The oldest marine Cretaceous sediments in West Greenland (Umiivik-1 borehole) – record of the Cenomanian–Turonian Anoxic Event?

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The stratigraphic borehole Umiivik-1 on Svartenhuk Halvø was drilled in August–September 1995 as part of a joint programme between the Government of Greenland, Minerals Office (*now* Bureau of Minerals and Petroleum) and the Danish State (Mineral Resources Administration for Greenland). The joint programme was based on a political decision from November 1994 made in order to attract the oil and mineral industry to Greenland. The drilling of Umiivik-1 is one of several petroleum geological projects in West Greenland that were initiated early in 1995. Analyses on the core include detailed sedimentological, palynological and organic geochemical studies. The other petroleum geological projects comprise: description and interpretation of the three exploration boreholes on Nuussuaq, GANT#1, GANE#1 and GANK#1 that the Canadian oil company grønArctic Energy Inc. drilled in the summer of 1995 (e.g. Christiansen *et al.* 1996a, c; Dam 1996a–c; Nøhr-Hansen 1997a); seismic surveys in the fjords around Disko, Nuussuaq and Svartenhuk Halvø (FjordSeis 95); seismic surveys in the offshore area between 68° and 71°N (DiskoSeis 95); and seismic surveys in the offshore area south of 68°N (IkerSeis 95, KangaSeis 95 and ExtraSeis 95; Chalmers *et al.* 1998, this volume; Skaarup & Chalmers 1998, this volume).

The prime objective of Umiivik-1 was to document oil-prone source rocks in mid-Cretaceous strata. Although several types of crude oil have been found in seeps and slim-hole cores in West Greenland since 1992, there was only limited knowledge on actual source rocks when the project was initiated. Detailed organic geochemistry, especially the distribution of biomarkers in seeping oils, provides important information on the type of organic material, the depositional environment and the thermal history of the source rocks that generated these oils (Christiansen *et al.* 1996b, 1997b; Bojesen-Koefoed *et al.* in press). However, there are only limited data on thickness, areal distribution, generative potential, and stratigraphic age of the actual source rocks. Considering the exploration possibilities in West Greenland, the presence of source rocks seems to be one of the main risk elements, if not the most critical factor. It was therefore generally accepted in 1994 that the level of exploration interest in West Greenland would strongly benefit from the actual demonstration of the existence, age and depositional environment of oil-prone source rocks and by quantifying their generation potential. The most likely candidate in this context was a possible mid-Cretaceous marine source rock (Cenomanian–Turonian) that was first suggested in West Greenland by Chalmers *et al.* (1993) on the basis of world-wide analogies, but later supported by direct data from Ellesmere Island in Arctic Canada (Núñez-Betelu 1994).

The Svartenhuk Halvø area is one of the few areas where Upper Cretaceous and Lower Tertiary marine sediments are exposed onshore West Greenland (Fig. 1), and the mudstones outcropping on Svartenhuk Halvø are the oldest known, fully marine deposits from West Greenland (Birkelund 1965; Nøhr-Hansen 1996). These mudstones have recently been studied during field work by the Geological Survey of Greenland in 1991 and 1992, a programme which also included five shallow boreholes between 66 and 86 m deep (Fig. 1; Christiansen 1993; Christiansen *et al.* 1994). Based on analytical work from these cores and samples from nearby outcrops, thermally immature mudstones of Coniacian to Early Santonian age have been documented (Nøhr-Hansen 1996), thereby giving hope that immature or early mature sediments of Cenomanian–Turonian age could be reached by drilling to relatively shallow depths along the southern shoreline of Umiiviup Kangerlua (Fig. 1).

Drilling project

The Umiivik-1 borehole is located on the southern coast of the bay Umiiviup Kangerlua, Svartenhuk Halvø

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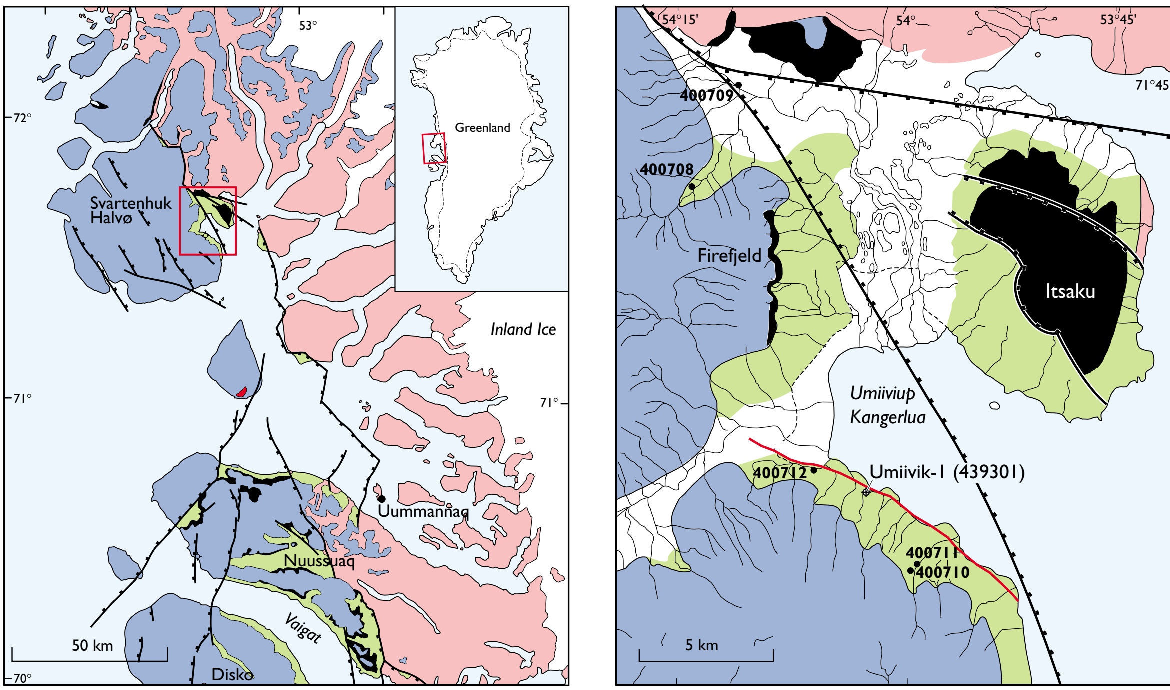


Fig. 1. Simplified geological maps of part of central West Greenland showing location of the Umiivik-1 borehole (with sample number) and other drill holes in the Svartenhuk Halvø area. Based on maps from the Geological Survey of Greenland.

(Fig. 1). The drill site was selected on the basis of a single 11.5 km long refraction and reflection seismic line acquired in the summer of 1994 (Christiansen *et al.* 1995; Fig. 1). The actual drilling position is close to shot point 86 on seismic line GGU SV94–01 in an area with a presumed large thickness of marine mudstones (Bate & Christiansen 1996). The drill site is 500 m inland from the coast at an elevation of approximately 5 m above mean sea level at the position 71°36′42″N, 54°02′31″ W.

Operational services were undertaken by grønArctic Energy Inc. on a 'turn-key' contract with the Government of Greenland, Minerals Office. The Geological Survey of Denmark and Greenland (GEUS) was responsible for selecting the drill site and performing all drill site geological services. This included a preliminary geological description of the core and collection of various types of samples (Bate 1996). Detailed organic geochemical, sedimentological and palynological studies have subsequently been carried out at GEUS, where the core is now stored (Christiansen *et al.* 1997b; Dam 1997; Nøhr-Hansen 1997b).

Technical details of Umiivik-1 are given in the well completion report by Bate (1996) which includes a preliminary geological log, description of penetrated lithologies, sample lists and information on hydrocarbon shows. Preliminary results and the geological background for the drilling programme have been summarised by Bate & Christiansen (1996). A total of 1200 m of core (GGU 439301) was drilled in Umiivik-1 in the period from 21 August to 13 September, 1995. The recovery was close to 100% with a core diameter of 63.5 mm in the uppermost 148 m of the hole and 47.6 mm in the remaining part. Almost the entire core consists of Upper Cretaceous marine mudstones cut by Paleocene dolerite intrusions (Fig. 2). The mudstones are dark grey with

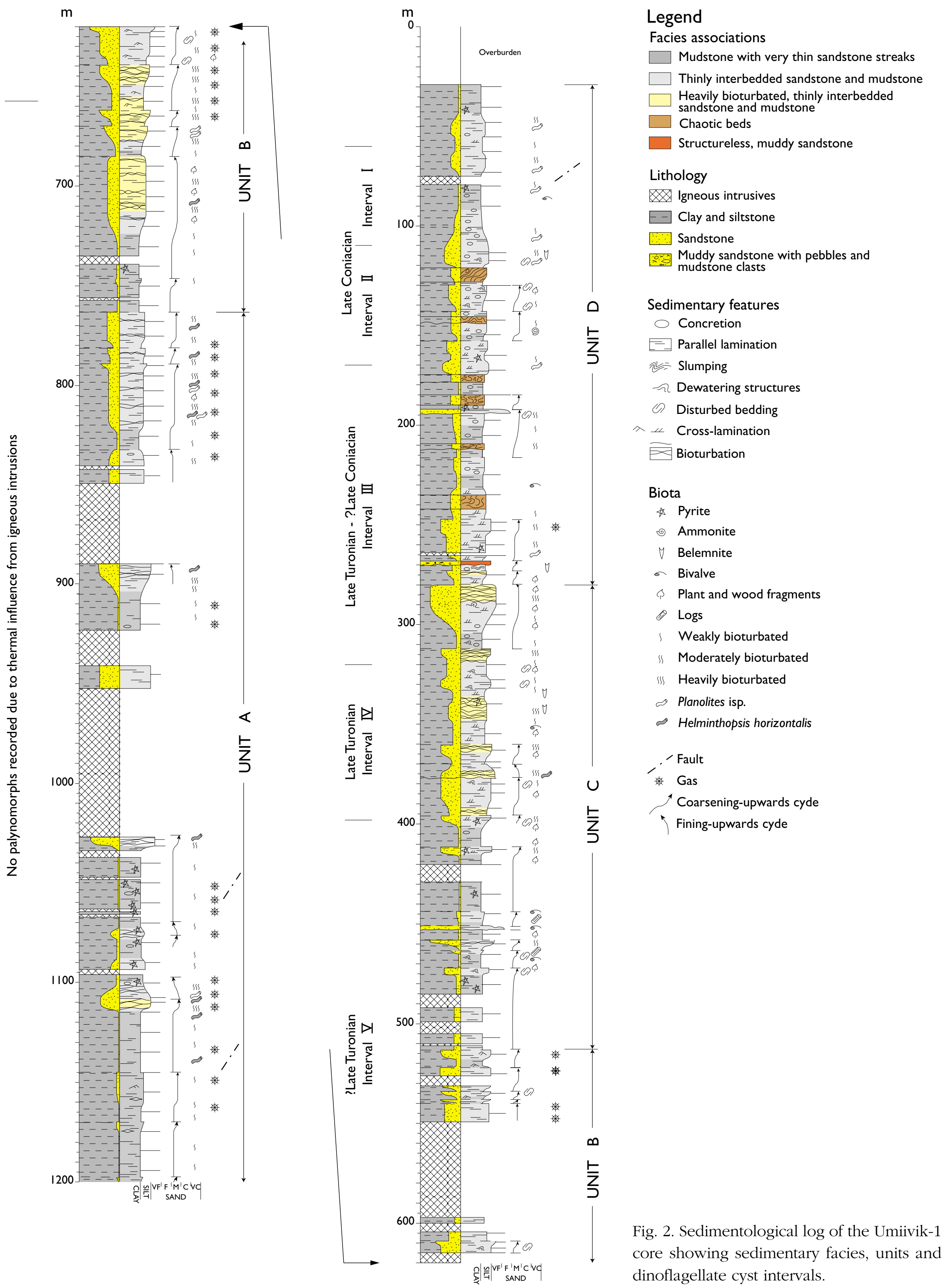


Fig. 2. Sedimentological log of the Umiivik-1 core showing sedimentary facies, units and dinoflagellate cyst intervals.

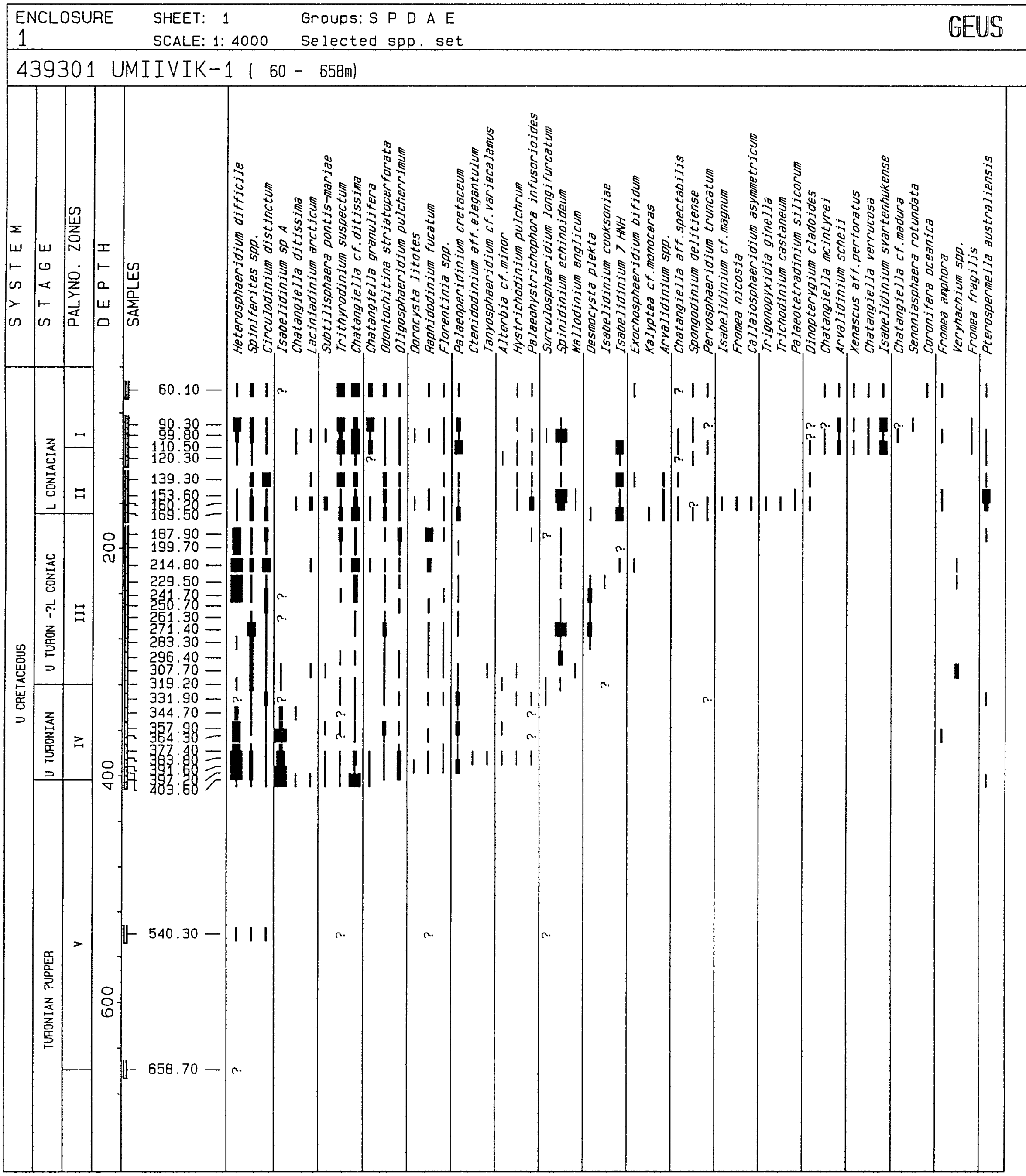
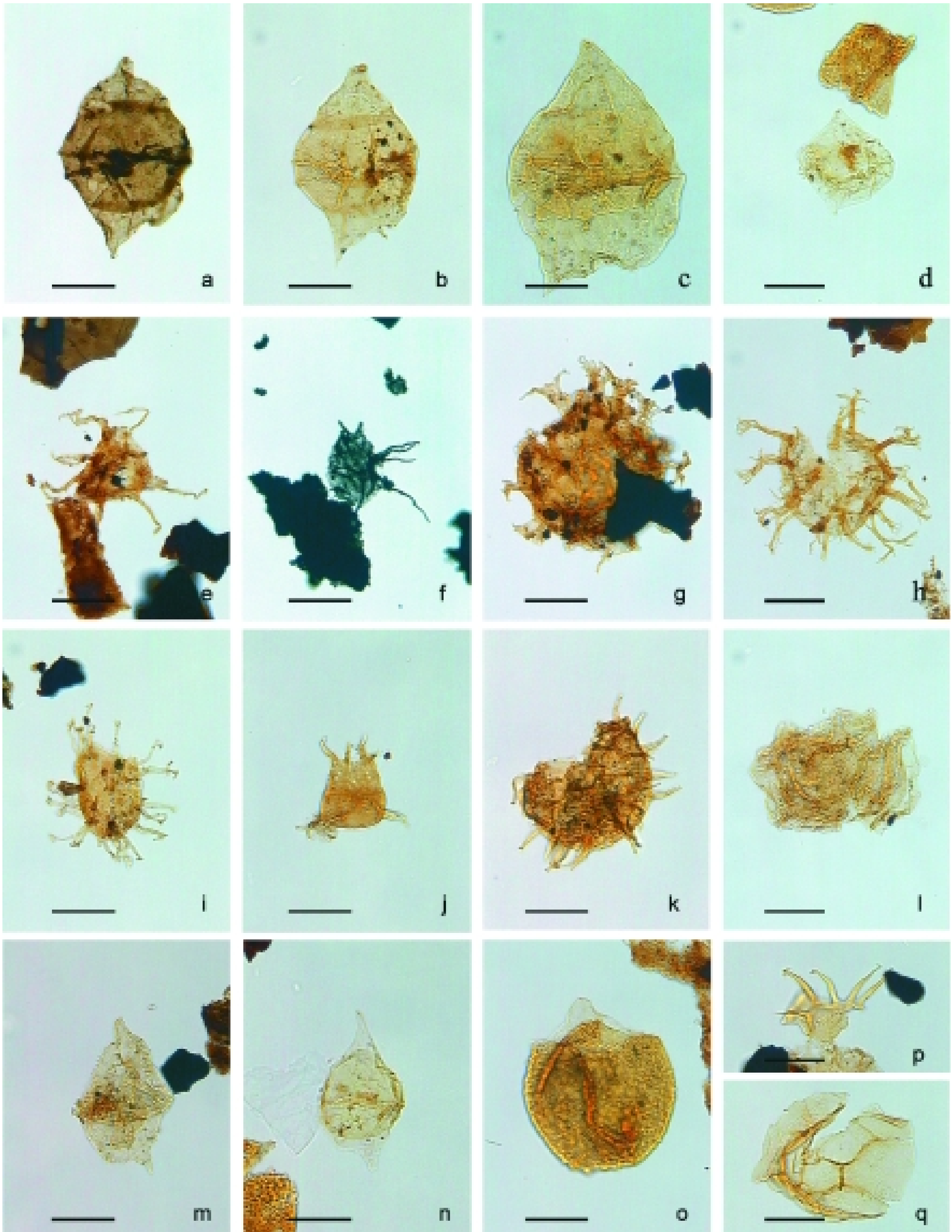


Fig. 3. Range chart of selected palynomorphs from the Umiivik-1 borehole, with division of the core into five dinoflagellate cyst intervals.

abundant silty interbeds and only a few sandstone intervals are present. A total of 22 dolerite intrusions with a cumulative thickness of 240.2 m were intersected throughout the borehole. The thick intrusions from 548.6 to 596.9 m, from 849.1 m to 890.2 m, and from 923.4 m to 1027.1 m have severely altered the marine mudstones, and have thereby limited the possibilities for both detailed organic geochemical and palynological studies in the deeper part of the borehole.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Palynostratigraphy

The dinoflagellate cyst stratigraphy of the Umiivik-1 borehole is based on a study of material from 36 mudstone samples (Fig. 3), of which the lowermost four samples (below 658 m) were barren of dinoflagellate cysts due to severe thermal alteration from dolerite intrusions (Nøhr-Hansen 1997b). The stratigraphic range of selected dinoflagellate cysts is shown in Figure 3. Based on the stratigraphical important species (Fig. 4) the uppermost 658 m of the borehole has been dated as Late Turonian to Early Coniacian. It is divided into five informal dinoflagellate cyst intervals (Fig. 2, 3; Nøhr-Hansen 1997b), of which the uppermost two intervals can be correlated with previous studies on Svartenhuk Halvø (Nøhr-Hansen 1996, 1997b). Previous biostratigraphic studies of ammonites and dinoflagellate cysts from the Umiivik area dated the oldest deposits as Coniacian to Early Santonian (Birkelund 1965; Nøhr-Hansen, 1996). However, Nøhr-Hansen (1996) noted that a Late Turonian age of the sediments from two shallow cores (GGU 400709 and 400712; Fig. 1) could not be excluded.

The dinoflagellate cyst assemblages from Umiivik-1 are characterised by a large number of specimens of *Chatangiella* and *Isabelidinium*. According to the literature the genus *Chatangiella* ranges from the Late Cenomanian to the Late Maastrichtian (Costa & Davey 1992). The presence of *Heterosphaeridium difficile* down to 540.3 m in Umiivik-1 indicates an Early Turonian to Early Santonian age according to e.g. Costa & Davey (1992), whereas Bell & Selnes (1997) suggest a first appearance datum (FAD) for *H. difficile* close to the Early to Middle Cenomanian boundary based on data from the Norwegian shelf. The possible presence of *Raphidodinium fucatum* down to 540.3 m dates the core as post-middle Middle Turonian according to Costa & Davey (1992) or post-early Late Turonian according to Foucher (1979). The presence of *Pervosphaeridium truncatum* in the uppermost part of the core suggests an age no younger than Early Coniacian.

The lowermost recorded dinoflagellate cyst from 658.7 m has been identified as a *Chatangiella* sp. suggesting a post-Middle Cenomanian age (Costa & Davey 1992). The core from 687.7 m to 1191.4 m does not contain preserved dinoflagellate cysts. Thus the succession between 60.1 m and 540.3 m represents a Late Turonian to Early Coniacian age.

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Fig. 4. Stratigraphically important species in the uppermost 658 m of the Umiivik-1 borehole. Bar scale is 20 µm.

a. *Isabelidinium* sp. A, MGUH 24558 from GGU 439301-116-8, 27.3–98.4; LVR 1.8255; MI 5978.

b. *Isabelidinium* sp. A., MGUH 24559 from GGU 439301-110-4, 51.5–103.7; LVR 1.8283; MI 6004.

c. *Isabelidinium* sp. cf. *I. magnum*, MGUH 24560 from GGU 439301-38-2, 22.5–110.1; LVR 1.8321; MI 6040.

d. *Alterbia* sp. cf. *A. minor*, MGUH 24561 from GGU 439301-38.2, 19.4–105.5; LVR 1.8323; MI 6042.

e. *Raphidodinium fucatum,* MGUH 24562 from GGU 439301-112-8, 40.5–98.0; LVR 1.8265; MI 5988.

f. *?Raphidodinium fucatum,* MGUH 24563 from GGU 439301-160-3, 24.1–99.1; LVR 1.8250; MI 5973.

g. *Heterosphaeridium difficile,* MGUH 24564 from GGU 439301-112-8, 24.8–96.4; LVR 1.8263; MI 5986.

h. *Surculosphaeridium longifurcatum*, MGUH 24565 from GGU 439301-94-9, 45.3–103.6; LVR 1.8290; MI 6011.

i. *Tanyosphaeridium* sp. cf. *T. variecalamus,* MGUH 24566 from GGU 439301-110-2, 50.0–110.5; LVR 1.8282; MI 6003.

j. *Dorocysta litotes*, MGUH 24567 from GGU 439301-38-2, 31.6–108.5; LVR 1.8322; MI 6041.

k. *Pervosphaeridium truncatum*, MGUH 24568 from GGU 439301-41-4, 40.3–95.6; LVR 1.8302; MI 6023.

l. *Senoniasphaera rotundata,* MGUH 24569 from GGU 439301-15-3, 19.6–94.1; LVR 1.8368; MI 6085.

m. *Spinidinium echinoideum,* MGUH 24570 from GGU 439301-36-2, 20.0–102.6; LVR 1.8308; MI 6027.

n. *Subtilisphaera pontis-mariae,* MGUH 24571 from GGU 439301-38-4, 46.8–108.7; LVR 1.8339; MI 6057.

o. *Trithyrodinium suspectum*, MGUH 24572 from GGU 439301-38-4, 48.9–96.7; LVR 1.8342; MI 6059.

p. *Ctenidodinium* sp. aff. *C. elegantulum,* MGUH 24573 from GGU 439301- 110-4, 45.9–97.4; LVR 1.8280; MI 6001.

q. *Ctenidodinium* sp. aff. *C. elegantulum,* MGUH 24574 from GGU 439301- 110-3, 26.0–98.6; LVR 1.8277; MI 6000.

Sedimentology

A detailed core description, based on measurement in scale 1:1000 has been given by Dam (1997). Five facies associations have been recognised (Fig. 2). These are: (1) mudstone with very thin sandstone streaks; (2) thinly interbedded sandstone and mudstone; (3) heavily bioturbated thinly interbedded sandstone and mudstone; (4) chaotic beds; and (5) structureless, muddy sandstone.

The former three facies associations dominate the succession. The mudstones of these facies associations were all deposited from low-velocity, low-density turbidite currents dominated by Bouma D and E intervals. The sandstone streaks, laminae and beds are interpreted as deposits of traction and fall-out processes associated with sedimentation from waning, low-density turbitite currents.

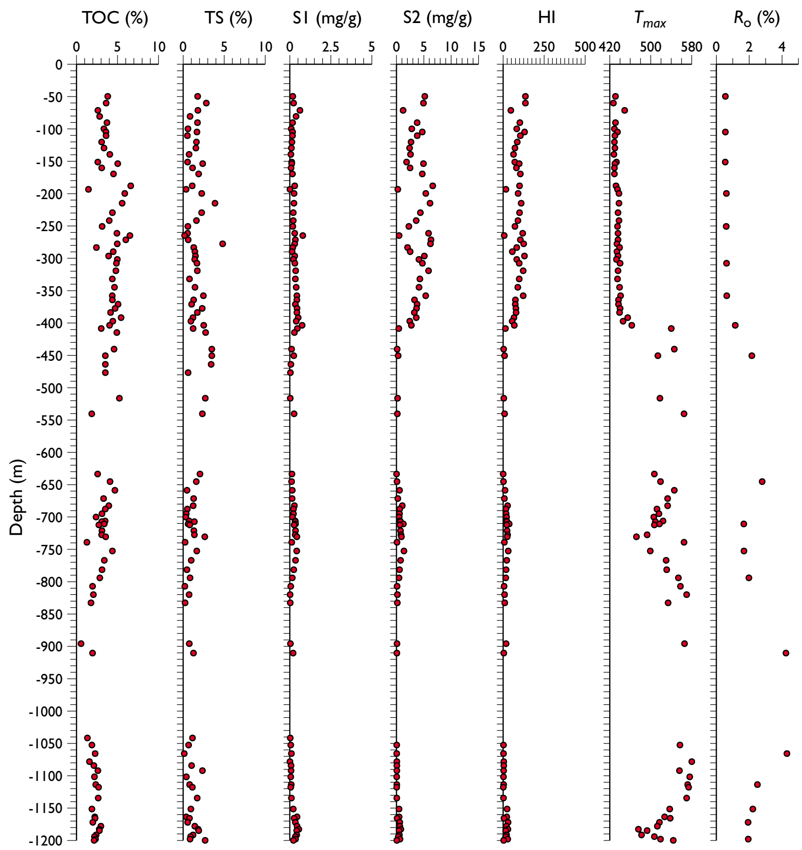

Fig. 5. Simplified geochemical log with LECO/Rval data (TOC, TS, S1, S2, HI, T_{max}) and vitrinite reflection data (R_o).

The trace fossils *Planolites* isp. and *Helminthopsis horizontalis*, and possible *Zoophycus* isp. and *Gyrochorte comosa*, have been recognised in the bioturbated intervals. The chaotic beds have only been recognised in the upper part of the core and consist of contorted beds of mudstone and thinly interbedded sandstone and mudstone of facies associations 1 and 2. The contorted bedding is attributed to slumping in an unstable slope environment. Structureless muddy sandstones deposited from sandy debris flows have only been recognised at one level in the upper part of the core. Dinoflagellate cyst assemblages, ammonites and belemnites, and the total sulphur content in the mudstones indicate a marine depositional environment for the complete cored succession.

Deposition of the Umiivik-1 sedimentary succession took place in the distal part of a major turbidite complex, probably the northern extension of the turbidite complex known from farther south in western and northern Nuussuaq (cf. Dam & Sønderholm 1994). The sedimentary succession is divided into four depositional units (Fig. 2; Dam 1997). The lower three units are 184 m to 295 m thick and show an overall thickening- and coarsening-upward trend interpreted as the result of progradation of the distal part of major submarine lobes. The overall coarsening-upward successions include well-developed coarsening-upward cycles 2–57 m thick. These are interpreted to represent smaller lobes formed in front of minor distributaries or as channel-levee-overbank complexes (Dam 1997). The uppermost Unit D is 247 m thick and differs from the three underlying units by the lack of an overall coarsening-upward trend, by the decrease in well-developed fining-upward cycles and the relatively large amount of slump deposits. The scarcity of systematic vertical variations in the thinly interbedded sandstone and mudstone of Unit D, suggests that these deposits were not confined to channel-levee systems, and that they more likely represent interchannel slope apron deposits. The increase of bioturbation from Unit A to Units B and C and the possible steepening of the slope, represented by the topmost Unit D, suggest that the cored succession in the Umiivik-1 borehole represents an overall progradation of a turbidite complex. However, the increase in slump and debris flow deposits may also suggest that the area became tectonically more unstable.

Organic geochemistry of mudstones

A standard analytical programme has been undertaken on the Umiivik-1 core (Christiansen *et al.* 1997) which included the following techniques: (1) LECO/Rock Eval pyrolysis (n = 98); (2) total sulphur analysis (n = 98); (3) vitrinite reflectance, R_o (n = 20); (4) extraction in a Soxtech apparatus with subsequent deasphalting and column separation into saturated and aromatic hydrocarbons and NSO compounds (n = 9); (5) analysis of saturated hydrocarbons by gas chromatography/mass spectrometry (GC/MS) (n = 9); (6) head space gas composition (n = 27), C isotopes of methane (n = 17), in some cases of ethane (n = 8) and propane (n = 6).

There is a significant difference in thermal maturity between the upper part of the core (above 390 m), and the deeper part below 405 m with only a thin transition zone. In the upper part T_{max} values range from 427°C to 441°C whereas vitrinite reflectance values range from 0.55% to 0.63% (Fig. 5). This suggests that the sediments are thermally immature or at a level corresponding to the early part of the oil window. In the lower part T_{max} values and vitrinite reflectance values are very high and seem to be controlled by the position of major intrusions.

The content of total organic carbon (TOC) of the mudstones is moderate to high with most values between 2% and 6% (Fig. 5). In the upper part, the Hydrogen Index (HI) varies from 63–136. These values suggest a poor to fair source rock potential for oil. In the lower post-mature part of the core HI values are typically below 25, in many cases below 10. Total sulphur values (TS) typically vary from 0.5% to 3.5% with a few very low and very high values. This range of values suggests a marine depositional environment for mudstones.

Due to the high thermal maturity below *c.* 405 m only nine mudstones from the upper part of the core were extracted and analysed by gas chromatography and gas chromatography/mass spectrometry. The analytical details and interpretations are given in the report by Christiansen *et al.* (1997b). All data from these samples are rather similar and suggest a significant input of terrestrial organic matter and a relatively low thermal maturity. The biomarker distributions show very low concentrations of angiosperm biomarkers and a notable concentration of bisnorhopane in several samples. This composition shows some similarities to the Itilli oil type described by Bojesen-Koefoed *et al.* (in press) and to the Kanguk Formation source rock from Ellesmere Island (Bojesen-Koefoed *et al.* 1997), although both the Itilli oil type source rock and the Kanguk source rock seem to have been deposited during more restricted conditions than the analysed sediments from Umiivik-1.

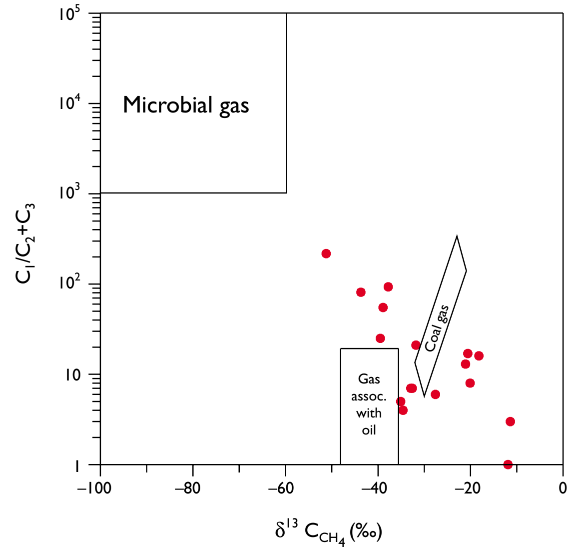

Fig. 6. $C_1/C_2 + C_3$ (= wetness) versus ^{13}C-isotope composition of methane.

Gas geochemistry

Head space analyses on cans containing core samples show that considerable quantities of gas were released from some intervals (Christiansen *et al.* 1997b). The highest recorded gas values are from the intervals 100–300 m and 1150–1200 m, but scattered high values have been recorded throughout the core. Methane is the most abundant hydrocarbon gas, the $C_1/C_2 + C_3$ ratio being 3 to 200 with a general decrease with depth. Samples from deeper than 794 m in particular are very wet ($C_1/C_2 + C_3$<10), and one interval from 1151 to 1182 m shows very high concentrations of wet gases (including both normal and isobutane and pentane).

The isotope composition of the gases varies considerably, especially for methane (Fig. 6), whereas the variation for ethane and propane is much smaller. These isotope values together with the often relatively high wetness are in accordance with a thermogenetic origin of the gases. Some of the samples have a composition typical of gas associated with oil, although the composition is clearly affected by diffusion (see details in Christiansen *et al.* 1997b).

Conclusions and recommendations for future work

Although Umiivik-1 did not give the ultimate break-through that was hoped for from this stratigraphic borehole, it has added important geological knowledge that will be useful in the evaluation of the exploration possibilities on- and offshore West Greenland in the future.

The Umiivik-1 borehole penetrated the oldest marine sediments recorded so far in West Greenland, and the documentation of a thick prograding turbidite complex at this time in the basin development has important implications for deposition of source rocks and reservoir sandstones in the Nuussuaq Basin, as well as in neighbouring offshore basins. The overall progradational trend of the turbidite complex and the presence of a thick mudstone unit at the base of the drilled succession with very high concentrations of wet gases, suggest that the lower mudstone unit represents a major condensed section. Although it has not been possible to date this mudstone due to the thermal influence from the nearby igneous intrusives, the presence of Upper Turonian strata *c.* 500 m above the mudstone might indicate that this is the interval which has been recognised as a world wide Cenomanian–Turonian Oceanic Anoxic Event (cf. Schlanger *et al.* 1987). This event occurs at the base of a highstand systems tract, and occupies a similar position in the Umiivik-1 borehole.

The palynological results obtained have extended the biostratigraphic correlation scheme into a considerably older succession than previously documented, results that will be important for correlation of future wells in West Greenland. The combination of palynostratigraphy and organic geochemistry of the marine mudstones in the upper part of the core has given good possibilities for correlating biomarker distributions with stratigraphic age, and thereby making correlations between seeping oils and presumed source rock intervals much more certain.

The organic geochemical results suggest the existence of a possible source rock for condensate, perhaps even oil, in the deeper part of Umiivik-1. Due to the high thermal maturity (late part of oil window – early part of gas window) this possible Cenomanian–Turonian source rock cannot be dated in detail and it is not possible to document the detailed composition of generation products and the generative potential.

The results are encouraging for further studies on Svartenhuk Halvø, especially after the discovery of oil seepage there in 1997 (see Christiansen *et al.* 1998, this volume). New drilling is risky and is not recommended without very careful planning of how intrusions can be avoided at an alternative drill site. Follow-up field work aiming at more detailed sedimentological and palynological studies of outcropping Upper Cretaceous sediments as well as systematic 'oil hunting' combined with structural studies may give the most likely break-through in coming years.

Acknowledgements

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