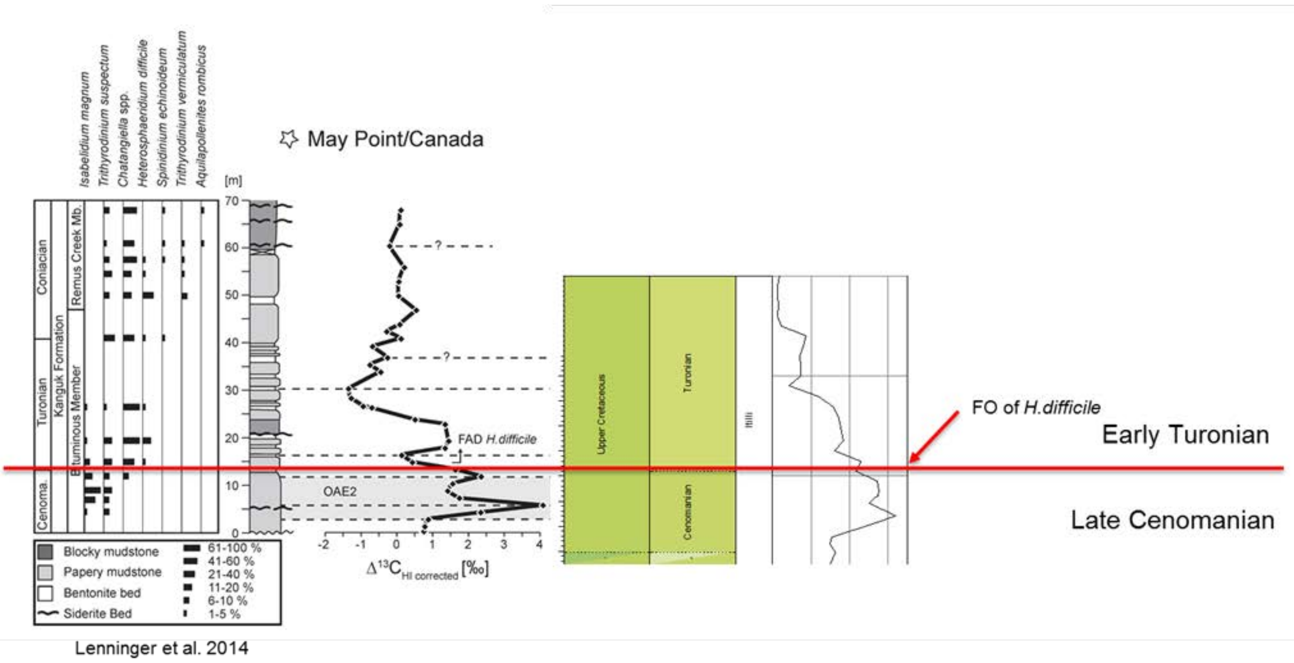


Figure 23. The palynological assemblage from the Itilli Fm succession within the Ikorfat fault zone correlates with similar assemblages of late Cenomanian–Early Turonian age from the organic-rich “paper” shale of the lower part of the Kanguk Formation on Axel Heiberg Island, Arctic Canada.

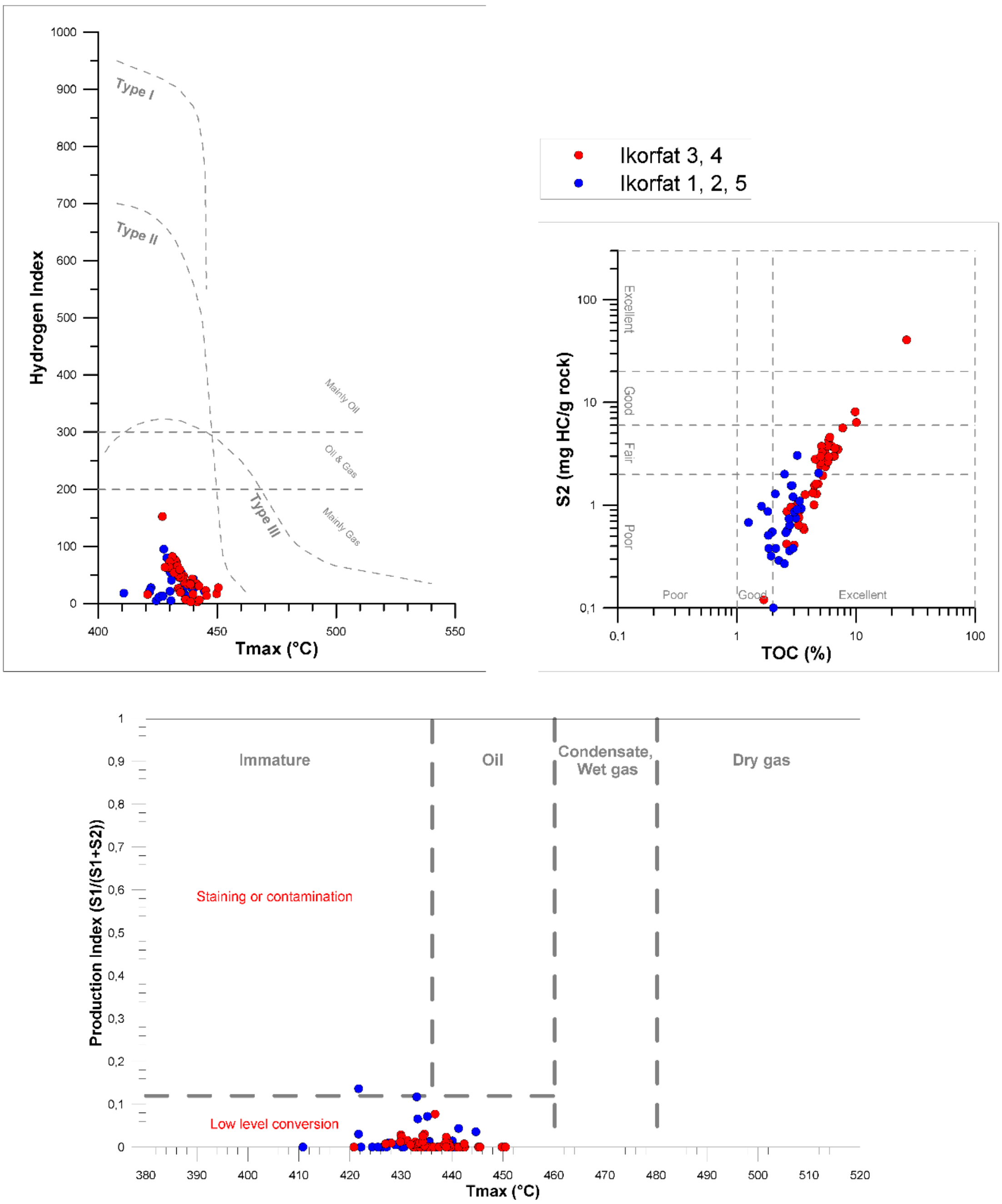


Figure 24. Petroleum geochemical data for the sections Ikorfat-2016-1 to 2016-5. TOC: total organic carbon (wt-%), TS: total sulphur (wt-%); S2: Rock-Eval type pyrolysis S2 parameter (mg/g); Tmax: Rock-Eval type pyrolysis Tmax parameter (°C), HI: Hydrogen Index; PI: Production index. See text for further information.

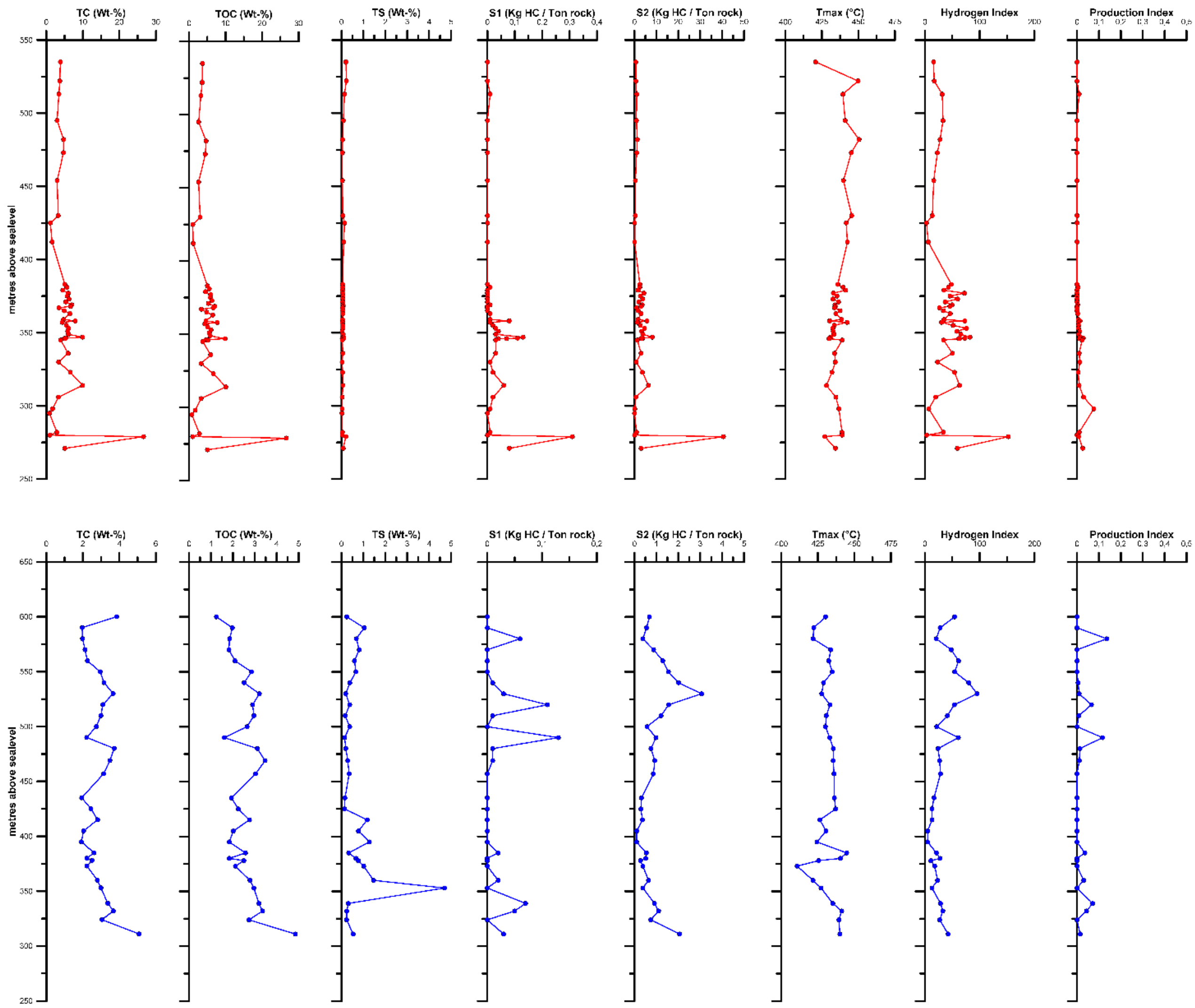


Figure 25. Petroleum geochemical data for the Ikorfat-3,4 (upper part, red) and Ikorfat-1,2,5 (lower part, blue) sections. TC: total carbon (wt-%), TOC: total organic carbon (wt-%), TS: total sulphur (wt-%), S1: Rock-Eval type pyrolysis S1 parameter (mg/g); S2: Rock-Eval type pyrolysis S2 parameter (mg/g); Tmax: Rock-Eval type pyrolysis Tmax parameter (°C), HI: Hydrogen Index; PI: Production index.

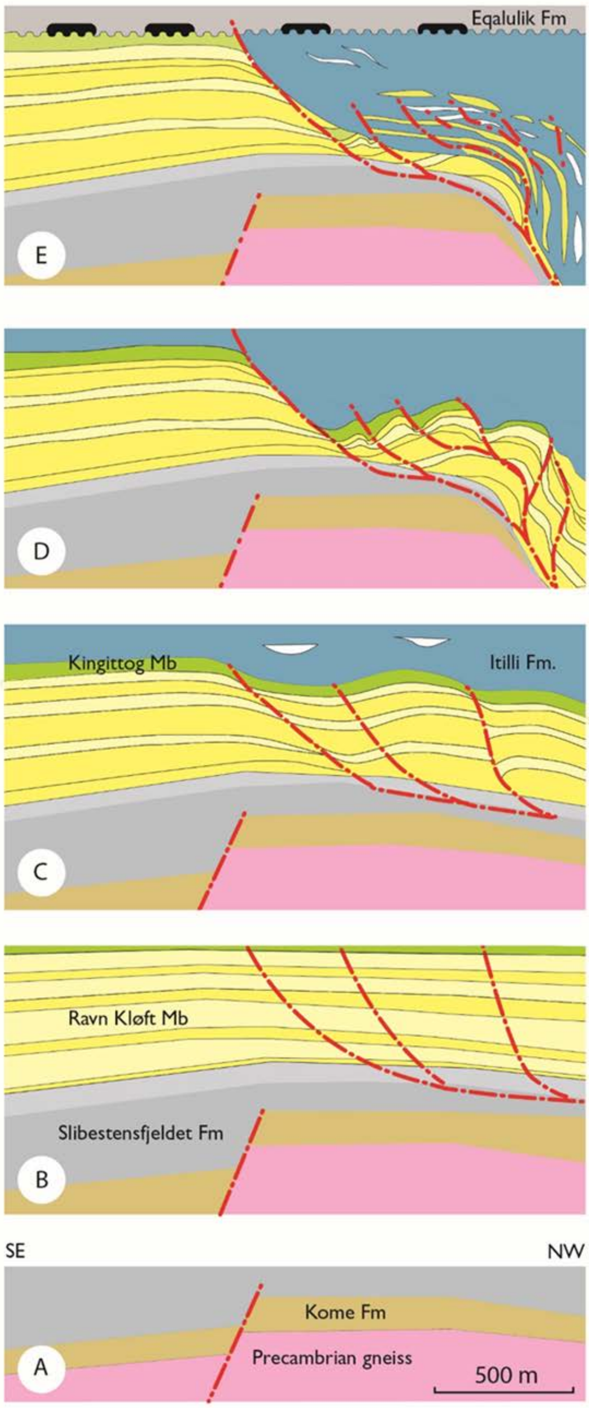


Figure 26. Conceptual model for the structural development of the Ikorfat fault zone with focus on the eastern fault block (the footwall block) during the Cretaceous. A. Deposition of the fluvial Kome Formation (Albian) on Precambrian gneiss. B. The Kome Formation is overlain by the Slibestensfjeldet Formation (Albian), which forms a CU-succession deposited in a large and deep brackish embayment. The formation is thicker east of Ikorfat than on top of the gneiss, and the fault is interpreted as syn-sedimentary. The Ravn Kløft Member (Atane Fm) overlies an erosional unconformity and comprises fluvial and estuarine deposits. The Kingittoq Member (Atane Formation) is interpreted as delta plain deposits. C. Slides along extensional faults are initiated with a decollement surface in the mudstones of the Slibestensfjeldet Formation. D. The slides redeposit the upper part of the Slibestensfjeldet Formation and parts of the Ravn Kløft Member. E. A new phase of slides involved mainly the Itilli Formation, although some large redeposited sandstone clasts may have originated from the Ravn Kløft Member. A phase of erosion in the late Cretaceous and Paleocene preceded a marine transgression and deposition of the syn-volcanic marine mudstones of the Eqalulik Formation. These mudstones are only known from small outcrops. Most of the Eqalulik Formation is covered by debris from the overlying volcanic succession. Fault movements along the Itilli fault continued in the Paleocene (not shown here).

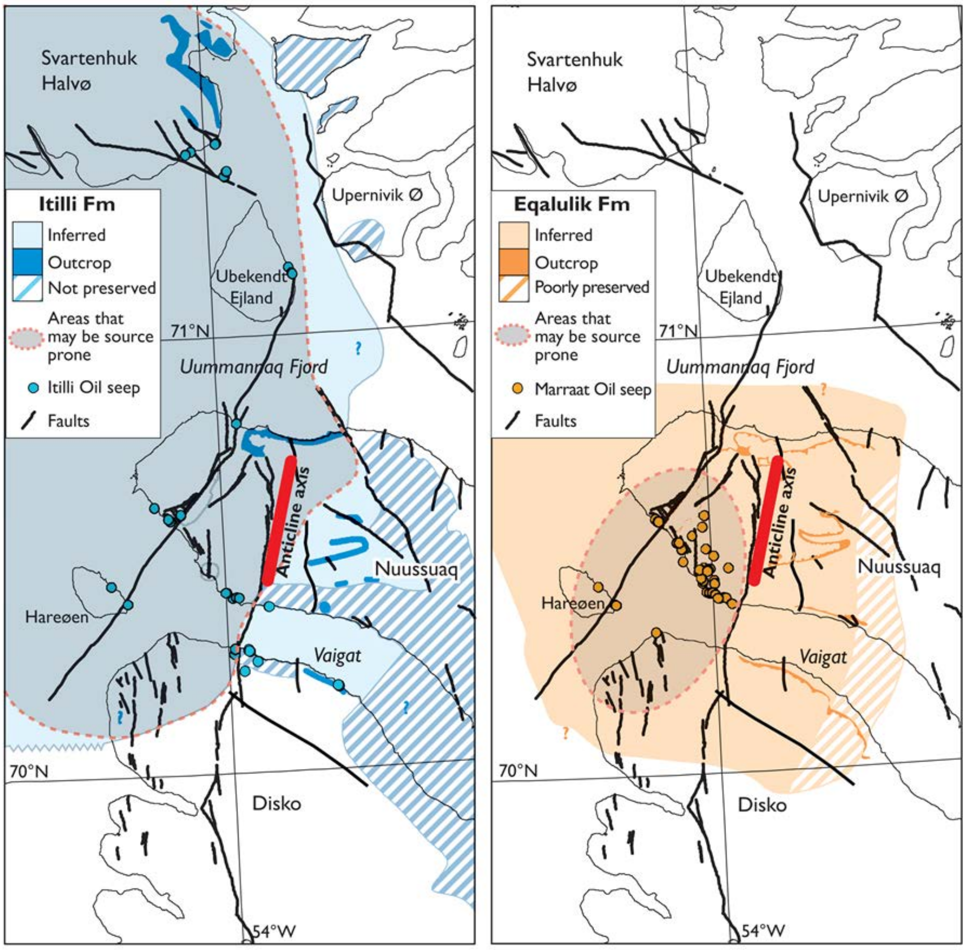


Figure 27. Inferred distribution maps of the Itilli and Eqalulik formations. Black lines are faults. The overall trend of the fold axis of the anticline mapped from the Tunoqqu surface is shown by the red line. The maps are based on the known distributions from onshore outcrops and from offshore seismic data that indicate the presence of significant Cretaceous–Paleocene sedimentary strata (Marcussen et al. 2002).

Locations of seeps and stains of Marraat and Itilli oil-types are also shown. Note that the Marraat oil-type is known only from Nuussuaq between the Qunnilik and Itilli Faults whereas the Itilli oil is known regionally. The distribution of areas where oil prone intervals may occur is shown by the grey shading. This is highly speculative and based on the locations of oil seeps and outcrops. Along southern Nuussuaq and northern Disko, the lower Itilli Formation is absent east of the K–Q Fault, but recent samples collected suggest it is present near the Ikorfat Fault at the north coast of Nuussuaq.

The distribution of the Itilli Formation is regarded to be of regional extent, extending west and north-west into the Davis Strait and Baffin Bay. Based on sediment thicknesses modelled by Chalmers et al. (1999), it is suggested here that the lower Itilli Formation was probably sufficiently buried to have generated oil in large areas west and north-west of the Ikorfat Fault, although the timing of hydrocarbon generation is highly uncertain. The map is thus consistent with the broad distribution of the Itilli oil type observed throughout the region (From Sørensen et al. 2017).