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Biostratigraphic correlation of the western and eastern margins of the Labrador–Baffin Seaway and implications for the regional geology

Henrik Nøhr-Hansen, Graham L. Williams
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Keywords
Baffin Margin, Labrador Margin, offshore West Greenland, Cretaceous, Cenozoic, biostratigraphy, palynology, dinocysts, palaeoenvironments

Cover illustration
The Canadian icebreaker *Amundsen* in Blanley Bay, southern Devon Island in the Canadian Arctic in the autumn of 2013. Immediately south-east of this locality, across Lancaster Sound, is Bylot Island where Cretaceous–Paleocene sediments are exposed. Photo: Kate Jarrett (GSC).

Frontispiece: facing page
Survey drilling team in Agatdalen, central Nuussuaq, West Greenland, recovering core from the lower–middle Campanian Aaffarsuaq Member (Itilli Formation); the mountain in the background is composed of Paleocene volcanic rocks of the Vaigat Formation. Such fully cored stratigraphic wells have been invaluable in documenting the detailed stratigraphy of the onshore area of the West Greenland Margin.

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Contents

Abstract

Nøhr-Hansen, H., Williams, G.L. & Fensome, R.A. 2016: Biostratigraphic correlation of the western and eastern margins of the Labrador–Baffin Seaway and implications for the regional geology.
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New analyses of the palynological assemblages in 13 offshore wells on the Canadian margin and six on the West Greenland Margin, in conjunction with onshore data, have led to a new biostratigraphic framework for the Cretaceous–Cenozoic strata of the Labrador Sea – Davis Strait – Baffin Bay (Labrador–Baffin Seaway) region and the first broad biostratigraphic correlation of the Canadian and Greenland margins. This framework is based on 167 last occurrences and 18 local/regional peak/common-occurrence events for dinocysts, miospores, fungal spores and *Azolla*. Detailed biostratigraphic evidence has confirmed the following hiatuses: pre-Aptian in the Hopedale Basin; pre-Albian in the Saglek Basin; Albian–Turonian in some wells of the Hopedale Basin; Turonian–Santonian/Campanian in some areas; pre-Campanian and late Campanian – Thanetian on the Greenland Margin; late Maastrichtian and Danian in some wells of the Hopedale Basin and in the Saglek Basin; Selandian in part of the Hopedale Basin, in all the Saglek Basin wells and in two wells on the West Greenland Margin; late Ypresian and/or Lutetian on both sides; Oligocene to middle Miocene of considerable variability on both margins, with all of the Oligocene and the lower Miocene missing in all the West Greenland Margin wells; and middle to late Miocene on the western side. On the Canadian margin, the hiatuses can be partially matched with the five previously recognised regional unconformities; on the Greenland margin, however, the relationship to the five unconformities is more tenuous. Palynomorph assemblages show that most Aptian to Albian sediments were deposited in generally non-marine to marginal marine settings, interrupted by a short-lived shallow marine episode in the Aptian. A marine transgression started in the Cenomanian–Turonian and led to the most open-marine, oceanic conditions in the Campanian–Lutetian; shallowing probably started in the late Lutetian and continued into the Rupelian, when inner neritic and marginal marine palaeoenvironments predominated. Throughout the rest of the Cenozoic, inner neritic palaeoenvironments alternated with marginal marine conditions on the margins of the Labrador–Baffin Seaway. These observations broadly reflect the tectonic evolution of the seaway, with rift conditions prevailing from Aptian to Danian times, followed by drift through much of the Paleocene and Eocene, and post-drift from Oligocene to the present. Dinocysts indicate that climatic conditions in the Labrador–Baffin Seaway region were relatively temperate in the Cretaceous, but varied dramatically through the Cenozoic. The Danian was a time of increasingly warmer climate, a thermal maximum being reached around the Paleocene–Eocene boundary reflecting the global thermal event at this time. Warm to hot conditions prevailed throughout the Ypresian, but the climate began to cool in the Lutetian, a trend that accelerated through the Priabonian and Rupelian. Throughout the Neogene, temperatures generally declined, culminating in the Quaternary.

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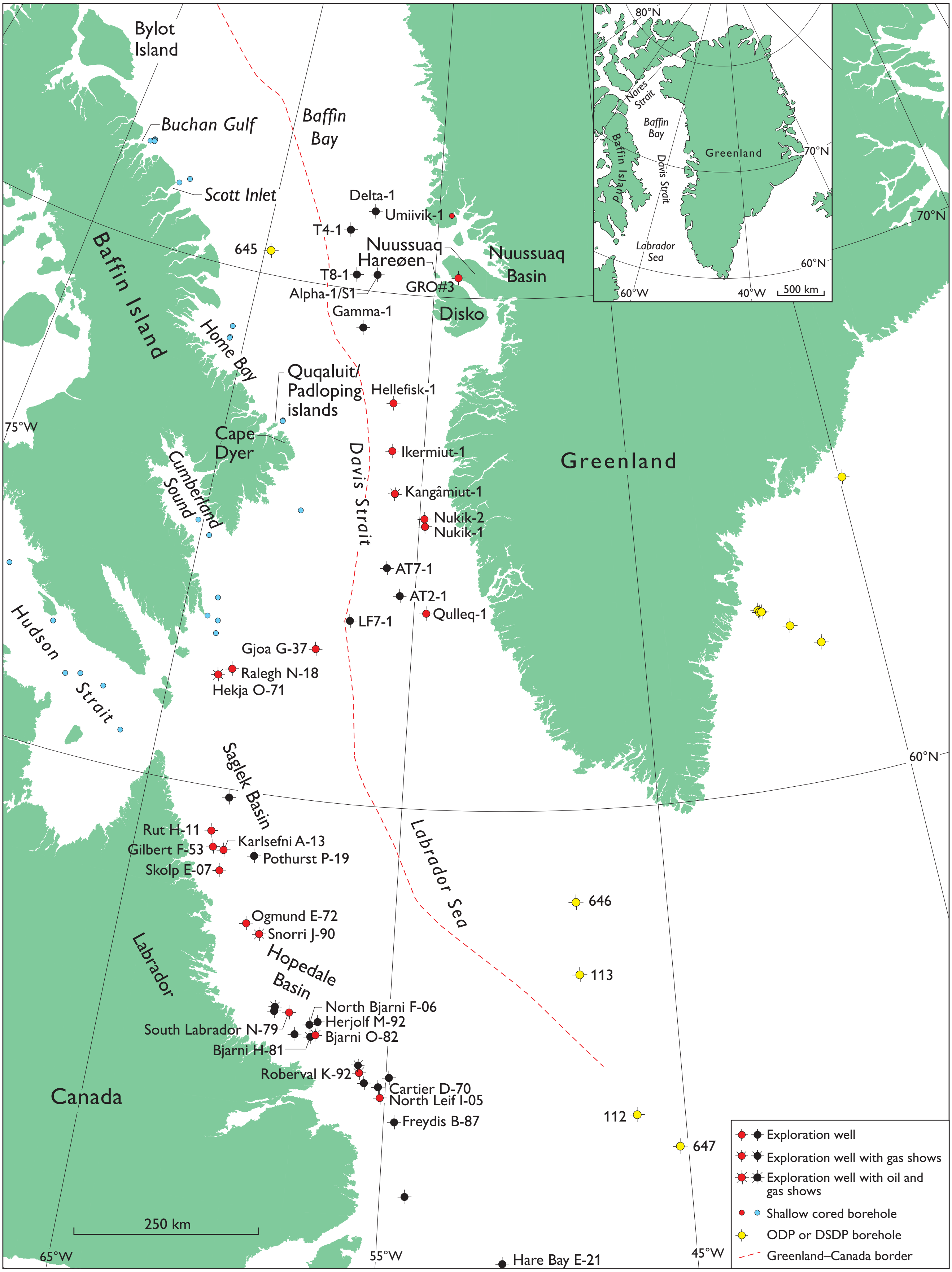
Bylot Island
Buchan Gulf
Baffin Bay
Scott Inlet
Baffin Island
Home Bay
Quqaluit/ Padloping islands
Cape Dyer
Cumberland Sound
Hudson Strait
Davis Strait
Saglek Basin
Labrador Sea
Labrador
Hopedale Basin
Canada
Greenland
Nuussuaq
Hareøen
Nuussuaq Basin
Disko
Delta-1
Umiivik-1
T4-1
645
T8-1
Alpha-1/S1
GRO#3
Gamma-1
Hellefisk-1
Ikermiut-1
Kangâmiut-1
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AT7-1
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Pothurst P-19
Skolp E-07
Ogmund E-72
Snorri J-90
North Bjarni F-06
Herjolf M-92
Bjarni O-82
South Labrador N-79
Bjarni H-81
Roberval K-92
Cartier D-70
North Leif I-05
Freydis B-87
Hare Bay E-21
646
113
112
647
75°W
70°N
60°N
65°W
55°W
45°W
250 km
80°N
Nares Strait
Baffin Bay
Baffin Island
Davis Strait
Greenland
70°N
Labrador Sea
60°N
60°W
40°W
500 km
Exploration well
Exploration well with gas shows
Exploration well with oil and gas shows
Shallow cored borehole
ODP or DSDP borehole
Greenland–Canada border

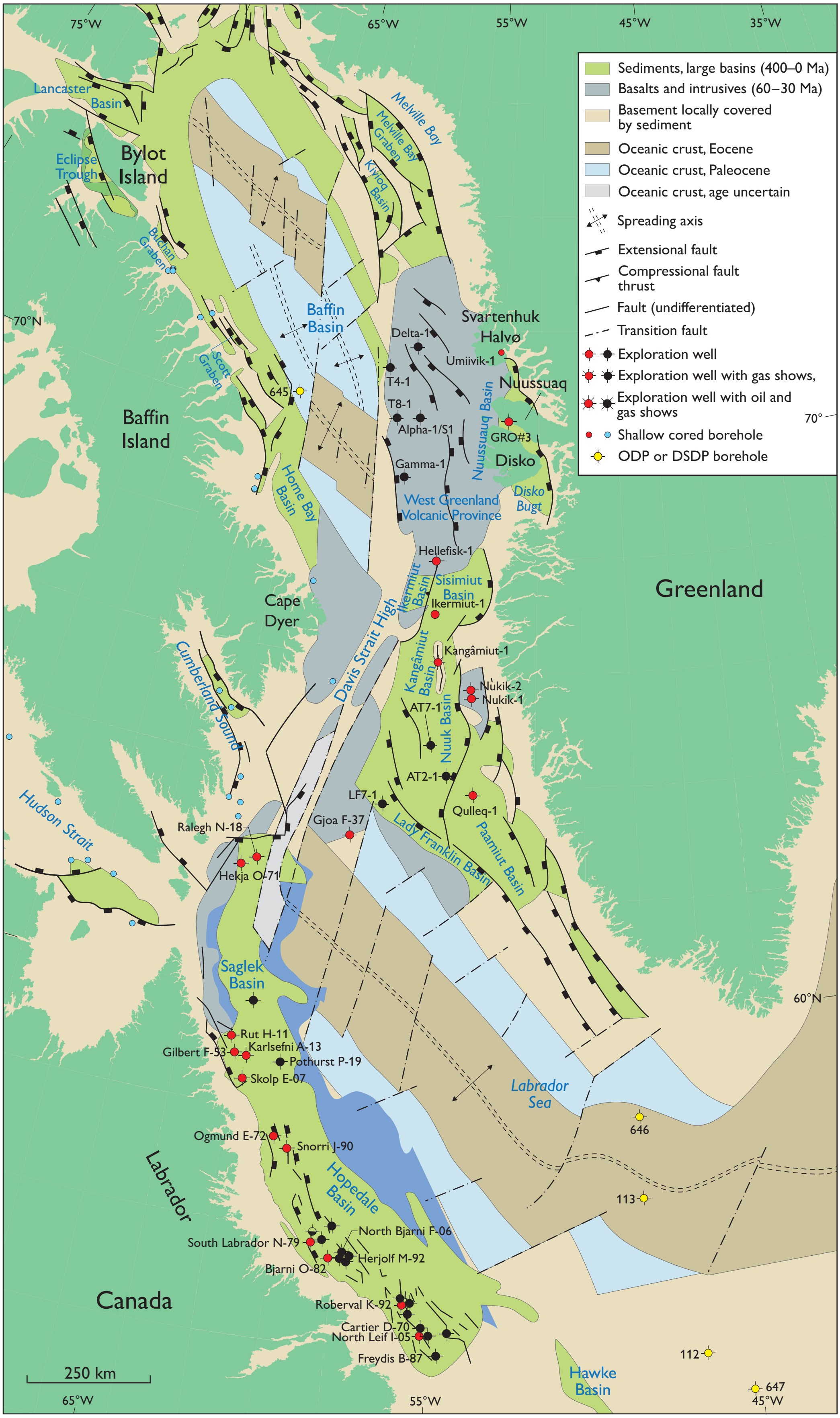
Introduction

Canada and Greenland are separated, from south to north, by the Labrador Sea, the Davis Strait, Baffin Bay (referred to here collectively as the Labrador–Baffin Seaway), and the narrow Nares Strait (Fig. 1). As summarised in Monger *et al.* (2014) and Fensome *et al.* (2014), the Labrador–Baffin Seaway originated as a series of rift basins that developed successively from south to north during the Early Cretaceous, and which ultimately became connected to form a seaway in the Late Cretaceous. A drift phase in the seaway, causing the Greenland Plate to rotate away from North America, was heralded by an episode of volcanic activity between 62 and 56 million years ago, perhaps resulting from the passage of the Icelandic mantle plume (Dam *et al.* 1998a; Larsen *et al.* 2016). This episode involved vast outpourings of basalt in central West Greenland and south-eastern Baffin Island. As drift ensued, sea-floor spreading resulted in progressive widening of the Labrador–Baffin Seaway until the Priabonian. This development meant that Greenland changed course, its northern end colliding with Arctic Canada, resulting in an episode of deformation known as the Eurekan Orogeny. The collision inhibited the rotation of Greenland away from North America, and sea-floor spreading in the Labrador–Baffin Seaway ceased around the latest Eocene. From that time on, sea-floor spreading in the northern North Atlantic Ocean occurred only between Greenland and northwestern Europe, where a spreading axis had opened about 55 million years ago. Thus, until this time, Greenland was part of Laurasia, between about 55 and 35 million years ago it constituted a separate plate, and after 35 million years ago it became part of the North American Plate.

The Labrador–Baffin Seaway stretches from about 52°N to 75°N, a distance of roughly 2500 km (Fig. 1). Knowledge of the timing of the geological evolution of the Seaway is based primarily on biostratigraphic analyses on exploration wells drilled between 1971 and 2000 on the Labrador Margin, offshore West Greenland and in the Davis Strait, and from some shallow cored boreholes drilled in Baffin Bay in the 1970s and 1980s and in the Nuussuaq Basin in the 1990s (Fig. 1). Additional information comes from numerous Cretaceous–Cenozoic outcrop sections in the Nuussuaq Basin in West Greenland, a few onshore sections in Labrador and on Baffin and Bylot Islands, and from ODP Leg 105, hole 645 in Baffin Bay (Fig. 1). Although previous work on these wells and sections has provided a good stratigraphic foundation for the Cretaceous–Cenozoic of the region, renewed petroleum exploration interest in recent years has revealed gaps in our knowledge and a need to correlate the western and eastern margins of the seaway. Consequently, for the past decade the Geological Survey of Denmark and Greenland (GEUS) and the Geological Survey of Canada (Atlantic) (GSCA) have undertaken an exhaustive palynological study, with the goal of providing more detailed age control. This study is based on palynological analysis of more than 2000 well samples from the Labrador Margin, the Davis Strait and offshore West Greenland. Organic-walled dinoflagellate cysts (dinocysts) are the primary palynomorph group evaluated, but spores and pollen (miospores), a fern microspore massula (*Azolla*), algal and fungal microfossils and acritarchs have also been considered.

The new age determinations presented here and documented in detail in a companion publication (Fensome *et al.* 2016) are more precise than those of previous studies because of advances made in refining the stratigraphic ranges of dinocysts (e.g. Williams *et al.* 2004). Moreover, the number of species for which detailed stratigraphic information is available has increased immeasurably since early studies in the region in the 1970s. Using the more detailed stratigraphic data, 187 bioevents are identified for the Labrador–Baffin Seaway. Some events are coeval, so the 187 bioevents define 106 bioevent horizons. Bioevent data are also incorporated from Piasecki (2003) for the Neogene of offshore West Greenland and from Pedersen & Nøhr-Hansen (2014) for Albian to Paleocene strata of the Nuussaq Basin, West Greenland. In addition to biostratigraphic determinations, palaeoenvironmental inferences are made from the data, using, for example, individual dinocyst species and dinocyst assemblages. We have also endeavoured to decipher palaeooceanographic conditions and palaeoclimates, the results revealing similarities to high southern latitudes in the Late Cretaceous.

Facing page:
Fig. 1. Map of the Labrador–Baffin Seaway showing the location of relevant wells, boreholes and onshore localities; wells and boreholes shown in red were used in this study. Inset map shows the regional context of the Labrador–Baffin Seaway between Canada and Greenland.


75°W
65°W
55°W
45°W
35°W
Sediments, large basins (400–0 Ma)
Basalts and intrusives (60–30 Ma)
Basement locally covered by sediment
Oceanic crust, Eocene
Oceanic crust, Paleocene
Oceanic crust, age uncertain
Spreading axis
Extensional fault
Compressional fault thrust
Fault (undifferentiated)
Transition fault
Exploration well
Exploration well with gas shows,
Exploration well with oil and gas shows
Shallow cored borehole
ODP or DSDP borehole
Lancaster Basin
Eclipse Trough
Bylot Island
Melville Bay
Melville Bay Graben
Kivioq Basin
Buchan Graben
Baffin Basin
Svartenhuk Halvø
70°N
Delta-1
Umiivik-1
Scott Graben
T4-1
Nuussuaq
645
T8-1
Nuussuaq Basin
70°
Baffin Island
Alpha-1/S1
GRO#3
Disko
Gamma-1
Home Bay Basin
Disko Bugt
West Greenland Volcanic Province
Hellefisk-1
Ikermiut Basin
Sisimiut Basin
Greenland
Cape Dyer
Ikermiut-1
Davis Strait High
Kangâmiut-1
Cumberland Sound
Kangâmiut Basin
Nukik-2
Nukik-1
AT7-1
Nuuk Basin
AT2-1
Hudson Strait
LF7-1
Qulleq-1
Ralegh N-18
Gjoa F-37
Lady Franklin Basin
Paamiut Basin
Hekja O-71
Saglek Basin
60°N
Rut H-11
Karlsefni A-13
Gilbert F-53
Pothurst P-19
Skolp E-07
Labrador Sea
646
Ogmund E-72
Snorri J-90
Labrador
Hopedale Basin
113
North Bjarni F-06
South Labrador N-79
Herjolf M-92
Bjarni O-82
Canada
Roberval K-92
Cartier D-70
North Leif I-05
Freydis B-87
112
250 km
Hawke Basin
647
65°W
55°W
45°W

Tectonic setting

Labrador Sea

Kerr (1967) and Grant (1980) considered the Labrador Sea to be floored by foundered continental crust. Umpleby (1979) explained the formation of this seaway by using a modification of the Undation Theory of Van Bemmelen (1949, 1972), but still considered that there was no underlying oceanic crust. The seismic, magnetic and gravity data (Le Pichon *et al.* 1971; Srivastava 1978), however, strongly supported a plate-tectonic model of lithospheric extension and spreading, accompanied by generation of oceanic crust. Srivastava (1978) considered the oldest oceanic crust in the southern Labrador Sea to be assignable to Anomaly 34 (Coniacian–Santonian) and in the north to Anomaly 31 (Maastrichtian). He observed that a change in the direction of spreading occurred between Anomaly 25 (early Thanetian) and Anomaly 24 (late Thanetian to early Ypresian), and noted that Anomaly 13 (late Priabonian to earliest Rupelian) and subsequent anomalies were missing.

Roest & Srivastava (1989) and Srivastava & Roest (1999) interpreted the oldest oceanic crust in the Labrador Sea as Anomaly 33 (most of the Campanian; 73.6–79 Ma). However, biostratigraphic analyses of the Qulleq-1 well, offshore West Greenland, demonstrated that the well reached total depth (TD) in Santonian sedimentary rocks (Nøhr-Hansen *et al.* 2000; Christiansen *et al.* 2001; Henriksen *et al.* 2009), which would imply that the crust underlying Qulleq-1 is the oldest-known oceanic crust north of 56°N in the Atlantic (Henriksen *et al.* 2009). However, Chalmers (1991) and Chalmers & Laursen (1995) could not identify any anomalies in the Labrador Sea older than Chron 27n (latest Danian) and concluded that sea-floor spreading began between 63 and 61.7 Ma (latest Danian), and that a transition zone exists between continental and oceanic crust. The interpretations of Chalmers (1991) were later supported by those of Chalmers & Pulvertaft (2001) and Oakey & Chalmers (2012), and followed by Sønderholm *et al.* (2003a, b). Moreover, Funk *et al.* (2007, 2012) suggested that the crust underlying Qulleq-1 is of continental origin.

Based in part on the understanding of magnetic anomalies at the time and in part on biostratigraphy, Balkwill & MacMillan (1990) proposed three megasequences for the lithostratigraphic units encountered in offshore wells: synrift (Neocomian to Campanian), drift (Late Cretaceous to Eocene), and post-drift (Oligocene to Recent). Similarly, but based on updated knowledge of the timing of sea-floor spreading, Sønderholm *et al.* (2003b) recognised: an initial rifting phase (Phase 1) in the Early Cretaceous, a continued rifting phase (Phase 2) in the Late Cretaceous to Danian, and a subsequent drift and post-drift phase (Phase 3). Sønderholm *et al.* (2003b) speculated that Phase 1 may have started in the Jurassic based on tentative observations by Dalhoff *et al.* (2006) and Piasecki (2003), a notion supported by Larsen *et al.* (2009) who indicated that lithospheric stretching between Canada and West Greenland probably started in Jurassic time.

On the western margin of the Labrador Sea from south to north is a series of roughly SE–NW-aligned basins separated by basement highs, or arches, oriented perpendicular to the basins (Fig. 2). Exploration wells have been drilled in two of the basins, the Hopedale and Saglek Basins.

Facing page:

Fig. 2. Map of the basic geology of the Labrador–Baffin Seaway, showing the main structural features and relevant well/borehole locations; wells and boreholes shown in red were used in this study. Modified from Henriksen *et al.* (2009) and Oakey & Chalmers (2012).

Davis Strait and Baffin Bay

The Davis Strait High, where water depths can be as shallow as about 600 m, forms the northern periphery of the Labrador Sea and sits above a major transform margin that developed around the Paleocene–Eocene transition (Oakey & Chalmers 2012). Today, the Davis Strait connects the Labrador Sea with Baffin Bay. As was the case for the Labrador Sea, both non-plate-tectonic and plate-tectonic models have been proposed for Baffin Bay. Kerr (1967) and Grant (1975) considered Baffin Bay to be underlain by continental crust modified by basalt intrusions. Keen *et al.* (1972) and Srivastava (1978), however, postulated that oceanic crust underlies Baffin Bay. Support for a plate-tectonic origin was provided by Jackson *et al.* (1979), who identified anomalies 21 (earliest Lutetian) to 13 (late Priabonian to earliest Rupelian). Oakey (2005) recognised two sets of linear magnetic anomalies trending NNW–SSE and NW–SE, which correspond respectively to the Paleocene and Eocene anomalies in the Labrador Sea. Harrison *et al.* (2011) considered Baffin Bay to be underlain in part by oceanic crust, formed between Chron 27 and Chron 13 – i.e. late Danian to earliest Rupelian (Fig. 2).

In the east of Baffin Bay, off West Greenland, is a series of roughly SE–NW- and S–N-aligned basins separated by basement highs or ridges oriented parallel or oblique to the basins (Fig. 2). Some of these basins along the south-western part of the West Greenland Margin were penetrated by wells drilled between 1976 and 2000: Qulleq-1 in the Paamiut Basin, Nukik-1 and Nukik-2 in the Nuuk Basin, Kangâmiut-1 in the Kangâmiut Basin and Ikermiut-1 in the Sisimiut Basin. Another well, Hellefisk-1, was drilled in the same period within the West Greenland Volcanic Province (Figs 1, 2). The oil company Cairn drilled eight exploration wells in 2010 and 2011: one in the Lady Franklin Basin (LF7-1), two in the Nuuk Basin (AT2-1, AT7-1), and five in the West Greenland Volcanic Province (Delta-1, T4-1, T8-1, Alpha-1/S1, Gamma-1; Fig. 2); none of the samples or data from these wells are yet released.

General stratigraphy

Offshore

Labrador Margin

A formal Cretaceous–Cenozoic lithostratigraphic scheme was proposed for Labrador Margin wells by Umpleby (1979) and modified by McWhae *et al.* (1980); the version adopted here (Fig. 3) is that with the timescale calibrated by Sørensen (2006, fig. 2) and modified by Dickie *et al.* (2011).

The oldest rocks in some wells in the Hopedale and Saglek Basins are igneous or metamorphic and of Precambrian age. In other wells in the two basins, the oldest rocks are Ordovician or Carboniferous. Separating these basement rocks from overlying Cretaceous and Cenozoic strata is an unconformity, termed the Labrador Unconformity by McWhae *et al.* (1980) and McWhae (1981; Fig. 3). McWhae (1981) gave an age of 130 to 120 Ma for the Labrador Unconformity though the timescale on which this was based is not clear. The oldest Cretaceous unit is the Alexis Formation, which consists of basalts with subordinate claystone, siltstone and sandstone (Fig. 3). Corgnet & McWhae (1973) determined radiometric ages of 139 ± 7 Ma and 122 ± 6 Ma for two basaltic cores from the type section of the Alexis Formation in Bjarni H-81, viz. Valanginian to early Aptian on the timescale of Gradstein *et al.* (2012).

Sørensen (2006, fig. 2) gave an age of Barremian to Albian for the Bjarni Formation, which overlies the Alexis Formation. The Bjarni Formation is a predominantly sandstone unit and the main hydrocarbon reservoir in the Hopedale Basin (Figs 2, 3). According to McWhae (1981), the Bjarni Formation is separated from the overlying Markland Formation by the Avalon Unconformity, which McWhae considered to range from 100 to 85 Ma (timescale not specified). The Markland Formation consists mainly of a distal mudstone facies and its proximal sandstone equivalent, the Freydis Member. Sønderholm *et al.* (2003b) determined an age of Cenomanian to earliest Paleocene for the Markland Formation. A sandstone unit at the top of the Markland Formation, the informal lower Gudrid member, straddles the Cretaceous–Palaeogene boundary (Sørensen 2006).

Overlying the Markland Formation is the Cartwright Formation, which is predominantly a mudstone unit of Paleocene age (Sørensen 2006). In the Saglek Basin, the Cartwright Formation has lower and upper proximal sandstone facies, informally termed the middle and upper Gudrid members respectively (Balkwill & McMillan 1990). Separating the middle and upper Gudrid members is the Bylot Unconformity; the duration of the hiatus was dated by McWhae (1981) as being Danian, 60–63 Ma (timescale not specified) and which Dickie *et al.* (2011) placed at the Danian–Selandian boundary.

A major volcanic episode occurred in the northern Labrador Sea, the Davis Strait and southern Baffin Bay (Figs 2, 3) during the Paleocene to early Eocene. In the Rut H-11 well in the Saglek Basin, supposed tuff beds from this volcanic episode are reported to underlie the Upper Cretaceous – Danian Markland Formation, yet have been dated as 59 Ma (Klose *et al.* 1982). A thick sequence of basalts in Gjoa G-37 appears to be coeval with the tuff beds in Rut H-11, with two basalt samples dated at 59.5 ± 1.0 Ma and 59.2 ± 1.8 Ma (Williamson *et al.* 2001). In Gjoa G-37, however, the basalts occur above the Markland Formation; the implication is that the volcanic rocks in Rut H-11 are of intrusive origin. Also of closely similar age are the Cape Dyer volcanics, dated at 58 ± 2 Ma (Clarke & Upton 1971). Williamson *et al.* (2001) gave ages of 62.9 ± 2.5 Ma and 55.1 ± 2.3 for two basalt cores recovered off Cape Dyer. These volcanics may be related to the transform margin that was developing in the northern Saglek area through the Davis Strait, or to the onset of sea-floor spreading in southern Baffin Bay.

On the Labrador Margin, the top of the informal upper Gudrid member, and thus of the Cartwright Formation, roughly corresponds to the Paleocene–Eocene boundary. Successively above these rocks are the Kenamu (Eocene), Mokami (Oligocene to Miocene) and Saglek (middle Miocene to Pleistocene) Formations. Each of these units consists broadly of a mudstone sequence that becomes sandier and even conglomeratic upwards. McWhae *et al.* (1980) recognised a regional unconformity, the Baffin Bay Unconformity, between the Kenamu and Mokami Formations. These authors also named the regional unconformity between the Mokami and Saglek Formations as the Beaufort Unconformity. McWhae (1981) considered the hiatus at the Baffin Bay Unconformity to be within the early Oligocene, 38–34 Ma; he placed the Beaufort Unconformity in the early to middle Miocene, between 20 and 15 Ma (timescale not specified).

West Greenland Margin

Rolle (1985) formally defined seven formations from well sections released at that time in offshore West Greenland (Fig. 3). He assigned the oldest rocks, a sequence of interbedded mudstones and sandstones, to the Narssarmiut Formation and considered this to be equivalent to the Freydis Member of the Markland Formation to the west, and thus of Campanian age. Based on this study, the Narssarmiut Formation is now considered to be of Selandian age (Fig. 3).

According to Rolle (1985), the Narssarmiut Formation is unconformably overlain by the Ikermiut Formation, which comprises carbonaceous mudstone with some siltstone and sandstone. Rolle (1985) considered the Ikermiut Formation to be of Campanian to middle Eocene age and correlated it with the Markland and Cartwright Formations of the Labrador Margin. If these correlations are correct, then the Ikermiut Formation would straddle the Bylot Unconformity. Indeed, Sønderholm *et al.* (2003b) illustrated the presence of a major hiatus within the Ikermiut Formation, possibly spanning the late Campanian to earliest Paleocene and thus equivalent to the Bylot Unconformity. The Hellefisk Formation occurs only in the Hellefisk-1 well. Rolle (1985) dated it as Thanetian to Eocene and considered that it may interfinger laterally with the Ikermiut Formation; we consider it to be a correlative of the upper part of the Ikermiut Formation (Fig. 3).

Palaeogene formations of the West Greenland Margin are all siliciclastic, with mudstones dominant. The Ataneq Formation is mudstone-dominated; sandstone-dominated units are the Nukik, Kangâmiut and Manîtsoq Formations. Current age determinations of all these formations in individual wells are shown in Fig. 3, based on work by Dalhoff *et al.* (2003), Nøhr-Hansen (2003), Rasmussen *et al.* (2003), Rasmussen & Sheldon (2003), Sheldon (2003) and the results of this study. Neogene sediments are generally upward-coarsening sequences of marine mudstones interbedded with well-sorted fine-grained sandstones.

Although the lithostratigraphy of the West Greenland Margin confirmed in well sections extends back only to the Santonian, older Mesozoic strata are evident from seismic data. Three seismic sequences have been recognised within the Cretaceous succession (Fig. 3). From oldest to youngest, these are the Kitsissut (which probably includes volcanics), Appat and Kangeq sequences (Chalmers *et al.* 1993, 1995; Chalmers & Pulvertaft 2001). The Kitsissut sequence may be coeval with the lower part of the Bjarni Formation, with the inferred volcanics equivalent to the Alexis Formation. The Kangeq sequence has been partly drilled in the Ikermiut-1 and Qulleq-1 wells, where the succession encountered is of early Campanian (Sønderholm *et al.* 2003b) and Santonian–Campanian (Christiansen *et al.* 2001) age, respectively. The mudstone-dominated Kangeq sequence is the lithological equivalent of the Markland Formation of the Labrador Margin.

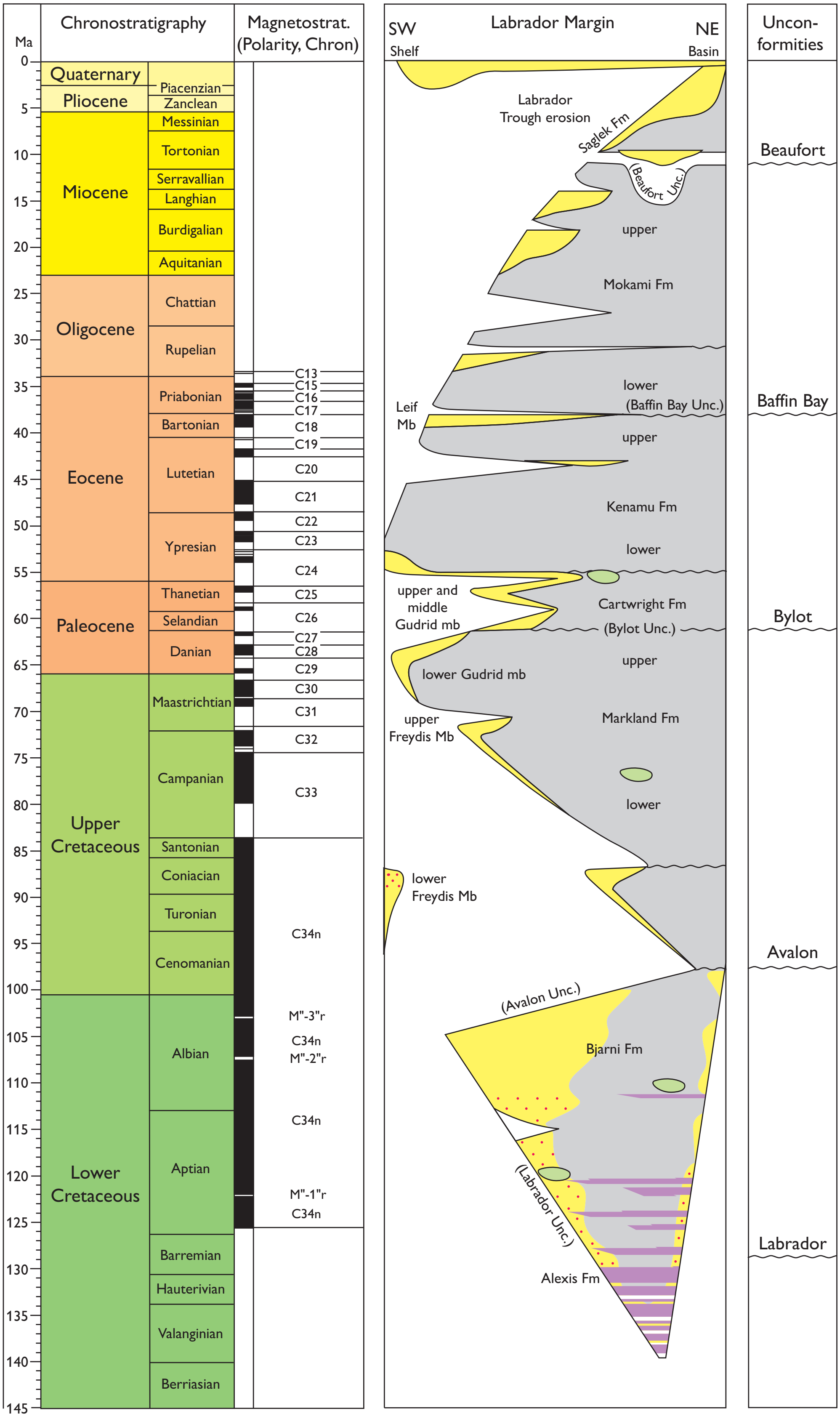
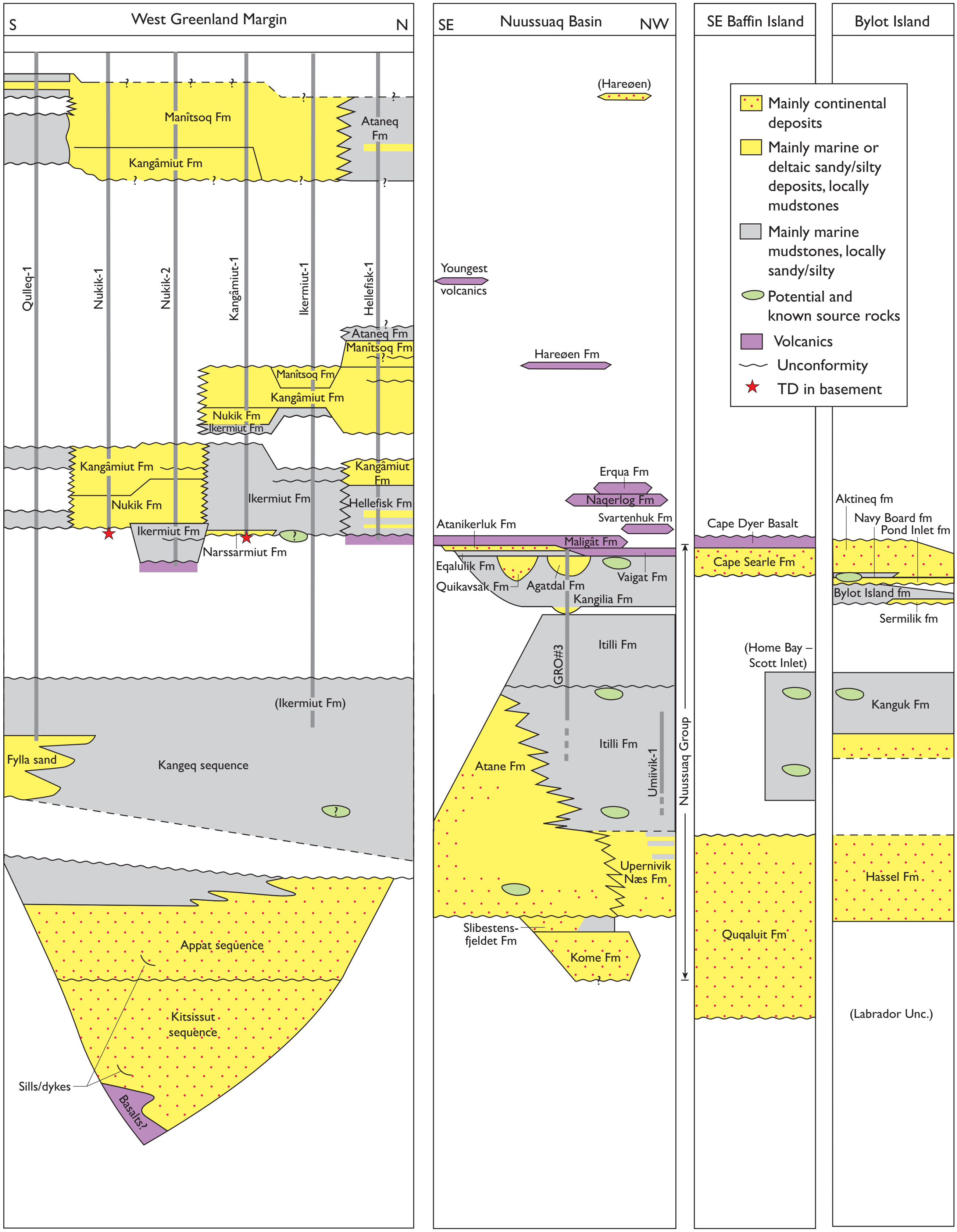


Fig. 3. Stratigraphic framework of the Mesozoic–Cenozoic rocks of the Labrador and West Greenland margins and adjacent onshore sections; modified from Gregersen *et al.* (2013). The Labrador Margin stratigraphy is from Dickie *et al.* (2011), with unconformities from McWhae (1981). The West Greenland Margin stratigraphy is based on well stratigraphic studies by Rolle (1985), Nøhr-Hansen (2003) and Sønderholm *et al.* (2003); the deeper sub-well section is based on Chalmers *et al.* (1993), Chalmers & Pulvertaft (2001) and Sørensen (2006). The Nuussuaq Basin stratigraphy is from Storey *et al.* (1998), Dam *et al.* (2009), Pedersen & Nøhr-Hansen (2014) and Larsen *et al.* (2015); these papers and this study are the source of the inferred ages. The southeast Baffin Island stratigraphy is from Burden & Langille (1990) and Pedersen *et al.* (2002), the Home Bay and Scott Inlet seabed samples from MacLean *et al.* (2014) and the north Baffin Island stratigraphy is based on Jackson *et al.* (1978) and McWhae (1981). The Bylot Island stratigraphy is from Miall (1986), Waterfield (1989), and Harrison *et al.* (1999). The timescale (Ma) and magnetostratigraphy are from Gradstein *et al.* (2012). **Fm**: Formation (formal). **fm**: formation (informal). **Mb**: Member (formal). **mb**: member (informal). **Unc.**: unconformity.


S
West Greenland Margin
N
SE
Nuussuaq Basin
NW
SE Baffin Island
Bylot Island
Mainly continental deposits
Mainly marine or deltaic sandy/silty deposits, locally mudstones
Mainly marine mudstones, locally sandy/silty
Potential and known source rocks
Volcanics
Unconformity
TD in basement
Qulleq-1
Nukik-1
Nukik-2
Kangâmiut-1
Ikermiut-1
Hellefisk-1
Manîtsoq Fm
Kangâmiut Fm
Ataneq Fm
Ataneq Fm
Manîtsoq Fm
Manîtsoq Fm
Kangâmiut Fm
Nukik Fm
Ikermiut Fm
Kangâmiut Fm
Nukik Fm
Ikermiut Fm
Ikermiut Fm
Kangâmiut Fm
Hellefisk Fm
Narssarmiut Fm
(Ikermiut Fm)
Fylla sand
Kangeq sequence
Appat sequence
Kitsissut sequence
Sills/dykes
Basalts?
(Hareøen)
Youngest volcanics
Hareøen Fm
Erqua Fm
Naqerlog Fm
Svartenhuk Fm
Atanikerluk Fm
Maligât Fm
Eqalulik Fm
Quikavsak Fm
Agatdal Fm
Vaigat Fm
Kangilia Fm
Itilli Fm
GRO#3
Itilli Fm
Atane Fm
Umiivik-1
Upernivik Næs Fm
Slibestens-fjeldet Fm
Kome Fm
Nuussuaq Group
Cape Dyer Basalt
Cape Searle Fm
(Home Bay – Scott Inlet)
Quqaluit Fm
Aktineq fm
Navy Board fm
Pond Inlet fm
Bylot Island fm
Sermilik fm
Kanguk Fm
Hassel Fm
(Labrador Unc.)

Baffin Margin

Offshore rocks of western Baffin Bay are known only from shallow cored boreholes drilled on the Baffin Shelf. According to MacLean *et al.* (2014), Cretaceous rocks of Aptian–Albian to Cenomanian age occur on the south-eastern Baffin Shelf, and of Coniacian to Campanian age on the north-eastern Baffin Shelf. The former equate to the Bjarni Formation, the latter to the Markland Formation. However, according to MacLean *et al.* (2014), Danian to Selandian rocks, of similar age and lithology to the Eureka Sound Group (a unit generally used for strata farther north and west, see below) have been recovered from cores off Cumberland Sound (MacLean & Williams 1983; MacLean *et al.* 1986).

Onshore

West Greenland

Mesozoic–Cenozoic rocks in West Greenland occur in the Nussuaq Basin, adjacent to Baffin Bay, where rocks of the Nuussuaq Group outcrop on several peninsulas and islands. Dam *et al.* (2009) provided a synthesis of this group, in which they formalised the lithological units proposed by previous researchers, especially Henderson *et al.* (1976), and proposed some new units. Stratigraphic control in Dam *et al.* (2009) was based on palynological studies, including those of Koppelhus & Pedersen (1993), Nøhr-Hansen (1993b, 1996), Nøhr-Hansen & Dam (1997), Dam *et al.* (1998b, c), Lanstorp (1999), Kennedy *et al.* (1999), Nøhr-Hansen & Heilmann-Clausen (2000), Nøhr-Hansen *et al.* (2002), Sønderholm *et al.* (2003a, b). Additional data were presented by Pedersen *et al.* (2013) and Pedersen & Nøhr-Hansen (2014).

In the Nuussuaq Basin, the oldest known rift to early post-rift sediments are Aptian? to Albian in age and consist of fan-delta, fluvio-deltaic and shallow marine deposits of the Kome Formation, which onlap Precambrian basement on Disko and Nuussuaq (Henderson *et al.* 1976; Dam *et al.* 2009; Pedersen & Nøhr-Hansen 2014). The succeeding Slibestensfjeldet Formation comprises lacustrine or lagoonal deposits, with palynofloras dominated by non-marine miospores and rare, brackish-water dinocysts of Albian, possibly middle Albian, age (Pedersen & Nøhr-Hansen 2014). Both the Slibestensfjeldet and the Kome Formations are unconformably overlain by Albian to upper Santonian post-rift, fluvial and wave-dominated deltaic to fully marine deposits of the Atane Formation (Pedersen & Pulvertaft 1992; Nøhr-Hansen *et al.* 2002; Dam *et al.* 2009; Pedersen & Nøhr-Hansen 2014). To the west of a major fault, sediments of the Atane Formation are replaced by deep-water submarine-fan deposits assigned to the Itilli Formation. Turonian – lower Maastrichtian slope deposits are also described from Svartenhuk Halvø (Dam *et al.* 1998b). Lithological and age similarities suggest that the Kome, Slibestensfjeldet and Bjarni Formations are coeval, the unconformity beneath the Atane Formation being equivalent to the Avalon Unconformity. A major angular unconformity separates the deltaic deposits of the Qilakitsoq Member (the upper part of the Atane Formation) from the marine gravity-flow deposits of the lower–middle Campanian Aaffarsuaq Member of the Itilli Formation in Nuussuaq (Dam *et al.* 2000, 2009).

Rifting continued through the Maastrichtian and into the Danian in the Nuussuaq Basin, with at least three tectonic phases associated with valley and submarine canyon incision (Dam *et al.* 1998a; Dam *et al.* 2009). The fill of the incised valleys represents three formations that are overlain by deep-water marine mudstones and volcanic tuffs (Dam *et al.* 2009). Although occurrences of Neogene rocks in West Greenland are sparse, a thin succession of Neogene sediments overlies the Eocene Hareøen Formation (Fig. 3; Hald 1976; Christiansen *et al.* 1999).

An insightful study of the rocks from onshore West Greenland was undertaken by Larsen (2006) and Larsen *et al.* (2009), who mapped and dated the dyke swarms in that region. These authors recognised the following phases of intrusion, which can be related to significant stages in the development of the Labrador Sea and the Davis Strait:

- early extension (220–150 Ma, Late Triassic to Late Jurassic)
- increased extension (around 150 Ma, Kimmeridgian)
- regional rifting and dyke intrusion (140–133 Ma, Berriasian to Valanginian/Hauterivian)
- subsidence and sedimentation (130–120 Ma, Barremian and Aptian)
- faulting, sedimentation and magmatism (around 120–100 Ma, Aptian–Albian)
- Late Cretaceous subsidence, sedimentation and faulting (100–65 Ma)
- Palaeogene rifting and magmatism (about 62 Ma).

The last phase gave rise to the West Greenland Palaeogene Volcanic Province (Fig. 2), with a volcanic succession up to 3 km thick (Storey *et al.* 1998; Larsen *et al.* 2016), occurring mainly onshore but extending offshore. Onshore, volcanism associated with this province commenced around 61–62 Ma (Chron 27n; latest Danian to early Selandian; Nøhr-Hansen *et al.* 2002), with most of the basalts being extruded in less than a million years (Storey *et al.* 1998; Larsen *et al.* 2009, 2016), followed by younger Paleocene volcanism in the Nuussuaq Basin. Other volcanic basalts are considered to be of Ypresian, late middle Eocene and middle Oligocene age. According to Larsen *et al.* (2009), the youngest volcanic rocks in West Greenland are 28 Ma (around the Rupelian–Chattian boundary; Fig. 3). Rolle (1985) noted that the Jurassic and Lower Cretaceous alkaline intrusions in southern Greenland are similar petrographically to the intrusives of north-western Newfoundland, which he believed were associated with the formation of the Labrador Margin basins.

North-eastern Canada

The oldest onshore Cretaceous rocks on the Canadian margin adjacent to the Labrador–Baffin Seaway are the Ford Bight volcanics, which crop out along the Labrador coast. These rocks were described by King & McMillan (1975) and dated by Balkwill *et al.* (1990) as 129 ± 6 Ma (Valanginian – earliest Aptian on the Gradstein *et al.* 2012 timescale) and 145 ± 6 Ma (Tithonian – earliest Valanginian). These ages are broadly compatible with those given for the Alexis Formation (122 and 139 Ma).

There are no known rocks onshore Labrador that equate with the Bjarni Formation, but such rocks do occur in eastern and north-eastern Baffin Island and on Bylot Island. From the Cape Dyer area of Baffin Island, Burden & Langille (1990) described sandstones, siltstones and coal beds that contain palynomorphs indicative of an Aptian to early Cenomanian age.

Outcrops of Cretaceous and lower Cenozoic rocks occur in the Eclipse Trough on Bylot Island and north-eastern Baffin Island. These deposits, which show similarities with rocks on the Labrador Margin (Figs 2, 3), were described by Miall *et al.* (1980), McWhae (1981) and Miall (1986), who used lithostratigraphic unit names with type sections in the Arctic Islands to the north-west. The units are, from oldest to youngest, the Hassel Formation (equivalent to the Bjarni Formation), the Kanguk Formation (equivalent in part to the Markland Formation) and the Eureka Sound Group (Fig. 3). The Eureka Sound Group was named by Troelsen (1950), reduced to formation status by Tozer (1963), and raised back up to group status independently by Miall (1986) and Ricketts (1986). Rather than using the Eureka Sound Formation/Group, Sparkes (1989) and Waterfield (1989) proposed an informal lithostratigraphic breakdown for equivalent rocks on Bylot Island. According to these authors, the Kanguk Formation is unconformably overlain by the informal Sermilik and Bylot Island formations, which are in part coeval. The top of the Bylot Island formation is unconformably overlain by the Pond Inlet formation, above which are the informal Navy Board and Aktineq formations (Fig. 3). This scheme was followed by Harrison *et al.* (1999) and Harrison *et al.* (2011).

McWhae (1981) considered the unconformity separating the Hassel Formation from the overlying Kanguk Formation to be the Avalon Unconformity and he named the hiatus between the Kanguk and Eureka Sound Group (as Eureka Sound Formation) as the Bylot Unconformity. Although not using the name Bylot Unconformity, Miall (1986) also recognised an unnamed unconformity between the Kanguk Formation and the Eureka Sound Group. Both of these authors indicated an early Paleocene age for this unconformity. However, Sparkes (1989) and Waterfield (1989) dated the Bylot Unconformity as Maastrichtian. Similarly, Harrison *et al.* (2011) gave a Maastrichtian to Danian age to the section extending from the Sermilliq Formation to the Aqtineq Formation (i.e. the former Eureka Sound Formation/Group), with an unconformity beneath these.

As discussed further below, the number of unconformities and/or hiatuses is probably greater than the five specified by McWhae *et al.* (1980). For example, our data seem to indicate two hiatuses associated with the Maastrichtian–Paleocene interval, one at the base of the Cenozoic and one in the Selandian.

On Baffin Island, Andrews *et al.* (1972) recorded marginal marine to lacustrine Palaeogene sediments from the north-central region, and Clarke & Upton (1971) found terrestrial sediments north of Cape Dyer. Burden & Langille (1990) described fluvial and debris-flow deposits of Danian age on the Quqaluit and Padloping islands (Figs 1, 2). Presumably these rocks and the overlying Cape Dyer Basalt represent the late rifting phase immediately before the opening of Baffin Bay. Pedersen *et al.* (2002) considered the Cape Dyer Basalt most likely to be time equivivalent to the lower part of the Vaigat Formation in the Nuussuaq Basin (Fig. 3).

Methodology

The results presented in this bulletin reflect data from analyses of offshore wells from both margins of the Labrador–Baffin Seaway; detailed taxonomic data are presented in the companion bulletin (Fensome *et al.* 2016). The Labrador Margin wells are from both the Hopedale Basin (Bjarni O-82, North Leif I-05, Ogmund E-72, Roberval K-92, Snorri J-90 and South Labrador N-79) and the Saglek Basin (Gilbert F-53, Gjoa G-37, Hekja O-71, Karlsefni A-13, Ralegh N-18, Rut H-11 and Skolp E-07). The wells on the West Greenland Margin are: Hellefisk-1, Ikermiut-1, Kangâmiut-1, Nukik-1, Nukik-2 and Qulleq-1. Also incorporated are some results from onshore West Greenland cored boreholes and surface sections, and from some shallow cored boreholes from western Baffin Bay.

An event-stratigraphic approach is adopted as we consider this to provide greater detail and precision than an approach based on zonations. An event-stratigraphic approach also better facilitates incorporation of events from multiple disciplines; the events used here are exclusively derived from palynology. Events can be originations of species, called first occurrences (FOs), extinctions, called last occurrences (LOs), or occasionally peak occurrences, or acmes, of species.

Although some stratigraphic control was obtained from analysis of conventional cores from several Labrador Margin wells and from some side-wall cores, the availability of and recovery from such samples were limited. It has been necessary therefore to rely mostly on ditch-cuttings samples, and hence on LOs for most of the events, as such samples usually contain down-section contamination (cavings). Reworked specimens also occur in many samples, being most frequent in what we consider to be Pliocene–Pleistocene sections. Piasecki (2003) noted that reworked species outnumbered *in-situ* species in his late Pliocene interval in the Qulleq-1 well. Contamination from drilling mud was also a minor concern; for example, the presence of the dinocyst *Ovoidinium verrucosum* in most of the ditch-cuttings samples in Hellefisk-1 and Nukik-2 is interpreted to have resulted from contamination from Cenomanian bentonite added during drilling.

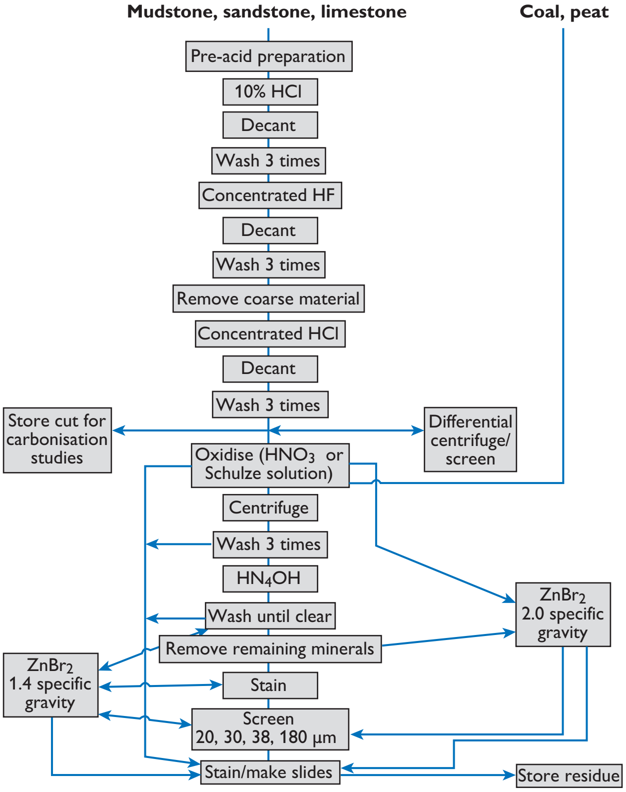


Fig. 4. Flow chart showing the palynological processing method used at the Geological Survey of Canada (Atlantic).

Samples processed at GSCA (Bjarni O-82, Gilbert F-53, Karlsefni A-13, Roberval K-92, Rut H-11, Snorri J-90, South Labrador N-79) followed the procedure outlined in Barss & Williams (1973) and carried out from 1971 to 2007 (Fig. 4). The first step after crushing the sample, if necessary, was the addition of 10% hydrocholoric acid to remove carbonates. After decanting the acid, the residue was washed and placed in hydrofluoric acid to remove the silicates. When the sample appeared to be broken down, the hydrofluoric acid was decanted and the sample washed several times. To remove any remaining fluorides, the sample was placed in concentrated hydrochloric acid, followed by washing. The fraction remaining was further concentrated using a heavy liquid such as zinc bromide. This was followed by oxidation in concentrated nitric acid or Schulze solution, followed by careful washing to remove the oxidising agents, and treatment with ammonium hydroxide. The final phase before making the slides was sieving, a technique that concentrates the dinocysts and larger miospores. All the slides were mounted in elvacite. Most residues were stained with Safranin red or Bismarck brown. Although oxidation, if done at all, was always carefully controlled, most samples were processed at a time when the detrimental selective effect of oxidation procedures on peridinioids, and especially protoperidinioids, was not fully appreciated. Hence the general scarcity of protoperidiniod cysts in our assemblages may be due to over-oxidation, although most samples stratigraphically predate times when protoperidinioids became common.

Samples from Hellefisk-1, Ikermiut-1, Kangâmiut-1, Nukik-1, Nukik-2, Qulleq-1, North Leif I-05, Ogmund E-72, Skolp E-07, Hekja O-71, Ralegh N-18 and Gjoa G-37 were processed at the Geological Survey of Greenland (GGU, now GEUS). Palynomorphs were extracted from 10–20 g of sediment from each sample by modified standard preparation techniques that included treatment with hydrochloric (HCl) and hydrofluoric (HF) acids, sieving using a 20 µm nylon mesh and oxidation (3–10 minutes) with concentrated nitric acid (HNO_3), often followed by washing with a weak potassium hydroxide solution (KOH). Finally, palynomorphs were separated from coal particles and woody material in most samples using the separation method described by Hansen & Gudmundsson (1978) or by swirling. After each of the steps mentioned above, the organic residues were mounted in a solid medium (Eukitt®) or in glycerine gel. The palynological slides were studied with transmitted light using a Leitz Dialux 22 microscope (no. 512 742/057691). Dinocysts, acritarchs and selected stratigraphically important spore and pollen (miospores) species were recorded from the sieved, oxidised or gravity-separated slides. Approximately 100 specimens were counted whenever possible.

Using transmitted light microscopy, qualitative and quantitative analyses were undertaken of the palynomorphs present in each well (see appendices 2, 3); the stratigraphically important events are plotted on summary charts (Figs 5, 6, in pocket). The LOs of species plotted in Figs 5 and 6 were generally based on occurrences in several wells, thus allowing correlation between well sections. However, few of the taxa recorded on the events plot are present in all the wells, due in part to the variable duration of the hiatuses in the individual wells.

A detailed chart has been generated for each well showing LOs and other key events, such as peak occurrencies and acmes (Appendix 3). Although broad consistency has been sought, the information included in these charts is variable to some degree, dependent on the source of the data. Those done by HN-H (Hellefisk-1, Ikermiut-1, Kangâmiut-1, Nukik-1, Nukik-2, Qulleq-1, North Leif I-05, Ogmund E-72, Skolp E-07, Hekja O-71, Ralegh N-18 and Gjoa G-37) present a zonation and events (predominantly LOs) that were published in Sønderholm *et al.* (2003b), Nøhr-Hansen *et al.* (2000) and Nøhr-Hansen (2003, 2004a, b) for the Aptian−Albian to Priabonian of the West Greenland and Labrador Margins of the Labrador Sea. Some of HN-H's plots in the present paper also show dinocyst species richness and *Azolla* abundances. Plots generated by GLW and RAF (Bjarni O-82, Gilbert F-53, Karlsefni A-13, Roberval K-92, Rut H-11, Snorri J-90 and South Labrador N-79) show events and ages only; a zonation was not developed.

In total, 187 bioevents are identified for the Labrador–Baffin Seaway; 169 of these represent the youngest or last occurrence (LO) of a taxon, the others represent peak occurrences or abundances. Some events are coeval, so the 187 bioevents define 106 bioevent horizons. Collectively, the bioevents are based on 177 taxa. Also incorporated are 22 events (13 event horizons) established by Piasecki (2003) for the Neogene of offshore West Greenland and 50 events (44 event horizons) established by Pedersen & Nøhr-Hansen (2014) for Albian to Paleocene strata of the Nuussuaq Basin, West Greenland (Figs 5, 6 in pocket). Most of the species are dinocysts but several are pollen and spores, and we also include a fungal spore peak and two *Azolla* peaks. To promote understanding, communication and future consistent recognition of taxa encountered in this study, a companion bulletin presents the systematic taxonomy (Fensome *et al.* 2016), describing and illustrating most of the species referenced in Figs 5 and 6 and specifying location and repository information for the material used in this study.

The timescale of Gradstein *et al.* (2012) is adopted. Detailed analyses and palaeoenvironmental curves for wells analysed in this study are presented in Appendices 2 and 3; those dinocyst taxa whose occurrences are considered to have significance as palaeoenvironmental indicators are listed under the appropriate palaeoenvironment in Table 1 (see p. 37).

Previous palaeontological studies

Palaeontological evidence used to interpret the evolution of the Labrador–Baffin Seaway region has been derived primarily from the study of Cretaceous–Neogene microfossil (including palynological) assemblages recovered from offshore wells on the Labrador Margin and on the West Greenland Margin. Papers, reports and two theses on the palynomorphs from Labrador Margin and Davis Strait wells, all drilled in the 1970s and 1980s, have been produced by Williams (1975), Gradstein & Williams (1976), Barss *et al.* (1979), Ioakim (1979), Gradstein & Williams (1981), Williams (1986), Bujak Davies Group (1987), Bell (1989), Williams *et al.* (1990), Nøhr-Hansen (2004a, b), Nøhr-Hansen (in Sønderholm *et al.* 2003b), Williams (2007a–f), Ainsworth *et al.* (2014) and Fensome (2015). Foraminiferal studies were undertaken by Gradstein & Williams (1976), Gradstein & Srivastava (1980), Gradstein & Agterberg (1982), Gradstein *et al.* (1994) and Ainsworth *et al.* (2014).

Williams (1986) is the only author to have presented a zonation for Labrador–Baffin Seaway wells based on Cenozoic spores and pollen. She analysed six wells: Kangâmiut-1, Hekja O-71, Karlsefni A-13, Herjolf M-92, Roberval K-92 and Cartier D-70. Based on these analyses, she recognised eight provisional spore and pollen zones of the following ages: early to middle Paleocene, middle to late Paleocene, early to middle Eocene, middle to late Eocene, latest Eocene/earliest Oligocene, early Oligocene, early to middle Miocene, and middle to late Miocene. The middle and upper Oligocene was inferred to be absent in the wells.

Ioakim (1979) analysed the dinocysts from two Hopedale Basin wells, Bjarni H-81 and Freydis B-87. She erected 11 zones and three subzones, which collectively spanned the Maastrichtian–Priabonian. Most of the zones were named after peridiniaceans, especially wetzelielloideans.

Ainsworth *et al.* (2014) undertook a detailed lithostratigraphic and biostratigraphic study of six Labrador Margin wells: Herjolf M-92, North Bjarni F-06, Ogmund E-72, Pothurst P-19, Roberval K-92 and Snorri J-90, plus Hare Bay E-21 from offshore north-eastern Newfoundland. They based their biostratigraphy on foraminifera and palynomorphs, with the latter being primarily dinocysts, and their palaeoenvironmental interpretations exclusively on fluctuations in the foraminiferal assemblages. Among their suggestions was a division of the Markland Formation into a lower member of Coniacian–Maastrichtian age and an upper member of Selandian age, with the boundary between the two units equivalent to a base-Cenozoic unconformity.

According to Ainsworth *et al.* (2014), the upper part of the Markland Formation was deposited in a predominately deep-water setting – a very different interpretation from that of Balkwill & McMillan (1990), who postulated a marginal marine to middle shelf environment. The re-interpretation by Ainsworth *et al.* (2014) was based on present-day knowledge of deep-water agglutinated foraminifera. Ainsworth *et al.* (2014) included the Gudrid member as part of the Cartwright Formation (instead of being parts of the Markland, Cartwright and Kenamu Formations as used here), and considered it to be Thanetian in age and deposited in a bathyal environment. Based on their interpretation of the Saglek Basin's Pothurst P-19 well, Ainsworth *et al.* (2014) regarded much of the 'lower' Mokami Formation (Chattian to Miocene) and all of the 'upper' Miocene to be absent. This is at variance with other studies, which indicate that Miocene sediments occur in this well. The interpretation of Ainsworth *et al.* (2014) supports the observations of Knutsen *et al.* (2012), however, who noted that off West Greenland during the Miocene there was uplift and erosion, which they related to hot-spot migration. A recent study of Pothurst P-19 (G.L. Williams, unpublished data) demonstrated that most of the lower and all of the middle Miocene are missing, but some upper Miocene is present.

Palaeogene nannofossil biostratigraphy was described for the Gilbert F-53 and Skolp E-07 wells by Crux & Gard (2004). In Gilbert F-53, they recorded a thick Palaeogene sequence succeeded by an indeterminate Cenozoic succession. Skolp E-07 contained a section with mixed nannofossils of Cretaceous and Cenozoic age overlain by Cenozoic strata. Crux & Gard (2004) interpreted the lower section to be probably Cenozoic with reworked Cretaceous nannofossils. Nannofossil recovery was generally disappointing.

On the West Greenland Margin, Rolle (1985) published the stratigraphy of the five wells drilled in 1976 and 1977 (Hellefisk-1, Ikermiut-1, Kangâmiut-1, Nukik-1, Nukik-2; Figs 1, 2), with age control based on palynology. Renewed interest in exploration of the West Greenland Margin in recent years has motivated new and detailed studies of the Cretaceous to Neogene palynology (e.g. Nøhr-Hansen 1996, 1997a–c, 2003; Nøhr-Hansen & Dam 1997; Dam *et al.* 1998b, 2009; Nøhr-Hansen *et al.* 2000, 2002; Sønderholm *et al.* 2003b; Piasecki 2003; Pedersen & Nøhr-Hansen 2014). Other microfossil groups utilised include nannofossils (Nøhr-Hansen *et al.* 2000; Sheldon 2003) in the Palaeogene–Neogene and foraminifera (Nøhr-Hansen *et al.* 2000; Rasmussen *et al.* 2003; Rasmussen & Sheldon 2003), plus ostracods, radiolarians and diatoms (Rasmussen *et al.* 2003).

Further information comes from numerous Cretaceous–Cenozoic outcrop sections from the Nuussuaq Basin in West Greenland, a few onshore sections in Labrador and on Baffin and Bylot Islands, and from ODP Leg 105, hole 645 from offshore Baffin Island (Fig. 2; Kaminski *et al.* 1989a, b). Invariably, the biostratigraphy is based on microfossils including palynomorphs.

Biostratigraphic results

Results from analyses of the cuttings provided the basis for the plots of LOs of taxa (Figs 5, 6, in pocket). Peak occurrences or abundances are also included in the Palaeogene. As noted previously, results are based on three areas: the Hopedale Basin on the Labrador Margin (Bjarni O-82, North Leif I-05, Ogmund E-72, Roberval K-92, Snorri J-90 and South Labrador N-79), and the Saglek Basin, partly on the Labrador Margin (Gilbert F-53, Karlsefni A-13, Rut H-11 and Skolp E-07) and partly off south-eastern Baffin Island (Gjoa G-37, Hekja O-71, Ralegh N-18). On the West Greenland Margin, the wells are: Hellefisk-1, Ikermiut-1, Kangâmiut-1, Nukik-1, Nukik-2, and Qulleq-1. Figures 5 and 6 represent composite compilations that involve the merging of data from both the Canadian and Greenland margins. One unexpected difficulty has been the identification of taxa common to both margins of the seaway. This may be because some taxa are endemic to one margin or even one area, and perhaps also because of the different latitudes of the overall location of wells on the two sides, the Greenland wells being farther north. However, there was enough overlap to provide a detailed event-stratigraphic framework (Figs 5, 6, in pocket), especially with the incorporation of information on known stratigraphic ranges of taxa in European sections (Powell 1992; Bujak 1994; Williams *et al.* 1999, 2004) and from other wells and cored boreholes from offshore eastern Canada and West Greenland (Williams 1975; Williams & Brideaux 1975; Williams & Bujak 1977; Barss *et al.* 1979; Williams *et al.* 1990; Sønderholm *et al.* 2003b; Nøhr-Hansen 2004a, b; Fensome & Williams 2005; Fensome *et al.* 2008, 2009).

Lower Cretaceous

The oldest Mesozoic rocks identified here in the Labrador–Baffin Seaway are Aptian (see below), and these are restricted to the Labrador Margin. However, H. Nøhr-Hansen has also observed reworked Late Jurassic – Early Cretaceous taxa such as *Lithodinia* sp., *Nelchinopsis kostromiensis*, *Sirmiodinium grossii*, and forms similar to *Gonyaulacysta pectinigera*/*fastigiata* from seabed samples collected by GEUS (Dalhoff *et al.* 2006). Piasecki (2003) also reported Late Jurassic dinocysts in dredge samples from the West Greenland Margin.

Aptian

Gradstein & Williams (1976), in their biostratigraphic study of Labrador Margin wells, defined a *Cerebropollenites mesozoicus* assemblage of Barremian–Aptian age. In this study, it has not been possible to confirm the presence of Barremian strata, but an Aptian age is demonstrated on the Labrador Margin by the presence of the dinocyst *Tenua hystrix,* which is the taxonomic senior synonym of *Cerbia tabulata* (see Fensome *et al.* 2016). *Tenua hystrix*, misidentified as *Cyclonepheliium attadalicum*, was the index species for an early Aptian zone in the Scotian Basin (Williams 1975). Duxbury (2001) placed the LO of *Cerbia tabulata* at the top of the

Aptian, which is at 113 Ma on the Gradstein *et al.* (2012) timescale. Other studies (e.g. Williams 2003b) have confirmed the LO of *Cerbia tabulata* to be a consistent marker for the top of the Aptian. Also in the Aptian of the Roberval K-92 and South Labrador N-79 wells is a form that we identify as *Pseudoceratium* sp. Wells with Aptian rocks include Bjarni O-82 (Appendix 3.3), Roberval K-92 (Appendix 3.2) and South Labrador N-79 (Appendix 3.4; Figs 1, 7). Palynomorphs found in the Aptian rocks in our study include the miospores *Callialasporites dampieri*, *Callialasporites obrutus*, *Cerebropollenites mesozoicus*, *Parvisaccites amplus*, *Appendicisporites jansonii*, *Cicatricosisporites australiensis* and *Klukisporites areolatus*.

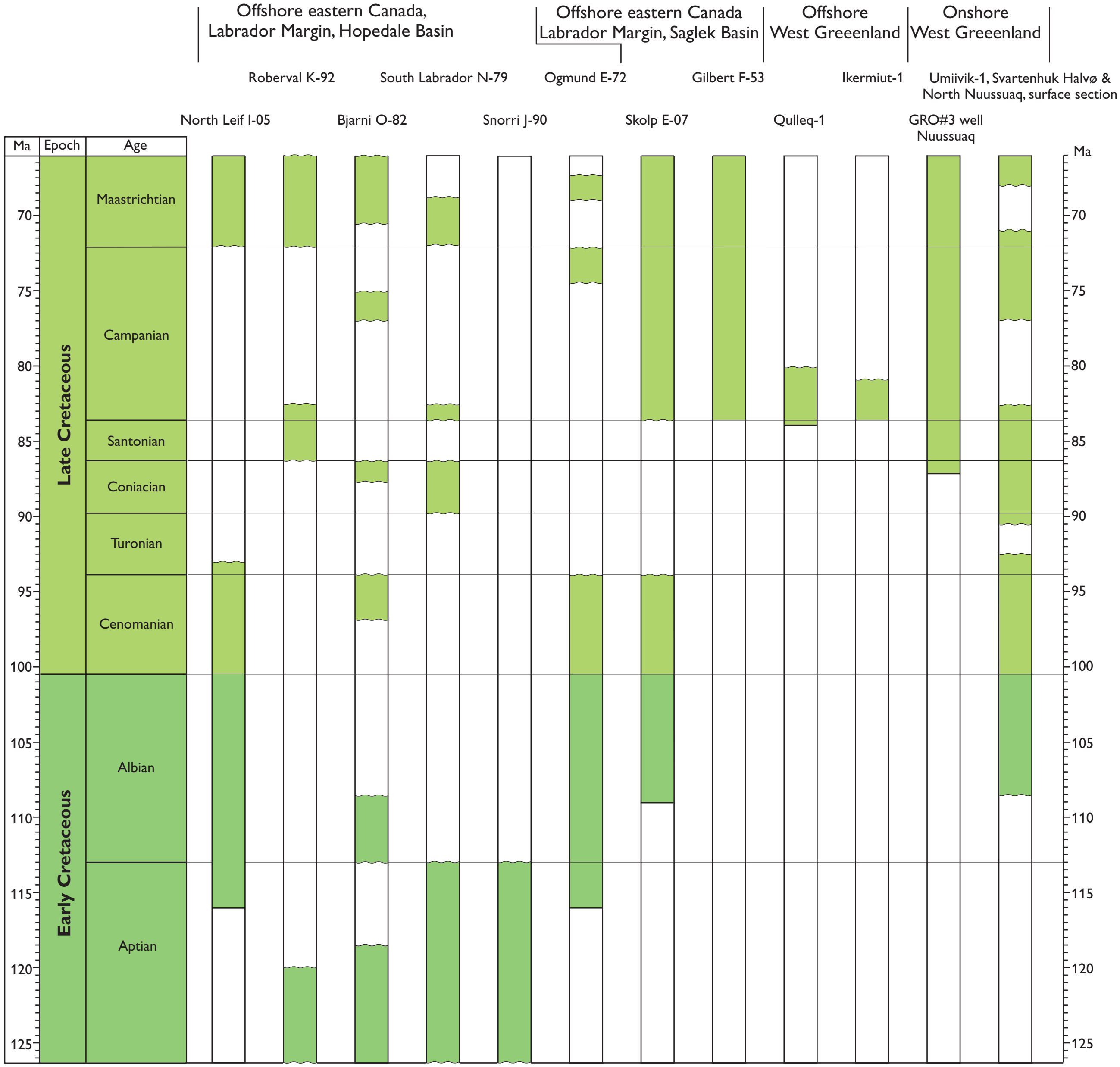


Fig. 7. Cretaceous ages (highlighted in green) identified from palynomorph assemblages in wells from the Hopedale Basin of the Labrador Margin (North Leif I-05, Roberval K-92, Bjarni O-82, South Labrador N-79, Snorri J-90 and Ogmund E-72), the Saglek Basin of the Labrador Margin and Davis Strait (Skolp E-07 and Gilbert T-53), offshore West Greenland (Qulleq-1 and Ikermiut-1), and a well (GRO #3, Nuussuaq), a borehole (Umiivik-1) and two surface sections (Svartenhuk Halvø and north Nuussuaq) from onshore West Greenland. Ages not coloured have not been identified. The timescale (Ma) is from Gradstein *et al.* (2012).

Albian

Albian assemblages in Labrador Margin wells strongly reflect marginal marine to innermost neritic palaeoenvironments. Dinocyst taxa with Albian LOs include *Nyktericysta davisii*, *Nyktericysta dictyphora, Nyktericysta tripenta*, *Oligosphaeridium albertense*, *Vesperopsis longicornis* and *Subtilisphaera perlucida*. *Nyktericysta davisii* was described from middle to upper Albian brackish-water deposits in the Western Interior Seaway of the USA by Bint (1986). In offshore eastern Canada, it has a consistent LO in the Albian and other records of its occurrence in the late Albian are from onshore East and West Greenland and Arctic Canada (Nøhr-Hansen 1992, 1993a, 2008; MacRae 1996; Nøhr-Hansen & McIntyre 1998) and the Scotian Margin (Fensome *et al.* 2008). However, a recent study by Pedersen & Nøhr-Hansen (2014) indicated that large forms of *Nyktericysta davisii* and *Nyktericysta arachnion* occur in the early Cenomanian of onshore Nuussuaq Basin based on co-occurrence with the pollen species *Rugubivesiculites multisaccus*, which is indicative of an early Cenomanian age according to Singh (1983). *Nyktericysta dictyphora* is also characteristic of brackish-water deposits in the Aptian–Albian of China (Mao Shaozhi *et al.* 1999). *Senoniasphaera microreticulata* occurs in the Albian of North Leif I-05 (Nøhr-Hansen 2004b).

Miospores dominate most Albian assemblages on the Labrador Margin. Bujak Davies Group (1987) defined a *Parvisaccites amplus* Zone which they considered early Albian. Conventional cores from North Leif I-05 contain *Parvisaccites radiatus* with *Rugubivesiculites rugosus*, *Rugubivesiculites multiplex*, *Rugubivesiculites reductus* and *Rugubivesiculites convolutus*, and conventional cores from Bjarni O-82 contain *Rugubivesiculites rugosus*. Williams (1975) erected a *Rugubivesiculites rugosus* Assemblage Subzone of late Albian age for the Scotian Shelf and Grand Banks. Singh (1983) placed the LO of *Rugubivesiculites rugosus* in the Cenomanian and Nøhr-Hansen (in Sønderholm *et al.* 2003b) recognised a ?late Albian to ?Cenomanian *Rugubivesiculites* spp. interval, based on a study of Skolp E-07 and Ogmund E-72. The cored interval in North Leif I-05 and Bjarni O-82 is thus no older than late Albian.

We have identified Albian sediments in Bjarni O-82 (Appendix 3.3), North Leif I-05 (Appendix 3.1), Ogmund E-72 (Appendix 3.6), and Skolp E-02 (Appendix 3.7; Figs 1, 7), and onshore in the Nuussuaq Basin. Several taxa other than those plotted on the events chart (Fig. 5, in pocket) have provided supporting data for age determinations in the Aptian–Albian, including *Pilosisporites verus*, *Cicatricosisporites reticicatricosus*, *Contignisporites glebulentus* and *Alisporites grandis,* all with LOs in the Albian (Williams 2007a).

Upper Cretaceous

Cenomanian

This study indicates that the Cenomanian is present in only four wells on the Canadian Margin. However, there are some characteristic markers for this stage, including the dinocyst species *Kiokansium williamsii* described by Singh (1983) from the Albian and Cenomanian of Alberta: in this study, it was found in North Leif I-05 and Bjarni O-82. The species was first recorded as *Cleistosphaeridium polypes* subsp. A by Williams (1975), who noted that its LO was in the Cenomanian. Other characteristic dinocyst taxa of the Cenomanian are *Oligosphaeridium totum* and *Odontochitina ancala*. Williams *et al.* (1999) placed the LO of *Oligosphaeridium totum* at 96.2 Ma, in the middle Cenomanian whereas Fensome *et al.* (2008) indicated its LO to be earliest Cenomanian. An expecially distinctive morphotype with an LO in the Cenomanian is the pollen *Afropollis* (Fensome *et al.* 2009); *Cicatricosisporites minutaestriatus* has a Cenomanian LO in Ogmund E-72. All the wells with Cenomanian strata – North Leif I-05 (Appendix 3.1), Ogmund E-72 (Appendix 3.6) and Skolp E-07 (Appendix 3.7) – are on the Labrador Margin (Figs 1, 7). The upper Cenomanian in the Nuussuaq Basin is characterised by the FOs of *Trithyrodinium suspectum, Isabelidinium magnum* and *Cauveridinium membraniphorum* (Pedersen & Nøhr-Hansen 2014; Fig. 5, in pocket).

Turonian–Santonian

The Turonian appears to be absent from all offshore wells, except possibly lower Turonian in North Leif I-05. Because of uncertainty we have tended to define a Turonian–Coniacian, rather than a Turonian, interval for the Labrador wells. Species of *Rugubivesiculites* appear to have their LOs in the Turonian, but may range higher. The lower Turonian in the Nuussuaq Basin is characterised by the FO of *Heterosphaeridium difficile* (Nøhr-Hansen 1997a; Pedersen & Nøhr-Hansen 2014). In the Umiivik-1 borehole on Svartenhuk Halvø (Fig. 2), Dam *et al.* (1998b) recognised an upper Turonian interval IV and an uppermost Turonian to lower Coniacian interval III; interval IV is characterised by a *Heterosphaeridium difficile* acme; *Heterosphaeridium difficile* and *Circulodinium distinctum* are common in the upper part of interval III and *Raphidodinium fucatum* has its acme in the upper part of Interval III. Interval III correlates in part with the early Coniacian *Spinidinium echinoideum* interval described by Nøhr-Hansen (1996). Bujak Davies Group (1987) recognised a *Heterosphaeridium difficile* Zone, which they considered to be early Campanian. The top of Nøhr-Hansen's (1996) Coniacian – early Santonian *Heterosphaeridium difficile* interval was defined by the LO of *Heterosphaeridium difficile* at the top of the early Santonian, citing as justification Costa & Davey (1992). Williams *et al.* (2004) plotted the FO of *Heterosphaeridium difficile* at about the early–middle Turonian boundary and its LO in the late Coniacian in northern mid-latitudes. In a study of some shallow cored boreholes from the Baffin Margin, MacLean *et al.* (2014) considered *Heterosphaeridium difficile* to have a range of late Coniacian to early Santonian, but noted that it was occasionally found as high as the early Campanian. Nøhr-Hansen (2012) and Radmacher *et al.* (2014) noted that the species occurred in Turonian–Coniacian sediments in the Kangerlussuaq Basin, southern East Greenland and in the south-western Barents Sea. In this study, we have placed the LO of *Heterosphaeridium difficile* at the top of the early Santonian. Support for this is provided by the LO of *Odontochitina porifera*, which Stover *et al.* (1996) placed in the early Santonian, although other authors (Costa & Davey 1992; Williams *et al.* 2004) have extended the range of the species into the Campanian. Neither *Heterosphaeridium difficile* nor *Odontochitina porifera* are found in the only two West Greenland wells with Cretaceous rocks, Qulleq-1 (Appendix 3.14), and Ikermiut-1 (Appendix 3.18), indicating that the oldest sediments in these wells are younger than early Santonian. On the Labrador Margin, Bjarni O-82 (Appendix 3.3) and South Labrador N-79 (Appendix 3.4) appear to have Coniacian sediments (Figs 1, 7).

Campanian

The LO of *Spongodinium* (originally *Scriniodinium*) *obscurum* is taken here to mark the Santonian–Campanian boundary, a somewhat arbitrary decision. *Spongodinium obscurum* was erected by Manum & Cookson (1964), who considered the sample from Graham Island, Arctic Canada, from which the species was first recovered, to be early Late Cretaceous in age. This was based on the occurrence of the species in what these authors considered to be the Hassel Formation, of late Albian to Early Cenomanian age. However, Felix & Burbridge (1976) demonstrated that the sample was from the upper Cenomanian – lower Campanian Kanguk Formation, and specifically from the upper Kanguk Formation. This reassignment would indicate that the age of the Graham Island sample is Santonian to early Campanian, and that the LO of *Spongodinium obscurum* is within this time interval. The base of the lower to middle Campanian *Aquillapollenites* interval described by Nøhr-Hansen (1996) from the Nuussuaq Basin is defined by the FO of *Aquillapollenites* species. In the Labrador Margin wells, the following dinocyst species have their LOs at the Campanian–Maastrichtian boundary: *Odontochitina costata*, *Trichodinium castanea* and *Xenascus ceratioides*. Stover *et al.* (1996) considered the LO of *Odontochitina costata* to equate with the Campanian–Maastrichtian boundary but extended the LO of *Odontochitina operculata* into the earliest Maastrichtian. These authors also extended the LO of *Xenascus ceratioides* to the top of the early Maastrichtian, but placed the LO of *Trichodinium castanea* just above the base of the late Campanian. Williams *et al.* (2004) gave the LO of *Xenascus ceratioides* as just above the Campanian–Maastrichtian boundary in northern mid-latitudes.

Trithyrodinium suspectum and *Raphidodinium fucatum* have LOs within the later Campanian. This range conforms with that in Williams *et al.* (2004), who placed the LOs of both species in the late Campanian, but considered *Raphidodinium fucatum* to be the younger. Nøhr-Hansen (in Sønderholm *et al.* 2003b) recognised an *Odontochitina operculata* interval, which was regarded as being of late Campanian age. One of the characteristic species was *Heterosphaeridium bellii* (as *Heterosphaeridium heteracanthum*), which has its LO in the latest Campanian in the Labrador–Baffin Seaway. *Heterosphaeridium bellii* was described by Radmacher *et al.* (2014), who stated that it had a common occurrence in the late Campanian to early Maastrichtian. Radmacher *et al.* (2014) defined the top of the early Campanian on the LO of *Callaiosphaeridium asymmetricum*, which accords well with our findings. Wells with Campanian sections are Roberval K-92 (Appendix 3.2), Bjarni O-82 (Appendix 3.3), Ogmund E-72 (Appendix 3.6), Skolp E-07 (Appendix 3.7) and Gilbert F-53 (Appendix 3.9) on the Labrador Margin and Qulleq-1 (Appendix 3.14) and Ikermiut-1 (Appendix 3.18) on the West Greenland Margin (Figs 1, 7).

Maastrichtian

Palynomorph taxa with LOs in the Maastrichtian include the dinocyst *Isabelidinium cretaceum*. In a study of dinocysts from the Campanian–Paleocene of Seymour Island and adjacent islands in Antarctica, Askin (1988) defined a Zone 1 that was characterised by *Isabelidinium cretaceum*. She considered the zone to be of late Campanian age. Bowman *et al.* (2012), based on updated data from Seymour Island, cited the age to be questionable late Maastrichtian but recognised two younger Maastrichtian zones. Thus, the LO of *Isabelidinium cretaceum* can be considered as early late Maastrichtian. The species is thus a key index species for determining whether part of the upper Maastrichtian is missing in the Labrador–Baffin Seaway.

One stratigraphically significant pollen species is *Wodehousiea spinata*, which occurs only in Skolp E-07 on the Labrador Margin: its LO approximately equates with the Maastrichtian–Danian boundary. A dinocyst species with a similar LO is *Palynodinium grallator*. Nøhr-Hansen (1996) described lower Maastrichtian *Cerodinium diebelii* and upper Maastrichtian *Wodehouseia spinata* intervals from the Nuussuaq Basin on the basis of the FOs of *Cerodinium diebelii* and *Wodehouseia spinata* respectively, and Nøhr-Hansen (in Sønderholm *et al.* 2003b) defined a *Palynodinium grallator* interval for the uppermost Maastrichtian. This was characterised by the LOs of *Palynodinium grallator* and *Wodehouseia spinata*. Williams *et al.* (2004) placed the FO of *Palynodinium grallator* in northern mid-latitudes within the late Maastrichtian and its LO in the earliest Danian. *Palynodinium grallator* has been recorded only from onshore West Greenland and from some Labrador Margin wells.

Disphaerogena carposphaeropsis, a dinocyst species that occurs in the latest Maastrichtian of some Labrador Margin wells and in the Nuussuaq Basin (Nøhr-Hansen & Dam 1997; Dam *et al.* 1998c) also appears to be a good index species. Other such species in the Maastrichtian include *Impagidinium victorianum*, *Isabelidinium cretaceum*, *Laciniadinium arcticum* and *Spiniferites scabrosus*. Confirmation of the Maastrichtian age for the LO of *Impagidinium victorianum* comes from combined palynological and micropalaeontological analyses of South Labrador N-79 by Bujak Davies Group (1987). In an interval designated as Maastrichtian based on foraminiferal data, they recognised an early Maastrichtian subzone for a taxon they identified as *Impagidinium* #LL. This taxon is probably conspecific with the species identified here as *Impagidinium victorianum* and the species that Nøhr-Hansen (1996) identified from the upper Maastrichtian in the Nuussuaq Basin as *Impagidinium* sp. cf. *I dispertitum*. Maastrichtian strata occur in several wells on the Labrador Margin (Figs 1, 7), including North Leif I-05 (Appendix 3.1), Roberval K-92 (Appendix 3.2), Bjarni O-82 (Appendix 3.3), South Labrador N-79 (Appendix 3.4), Ogmund E-72 (Appendix 3.6), Skolp E-07 (Appendix 3.7) and Gilbert F-53 (Appendix 3.9).

Several taxa other than those plotted on the events chart (Fig. 5, in pocket) have provided supporting data for age determinations in the Late Cretaceous, including *Senoniasphaera protrusa* (LO Coniacian; Williams 2007b), *Surculosphaeridium longifurcatum* (LO Coniacian), *Microdinium ornatum* (LO Coniacian), *Xenascus sarjeantii* (LO Coniacian), *Chatangiella ditissima* (LO early Campanian) and *Stiphrosphaeridium dictyophorum* (LO Maastrichtian). Triprojectate pollen are also potentially useful (see Braman 2013), but in the sections studied their occurrence was too sporadic and often clearly reworked.

Palaeogene

Danian–Selandian

Some major hiatuses occur in the Palaeogene sections on both margins of the Labrador–Baffin Seaway. The oldest is in the Danian, which seems to be missing or incomplete in all the wells, with the exception of South Labrador N-79. The presence of this stage is indicated by the occurrences of the dinocyst species *Cerodinium diebelii*, *Phelodinium kozlowskii*, *Spongodinium delitiense*, *Senoniasphaera inornata*, *Tanyosphaeridium xanthiopyxides* and *Trithyrodinium evittii*. According to Williams *et al.* (2004), *Senoniasphaera inornata* is restricted to the Danian, with its FO near the base and its LO at about 63 Ma in northern mid-latitudes. The same authors placed the LO of *Spongodinium delitiense* at about 64 Ma in Northern Hemisphere mid-latitudes. The lower Danian *Trithyrodinium evittii* Zone of Nøhr-Hansen *et al.* (2002) was recognised in North Leif I-05 (Nøhr-Hansen 2004b) and in Ogmund E-72 and Skolp E-07 (Nøhr-Hansen in Sønderholm *et al.* 2003b), indicating a late Danian – Thanetian hiatus in North Leif I-05 and Ogmund E-72 and a late Danian – Ypresian unconformity/hiatus in Skolp E-07. Williams (2007b) also concluded that in the South Labrador N-79 well, the LO of *Trithyrodinium evittii* is within the Danian. We place the LO of *Cerodinium diebelii* at the Danian–Selandian boundary, based on the records from Bjarni O-82 (Williams 2007a), South Labrador N-79 (Williams 2007b) and Snorri J-90 (Williams 2007c; Appendix 3.5). This is in slight conflict with Williams *et al.* (2004), who placed its LO at about 60 Ma in Northern Hemisphere mid-latitudes, within the early Selandian. *Cerodinium diebelii* has been recorded from the Selandian in Nukik-2 (Nøhr-Hansen 2003; Appendix 3.16), but this may represent reworking.

With the exception of this probably reworked record in Nukik-2, none of the index species above occur in the West Greenland Margin wells, indicating that Danian strata are generally absent. However, the presence of *Cerodinium kangiliense* and *Senegalinium iterlaaense* in the lower part of Nukik-2 may indicate a late Danian or early Selandian age (Fig. 8) according to Nøhr-Hansen & Heilmann-Clausen (2000). In the Labrador Margin and Davies Strait wells, the Danian is generally incomplete or missing, with the exception of South Labrador N-79 (Appendix 3.4; Fig. 8). Nøhr-Hansen *et al.* (2002) erected five dinocyst zones, of which three are correlated to nannofossil zones, for the Danian sedimentary succession underlying the radiometrically dated Selandian basalts in the Nuussuaq Basin.

Dinocyst species with an LO within or at the end of the Selandian include *Palaeoperidinium pyrophorum*, *Spinidinium echinoideum* and *Palaeocystodinium bulliforme*. Nøhr-Hansen (2003) recognised a late Danian and three late Thanetian intervals on the West Greenland Margin. However, Nøhr-Hansen (2003) was following a two-fold division of the Paleocene in which Selandian is represented by the lower part of Thanetian (see Powell 1992 and Mudge & Bujak 1996). The three Thanetian intervals, from oldest to youngest are: the *Palaeoperidinium pyrophorum* interval (P4), correlating with latest Selandian; the *Areoligera* interval (P5), correlating with lower Thanetian; and the *Apectodinium* spp. acme interval (P6), correlating with upper Thanetian (equivalences according to Mudge & Bujak 2001). Although not using the three-fold division of the Paleocene, Nøhr-Hansen (2003) recorded several of the species that appear to characterise a Selandian age. The top of his *Palaeoperidinium pyrophorum* (P4) interval is marked by the LOs of *Palaeoperidinium pyrophorum* and *Palaeocystodinium bulliforme*. Williams *et al.* (2004) placed the LOs of *Palaeocystodinium bulliforme* and *Palaeoperidinium pyrophorum* close to the Selandian–Thanetian boundary. Thus it seems reasonable to equate Nøhr-Hansen's P4 interval with the Selandian. In the present study, the three-fold division is adopted (following Gradstein *et al.* 2012) and the *Palaeoperidinium pyrophorum* interval (P4) is referred to the late Selandian for the West Greenland wells (Figs 1, 8), viz. Nukik-2 (Appendix 3.16), Kangâmiut-1 (Appendix 3.17), Ikermiut-1 (Appendix 3.18) and Hellefisk-1 (Appendix 3.19).

Nøhr-Hansen *et al.* (2002) defined the base of their late Danian *Palaeocystodinium bulliforme* Zone by the FO of *Palaeocystodinium bulliforme*; however they did not record the LO of *Palaeocystodinium bulliforme*. Powell & Brinkhuis (in Gradstein *et al.* 2012) placed the LO of *Palaeocystodinium bulliforme* at the Selandian–Thanetian boundary. Based on the co-occurrent LOs of *Palaeoperidinium pyrophrum* and *Palaeocystodinium bulliforme*, we place the latter LO at the Selandian–Thanetian boundary.

Thanetian

The Thanetian is characterised by maximum abundances of *Areoligera gippingensis* and *Glaphyrocysta divaricata* (referred to here as the *Areoligera gippingensis* complex). The upper part of the *Areoligera gippingensis* interval (P5) of Nøhr-Hansen (2003) must equate in part with the Thanetian. High abundances of *Areoligera gippingensis* complex cysts in a number of the wells – such as Gilbert F-53, Gjoa G-37, Hekja O-71, Hellefisk-1, Ikermiut-1, Kangâmiut-1, Karlsefni A-13, Nukik-1, Nukik-2 and Qulleq-1 – allow for correlation with the type Thanetian of southern England (Powell *et al.* 1996) and with the Skua E-41 (Williams 2003a) and Terra Nova K-18 wells (Williams 2003b) on the Grand Banks, offshore Newfoundland. One species with an LO at the Thanetian–Ypresian boundary is *Cerodinium glabrum* following immediately above the LO of *Cerodinium speciosum*. Gradstein & Williams (1976) and Bujak Davies Group (1987) both defined a *Cerodinium*

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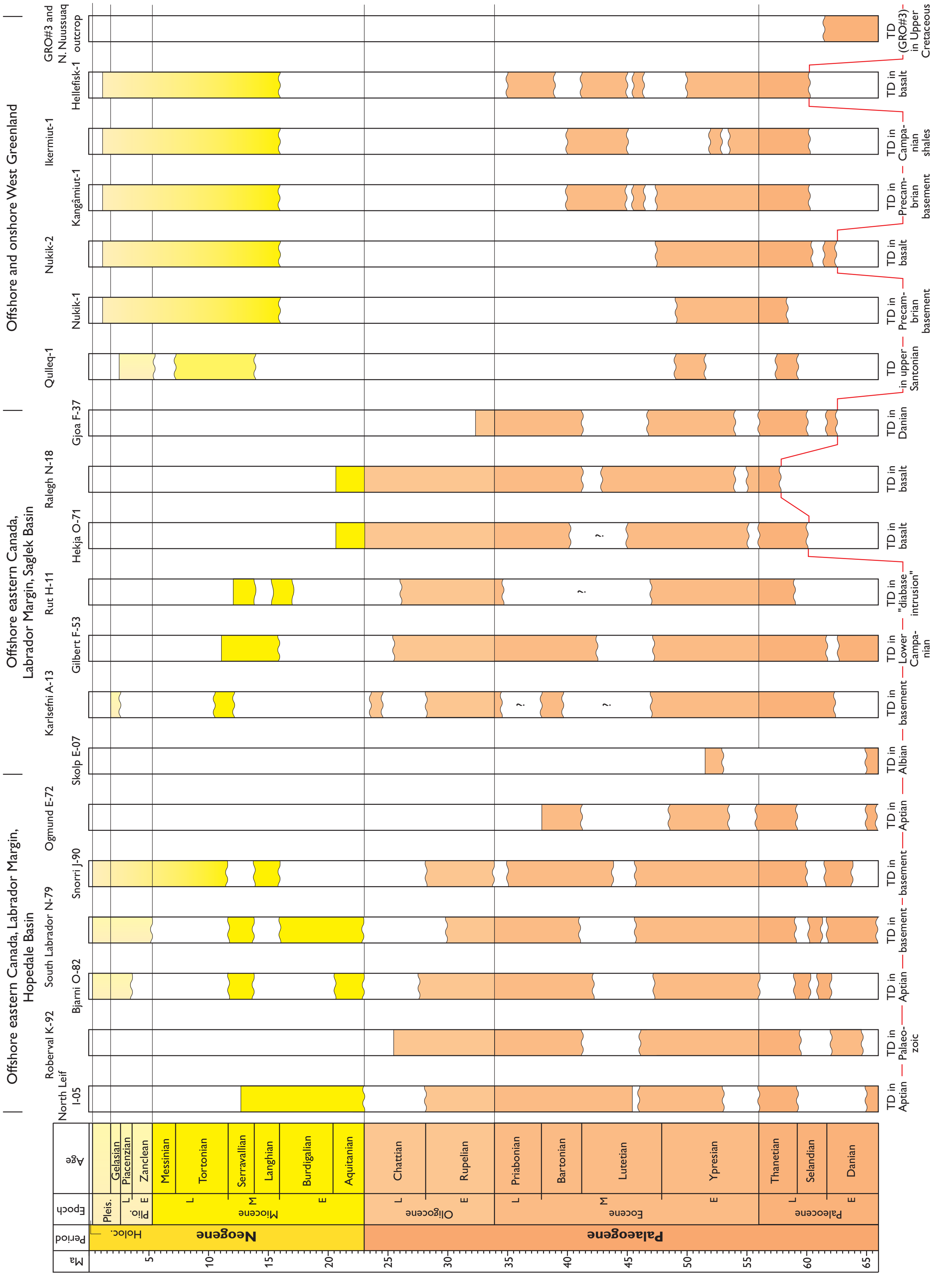
Fig. 8. Cenozoic ages (highlighted in brown for the Palaeogene and yellow for the Neogene) identified from palynomorph assemblages in wells from the Hopedale Basin of the Labrador Margin (North Leif I-05, Roberval K-92, Bjarni O-82, South Labrador N-79, Snorri J-90 and Ogmund E-72), the Saglek Basin of the Labrador Margin and Davis Strait (Skolp E-07, Gilbert F-53, Rut H-11, Hekja O-71, Ralegh N-18 and Gjoa F-37), offshore West Greenland (Qulleq-1, Nukik-1, Nukik-2, Kangâmiut-1, Ikermiut-1 and Hellefisk-1) and a well onshore West Greenland (GRO #3, Nuussuaq) and north Nuussuaq surface sections. Ages not coloured have not been identified. The timescale (Ma) is from Gradstein *et al.* (2012). **TD**: total depth.


Offshore eastern Canada, Labrador Margin, Hopedale Basin
Offshore eastern Canada, Labrador Margin, Saglek Basin
Offshore and onshore West Greenland
North Leif I-05
Roberval K-92
Bjarni O-82
South Labrador N-79
Snorri J-90
Ogmund E-72
Skolp E-07
Karlsefni A-13
Gilbert F-53
Rut H-11
Hekja O-71
Ralegh N-18
Gjoa F-37
Qulleq-1
Nukik-1
Nukik-2
Kangâmiut-1
Ikermiut-1
Hellefisk-1
GRO#3 and N. Nuussuaq outcrop
Ma
Period
Epoch
Age
5
10
15
20
25
30
35
40
45
50
55
60
65
Neogene
Palaeogene
Holoc.
Pleis.
Plio.
Miocene
Oligocene
Eocene
Paleocene
L
E
M
Gelasian
Piacenzian
Zanclean
Messinian
Tortonian
Serravallian
Langhian
Burdigalian
Aquitanian
Chattian
Rupelian
Priabonian
Bartonian
Lutetian
Ypresian
Thanetian
Selandian
Danian
?
TD in Aptian
TD in Palaeozoic
TD in Aptian
TD in basement
TD in basement
TD in Aptian
TD in Albian
TD in basement
TD in Lower Campanian
TD in "diabase intrusion"
TD in basalt
TD in basalt
TD in Danian
TD in upper Santonian
TD in Precambrian basement
TD in basalt
TD in Precambrian basement
TD in Campanian shales
TD in basalt
TD (GRO#3) in Upper Cretaceous

speciosum Zone, which they considered to be late Paleocene. Similarily, in his study of the North Leif I-05 well, Nøhr-Hansen (2004b) considered the LO of *Cerodinium glabrum* (as *Cerodinium speciosum* subsp. *glabrum*) to be in the late Thanetian. Two index species that have their LOs near the base of the Thanetian according to Williams *et al.* (2004) are *Alisocysta circumtabulata* and *Alisocysta margarita*. These two species occur in several of the West Greenland Margin, Davis Strait and Labrador Margin wells. For example, *Alisocysta margarita* has been recorded from Gilbert F-53, Hekja O-71, Gjoa G-37, North Leif I-05, Ogmund E-72, Ralegh N-18, Snorri J-90 and South Labrador N-79 on the Canadian margin and Hellefisk-1, Ikermiut-1, Kangâmiut-1, Nujkik-1, Nukik-2, and Qulleq-2 on the West Greenland Margin.

The uppermost Thanetian is characterised by maximum abundances of *Apectodinium* spp. and the range of *Axiodinium augustum* (Williams *et al.* 2015), and equates with the interval P6 of Nøhr-Hansen (2003). High abundances of *Apectodinium* spp. and the presence of *Axiodinium augustum* were recorded in several wells, e.g. North Leif I-05, South Labrador N-79, Snorri J-90, Ogmund E-72, Rut H-11, Gjoa G-37, Kangâmiut-1 and Ikermiut-1.

Ypresian

In the Labrador–Baffin Seaway, some of the richest dinocyst assemblages occur in Ypresian sediments. The top of the stage is considered here to be marked by the frequent but never abundant occurrence of the freshwater fern *Azolla*. Brinkhuis *et al.* (2006) stated that *Azolla* is abundant in basal middle Eocene marine sediments of Nordic seas. These authors placed the onset of this phase at *c.* 49 Ma and the termination at *c.* 48.3 Ma, probably based on the Gradstein *et al.* (2004) timescale. Barke *et al.* (2012) agreed with Brinkhuis *et al.* (2006) in considering the *Azolla* blooms to occur at 49 Ma and also regarded the age as early middle Eocene. Brinkhuis *et al.* (2006) postulated that the high concentrations of *Azolla* in an ACEX core taken on the Lomonosov Ridge reflected *in-situ* growth. Brinkhuis *et al.*(2006) also listed wells from the Labrador–Baffin Seaway (Karlsefni A-13 in the Saglek Basin and Bjarni O-82, North Leif I-05 and Snorri J-90 in the Hopedale Basin) as having lowermost middle Eocene abundances of *Azolla*. In this study, these wells were not found to contain notable numbers of *Azolla*. Some other wells, all in the northern Saglek Basin, had greater numbers: Hekja O-71, Ralegh N-18 and Gjoa G-37 (Appendices 3.11–3.13). Even in these wells, however, *Azolla* was not recorded in high concentrations, more suggestive of transported material than *in-situ* growth (see further discussion, p. 42–43).

Immediately below the *Azolla* occurrences are the LOs of the dinocyst species *Achilleodinium biformoides*, *Diphyes brevispinum* and *Piladinium columna*. Michoux (1988) described *Piladinium* (as *Charlesdowniea*) *columna* from upper Ypresian rocks of south-western France, stating that nannofossil analyses indicated an NP13 Zone age. Nøhr-Hansen (2003) designated a *Piladinium* (as *Charlesdowniea*) *columna* interval of late Ypresian age, whose top is marked by the LO of the zonal species. Bujak (1994) plotted the LO of both *Pilodinium* (as *Charlesdowniea*) *columna* and *Diphyes brevispinum* within the NP13 Zone. In the Norwegian–Greenland Sea, Eldrett *et al.* (2004) calibrated the LO of *Piladinium columna* with Chron 22n and within nannoplankton zone NP14a, at the top of the Ypresian; this is somewhat later than other records, but is in close accordance with this study. *Piladinium columna* is widespread in the Labrador–Baffin Seaway, occurring in the following wells: Gilbert F-53, Gjoa G-37, North Leif I-05, Ogmund E-72, Ralegh N-18, Snorri J-90 and South Labrador N-79 on the Canadian margin, and Kangâmiut-1, Nukik-2 and Qulleq-1 on the West Greenland Margin (Fig. 1).

Species of *Apectodinium* occur throughout the Ypresian. They include *Apectodinium parvum*, with an LO immediately above the Thanetian–Ypresian boundary, and *Apectodinium homomorphum*, which has a peak abundance at about 54 Ma. Species of *Apectodinium* are found in a number of wells, including Gjoa G-37, Gilbert F-53, Hekja O-71, Karlsefni A-13, North Leif I-05, Ogmund E-72, Falegh N-18, Rut H-11, Skolp E-07 and South Labrador N-79 on the Canadian margin, and Hellefisk-1, Ikermiut-1 and Kangâmiut-1 on the West Greenland Margin.

The Ypresian is informally subdivided here into early and late, with the boundary based on the LOs of *Petalodinium condylos*, *Evittosphaerula foraminosa* and *Scalenodinium scalenum*. Supporting evidence comes from Bujak (1994), who plotted the consistent occurrence of *Petalodinium condylos* within the nannofossil NP12 zone. Occurring above the LO of *Petalodinium condylos* is the LO of *Ginginodinium*? *flexidentatum*. This species appears to equate with *Trinovantedinium* #LA of Bujak Davies Group (1987). These authors defined a *Trinovantedinium* #LA Zone, which they considered to be late Ypresian based on foraminiferal data in South Labrador N-79. *Ginginodinium*? *flexidentatum* is present in the Ypresian in a number of wells, both on the eastern and western margins of the Labrador–Baffin Seaway. These include Gilbert F-53, Hekja O-71, Karlsefni A-13, North Leif I-05, Ogmund E-72, Rut H-11, Snorri J-90 and South Labrador N-79 on the Canadian margin, and Ikermiut-1 and Nukik-2 on the West Greenland Margin (Fig. 1).

One of the characteristic features of the Ypresian and succeeding Lutetian is the occurrence of fungal spore peaks in some of the wells. Selected fungal taxa are shown in Fensome *et al.* (2016, plate 20, figs 12–20).

Lutetian

Although much or all of the Lutetian seems to be absent in many of the wells, especially on the West Greenland Margin (Fig. 8), its top seems to be clearly defined by the LO of *Diphyes colligerum*. Bujak (1994) placed the last consistent LO of this species at the Lutetian–Bartonian boundary. Eldrett *et al.* (2004) considered the LO of *Diphyes colligerum* to approximate with the Lutetian–Bartonian boundary in the Norwegian–Greenland Sea. We follow Eldrett *et al.* (2004) in placing the LO of *Diphyes colligerum* close to the Lutetian–Bartonian boundary; this is in contrast to Nøhr-Hansen (2004b), who recorded the LO of *Diphyes colligerum* at the top of the Ypresian in North Leif I-05. Another important index species having its LO at the top of the Lutetian is *Alterbidinium*? *bicellulum*, originally described by Islam (1983) from the Earnley Formation of the middle Eocene Bracklesham Group of southern England; the age of the Bracklesham Group is latest Ypresian – Lutetian. Nøhr-Hansen (2003) defined the top of his late Lutetian interval on the LO of four taxa, one of which was *Alterbidinium*? cf. *bicellulum*.

Recognition of the earliest Lutetian is facilitated by the LOs of *Eatonicysta ursulae*, *Cordosphaeridium gracile* and *Hystrichosphaeridium tubiferum*. Bujak (1994) placed the LO of *Eatonicysta ursulae* just above the base of the Lutetian, in the nannofossil NP14 Zone. He signified the importance of this species by designating an *Eatonicysta ursulae* Zone. Eldrett *et al.* (2004) developed a refined biostratigraphy of a DSDP site and two ODP sites in the Norwegian–Greenland Sea based on magnetostratigraphic calibration. These workers determined that the LO of *Eatonicysta ursulae* was close to the top of the nannofossil NP14a Zone, broadly confirming the findings of Bujak (1994). This species is found in five wells: Kangâmiut-1 and Nukik-2 on the West Greenland Margin and Gjoa G-37, Snorri J-90 and South Labrador N-79 on the Canadian margin. Bujak (1994) also considered the LO of *Hystrichosphaeridium tubiferum* to be in the Lutetian, but in the lower part of the succeeding nannofossil NP15 Zone. Other LOs within the early Lutetian include those of *Diphyes ficusoides*, *Stichodinium lineidentatum* and *Sophismatia tenuivirgula*. Some of the events in the late Lutetian are the LOs of *Dapsilidinium pseudoinsertum* and *Glaphyrocysta vicina* and the peak of *Trithyrodinium*? *conservatum*.

Bartonian

The Bartonian is absent or condensed in the Greenland wells but more developed on the Canadian margin (Fig. 8). Following Bujak (1994), the top of this stage is defined at the LO of the dinocyst *Rhombodinium porosum*. Dinocysts with their LOs in the Bartonian include *Cerebrocysta bartonensis*, *Chiropteridium gilbertii*, and *Homotryblium tenuispinosum*. *Chiropteridium gilbertii* occurs only in wells on the Labrador Margin (Williams 2007e, under the informal name *Hystrichokolpoma* '*gilbertii*'). Pollen provide much of the stratigraphic control for recognition of Bartonian strata in the Labrador–Baffin Seaway. These include the LOs of *Extratriporopollenites* spp., *Corsinipollenites oculusnoctis*, *Pistillipollenites macgregorii* and *Cicatricososporites eocenicus*. *Azolla* spp. also occur for the last time.

Priabonian

Priabonian sediments have been identified in only one West Greenland Margin well (Hellefisk-1) but are present in most of the Labrador Margin and Davis Strait wells. The key species for defining the top of this stage are *Areosphaeridium diktyoplokum*, *Lentinia serrata* and *Phthanoperidinium multispinum*. Powell & Brinkhuis (in Gradstein *et al.* 2012) placed the LO of *Areosphaeridium diktyoplokum* at the Priabonian–Rupelian boundary. Unfortunately, this species is found only in Hellefisk-1 on the West Greenland Margin. The LOs of *Lentinia serrata* and *Phthanoperidinium multispinum* appear to define the top of the Priabonian in some Grand Banks wells (e.g. Williams 2003a, b). Support for the LO of *Lentinia serrata* is provided by Williams *et al.* (2004), who placed it 0.2 million years above the Priabonian–Rupelian boundary. *Lentinia serrata* is found in Gilbert F-53, North Leif I-05, Ralegh N-18 and South Labrador N-79 on the Canadian margin.

Other LO events in the Priabonian include those of the dinocysts *Glaphyrocysta texta*, *Schematophora speciosa*, *Cordosphaeridium funiculatum*, *Phthanoperidinium stockmansii, Rhombodinium draco* and *Heteraulacacysta porosa*. Williams *et al.* (2004) placed the LOs of *Schematophora speciosa* and *Cordosphaeridium funiculatum* within the Priabonian but, in contrast to the observations in this study, considered *Rhombodinium draco* to range well into the Rupelian. Most of the above species occur only in one well, all on the Canadian margin. Another distinctive Priabonian marker is the spore *Cicatricosisporites ornatus*, which occurs in Snorri J-90.

Rupelian

Strata of Rupelian age were not encountered in any of the West Greenland Margin wells, but rocks of this age are widespread on the Canadian margin, being present in Bjarni O-81 (Appendix 3.3), Gilbert F-53 (Appendix 3.9), Hekja O-71 (Appendix 3.11), Karlsefni A-13 (Appendix 3.8), North Leif I-05 (Appendix 3.1), Ralegh N-18 (Appendix 3.12) and South Labrador N-79 (Appendix 3.4; Figs 1, 8). The top of the stage is placed at the LO of the two dinocyst species *Enneadocysta magna* and *Licracysta semicirculata* (Fig. 6, in pocket). *Enneadocysta magna* was described by Fensome *et al.* (2007) from Oligocene sections in wells drilled on the Grand Banks. Williams (2003a) used the then-informal name *Enneadocysta magna* when he noted that it appeared to be a consistent Rupelian marker species in some Grand Banks wells. *Licracysta* (as *Areoligera*) *semicirculata* was described by Morgenroth (1966) from the middle Oligocene. Williams *et al.* (2004) placed the LO of *Licracysta* (as *Areoligera*) *semicirculata* just below the Rupelian–Chattian boundary. This seems to accord well with the findings of this study. Other dinocyst species that help to delineate the Rupelian are *Licracysta corymbus*, *Phthanoperidinium coreoides* and *Apteodinium australiense*. Miospores with LOs in the Rupelian include *Zlivisporis* spp. and *Periporopollenites* sp. Williams (2007b, e).

Chattian

The Chattian is difficult to delineate, primarily because it is partly or completely absent in all wells apart from Hekja O-71 and Ralegh N-18. We have been able to determine it based only on the LOs of two dinocyst species, *Chiropteridium galea* and *Deflandrea phosphoritica*. Williams *et al.* (2004) considered that both these species extended into the early Aquitanian in northern mid-latitudes, but for the purposes of this study the LOs of these species are considered to mark the Chattian–Aquitanian boundary.

Neogene

Miocene

Dinocyst assemblages in the Neogene of the Labrador–Baffin Seaway are sparse and preservation is generally poor. Both factors, which reflect the coarse clastics that predominate in this interval, may account for some gaps in our interpretations of ages, including the failure to define the Aquitanian, the oldest stage of the Miocene. But there is another possibility – that sediments of Aquitanian age are absent in a number of the wells (Fig. 8). Another difficulty in determining ages in the Neogene sections is the abundance of reworked palynomorphs, both Cretaceous and Palaeogene. However, there are some taxa that facilitate recognition of the early Miocene. These are primarily the dinocyst *Cordosphaeridium cantharellus* and the spore *Osmundacidites wellmannii*. Williams *et al.* (2004) placed the LO of *Cordosphaeridium cantharellus* in Northern Hemisphere mid-latitudes at about 19.5 Ma, within the Burdigalian.

Middle Miocene strata are indicated from several wells, though it has not been possible to differentiate the Langhian as all the index taxa appear to extend up into the Serravallian. These taxa include the pollen *Caryapollenites* spp. and *Tiliaepollenites crassipites*, and the dinocysts *Cleistosphaeridium diversispinosm*, *Apteodinium spiridoides* and *Cannosphaeropsis passio* (Fig. 6, in pocket). *Tiliaepollenites crassipites* was previously described as *Bombacacidites* sp. A by Williams (1975) and Williams & Bujak (1977). Williams (1975) considered the LO of this species to be middle Miocene in Scotian Margin wells. This age was slightly modified in Williams & Bujak (1977), who recorded the species from the Labrador Margin *Operculodinium centrocarpum* assemblage that they considered provisionally to be middle to late Miocene. Williams (2007e) agreed with Williams (1975) in assigning a middle Miocene age. *Cannosphaeropsis passio*, first recorded as *Nematosphaeropsis* sp. A by Williams & Brideaux (1975) from the upper Miocene of the Grand Banks, was described by de Verteuil & Norris (1996) from the upper middle Miocene of Maryland. Piasecki (2003) placed the LO of this species at the Serravallian–Tortonian boundary in Qulleq-l, an age confirmed by Williams *et al.* (2004), who likewise plotted its LO at the Serravallian–Tortonian boundary in Northern Hemisphere mid-latitudes and Equatorial low-latitudes. Powell & Brinkhuis (in Gradstein *et al.* 2012) considered the LO of *Apteodinium spiridoides* to be at the top of the early Miocene, which conflicts with the range documented here. Likewise, Head *et al.* (1989a) recorded the species from the lower Miocene of ODP Hole 645E, Baffin Bay (Figs 1, 2), but did not extend its range into the middle Miocene. Williams *et al.* (1999) plotted the LO of *Apteodinium spiridoides* within the Serravallian, however, which corresponds more closely with our data. *Cleistosphaeridium diversispinosum* is generally an abundant species worldwide, but is not common in samples from the offshore wells in the Labrador–Baffin Seaway. Head *et al.* (1989a) noted, however, that the closely related *Cleistosphaeridium* (as *Systematophora*) *ancyreum* was common in samples from the early and middle Miocene of ODP Hole 645E, Baffin Bay (Figs 1, 2). Another related species is *Cleistosphaeridium placacanthum*, which Schreck *et al.* (2012) considered to have an LO at 10.6 Ma (early Tortonian) in the dinocyst assemblages from an almost continuous middle Miocene to Pliocene section in ODP Site 907A in the Iceland Sea. Williams *et al.* (1999) plotted the LO of *Cleistosphaeridium diversispinosum* at the Serravallian–Tortonian boundary.

Upper Miocene sediments are more prevalent in the West Greenland wells than in those on the Canadian side, with the Qulleq-1 well appearing to have the most complete section (Piasecki 2003; Appendix 3.14). LOs occurring within the Tortonian include *Minisphaeridium latirictum*, (formerly *Cordosphaeridium minimum*), *Hystrichokolpoma rigaudiae*, *Palaeocystodinium golzowense*, *Spiniferites pseudofurcatus*, *Operculodinium janduchenei*, *Operculodinium giganteum*, *Operculodinium piaseckii*, *Edwardsiella sexispinosa* and *Labyrinthodinium truncatum*. In this study, the boundary between the two late Miocene stages, Tortonian and Messinian, is marked by the LOs of three dinocyst species *Tuberculodinium vancampoae* (at the boundary), and *Palaeocystodinium golzowense* and *Operculodinium centrocarpum* in the late Tortonian. *Tuberculodinium vancampoae*, described from the Pleistocene by Rossignol (1962) is a cyst of the extant genus *Pyrophacus*. Head *et al.* (1989a) recorded *Tuberculodinium vancampoae* from only one sample in the questionable early late Miocene of Hole 645E. This taxon is found in modern sediments, in warm lower latitudes. It is presumed that changing climatic conditions, as noted below, resulted in its migration from higher to lower latitudes toward the end of the Miocene, although there were warming trends in the Pliocene–Pleistocene. According to Powell & Brinkhuis (in Gradstein *et al.* 2012), the LO of *Palaeocystodinium golzowense* is within the later Tortonian. Head *et al.* (1989a) found that *Palaeocystodinium golzowense* was common in the early and middle Miocene of ODP Hole 545E, but became rare up section, in what these authors considered to be early late Miocene.

Two dinocyst species, *Spiniferites pseudofurcatus* and *Dapsilidinium pastielsii* have regional LOs within the Tortonian. Head *et al.* (1989a) recorded rare but consistent occurrences of the closely related *Dapsilidinium pseudocolligerum* from the middle Miocene in ODP Hole 645E, Baffin Bay, possibly extending into the early late Miocene. Although Mertens *et al.* (2014) treated *Dapsilidinium pseudocolligerum* as a taxonomic junior synonym of *Dapsilidinium pastielsii*, we prefer to retain *Dapsilidinium pseudocolligerum*, which appears to have a restricted stratigraphic range in the Labrador–Baffin Seaway. Head & Westphal (1999) noted that the latitudinal occurrences of this species contracted in the late Miocene and Pliocene, due to the cooling of the North Atlantic in the late Miocene and the evolution of the cold Labrador Current. Thus climatic changes and oceanic currents rather than extinction explain the disappearance of the genus *Dapsilidinium* and the species *Tuberculodinium vancampoae* from the Labrador–Baffin Seaway in the late Miocene.

Within the Messinian, species of the pollen *Quercoidites* are common but do not appear to range above the Miocene. *Spiniferites ovatus*, described from the late Miocene of Japan, also has its LO at the top of this stage.

Pliocene–Pleistocene

We have not been able to differentiate the Pliocene and Pleistocene in the wells analysed for this bulletin, but Piasecki (2003) made some determinations based on analysis of the Qulleq-1 well (Appendix 3.14). He plotted the LO of *Habibacysta tectata* immediately above the base of the Zanclean. This may be too high, based on the findings of Schreck *et al.* (2012), who placed its LO in the middle Langhian in ODP Hole 907A in the Iceland Sea. A probable explanation for this discrepancy is that the specimens from Qulleq-1 are reworked. Other species recorded by Piasecki (2003) as having their LOs in the Zanclean include *Barssidinium graminosum*, *Invertocysta lacrymosa*, *Selenopemphix nephroides*, *Selenopemphix brevispinosa*, and *Reticulatosphaera actinocoronata*. Piasecki (2003) also distinguished the Piacenzian–Gelasian boundary based on the LO of *Cymatiosphaera invaginata*.

In our analyses, we recognised the Pliocene–Pleistocene based on the presence of the LOs of the pollen taxa, *Zonalapollenites igniculus*, *Graminidites* sp. A of Williams & Brideaux (1975), and *Compositoipollenites* sp. B of Williams & Brideaux (1975). Williams (1975) defined an *Artemisia–Taraxacum* Zone, which he considered to be Pliocene–Pleistocene. Furthermore, Williams & Bujak (1977), in a study of four Labrador Margin wells, defined a *Zonalapollenites* (as *Tsugaepollenites*) *igniculus* assemblage of Pliocene–Pleistocene age.

Discussion

Cretaceous

According to Umpleby (1979), the oldest Mesozoic rocks beneath the Labrador Sea are of Barremian age. It has not been possible to confirm a Barremian age in this study, but the presence of Aptian rocks has been determined in the South Labrador N-79, Roberval K-92, Snorri J-90, and Bjarni O-82 wells (Figs 1, 2, 7). Questionable upper Aptian − Albian rocks occur in Ogmund E-72 and North Leif I-05. All of these wells are in the Hopedale Basin. In the Saglek Basin, Albian–Cenomanian rocks are encountered in the lowermost 475 m of Skolp E-07. Questionable Cenomanian strata are present in Bjarni O-82, North Leif I-05 and Ogmund E-72.

In the Bjarni O-82 well, a major hiatus is identified, with much of the Albian and Cenomanian missing. This is equivalent to the Avalon Unconformity (Fig. 3) identified by McWhae *et al.* (1980) as a regional unconformity in the Labrador–Baffin Seaway.

We recognise another hiatus in several wells: in South Labrador N-79, Aptian strata are overlain by Coniacian rocks; in Ogmund E-72, the Cenomanian is overlain by Campanian; in North Leif I-05, Cenomanian–Turonian is overlain by Maastrichtian; and in Skolp E-07, Albian–Cenomanian strata are overlain by Campanian strata. Thus, much of the Upper Cretaceous section appears to be missing in the Hopedale and Saglek Basins. These observations accord with those of Balkwill *et al.* (1990), who noted that the Cenomanian–Santonian succession is condensed, discontinuous and sometimes absent on the Labrador Margin. (Fig. 7). In offshore West Greenland, the oldest drilled Cretaceous rocks are in the Qulleq-1 well, where upper Santonian rocks were encountered in the lowermost *c.* 300 m of the well.

The continuation of the rift phase during the latest Cretaceous is represented by thicker, more continuous sequences, although significant gaps in the succession still occur. In parts of the Hopedale Basin, such as at Bjarni O-82 and Ogmund E-72, the Campanian is incomplete, with the lower part presumed missing. At North Leif I-05, the Campanian is absent. This contrasts with the situation in Skolp E-07, where the Campanian is about 1050 m thick. In offshore West Greenland, lower Campanian sediments occur only in the Ikermiut-1 and Qulleq-1 wells, with the upper Campanian and Maastrichtian absent. Reworked specimens of Albian, Turonian and late Maastrichtian taxa are present in the lowermost part of the Kangâmiut-1 well, which is dated as Paleocene.

The Upper Cretaceous – Palaeogene sequence on the Labrador Margin is variably developed. In the Skolp E-07 well, for example, the upper Maastrichtian succession appears to be overlain by a thin succession of possibly Danian age, which is in turn overlain by Ypresian strata. Other wells such as North Leif I-05 and South Labrador N-79 in the Hopedale Basin have more complete sections, including Maastrichtian rocks in the former and Danian rocks in the latter (Nøhr-Hansen 2004b). Onshore, in the Nuussuaq Basin, Aptian? to Albian strata are the oldest Mesozoic rocks overlying basement (Dam *et al.* 2009; Pedersen & Nøhr-Hansen 2014). Most of the Upper Cretaceous is represented except for hiatuses in the middle Turonian, lower Campanian and middle Maastrichtian (Figs 7, 9).

Palaeogene

The thickness of Paleocene sediments on the Labrador Margin varies considerably both between and within basins. This is shown by successions in the Gjoa G-37, Hekja O-71 and Ralegh N-18 wells, all of which are in that part of the Saglek Basin that underlies the Davis Strait (Figs 1, 2). Within these three wells, the most complete Paleocene sequence is in Gjoa G-37, which has minimal Danian, partial Selandian and Thanetian rocks. Hekja O-71 appears to have Selandian and Thanetian strata, whereas Ralegh N-18 has only Thanetian rocks. Wells farther south in the Saglek Basin contain minimal Paleocene (e.g. Skolp E-07, Figs 1, 2, 8) or a condensed Selandian and Thanetian succession (e.g. Gilbert F-53). In the Hopedale Basin, the Paleocene succession is thin and discontinuous in Bjarni O-82 and Ogmund E-72. In North Leif I-05 and Ogmund E-72, only Danian and Thanetian strata are present. And in South Labrador N-79, the Selandian is condensed (Fig. 8), perhaps reflecting slower sedimentation rates due to uplift.

A major Danian hiatus occurs in wells off West Greenland, with upper Paleocene strata directly overlying lower

Campanian rocks in Ikermiut-1 and Qulleq-1 (Fig. 8). A thin Danian section occurs, however, in Nukik-2 (Nøhr-Hansen 2003). Upper Selandian and Thanetian strata occur in the lowermost part of Kangâmiut-1 and Hellefisk-1, whereas Thanetian seems to be the oldest strata in Nukik-1 (Fig. 8). We consider this hiatus on the two margins to equate with the Bylot Unconformity of McWhae *et al.* (1980) and with the base-Tertiary unconformity of Sinclair (1988), although the gap is greater on the Greenland margin. This is considered to represent the break-up unconformity marking the onset of drifting in the Labrador Sea; this conforms with the conclusion of Chalmers & Pulvertaft (2001) that the drift phase started during the Selandian. Onshore in the Nuussuaq Basin, a lower Danian to possibly lower Selandian clastic succession is present (Nøhr-Hansen *et al.* 2002; Dam *et al.* 2009; Pedersen & Nøhr-Hansen 2014; Fig. 3); this is overlain by a thick pile of volcanic rocks (Larsen *et al.* 2016; Fig. 3).

A less obvious hiatus, involving the absence of part or all of the Selandian or a condensed sequence, occurs on the Labrador Margin in several wells, including Gjoa G-37 (as noted above) in the Saglek Basin and Bjarni 0-82, North Leif L-05, Snorri J-90 and South Labrador N-79 in the Hopedale Basin (Figs 1, 2, 8). On the West Greenland Margin, Danian sediments in the Nukik-2 well are overlain by upper Selandian sediments. At first glance, the Selandian hiatus appears to be part of the Bylot Unconformity, but the occurrence of Danian sediments suggests a more complex scenario.

In a number of wells on both sides of the Labrador Sea, parts of the middle Eocene are marked by a hiatus or a condensed section representing the Mid-Eocene Unconformity of Dalhoff *et al.* (2003; Fig. 8). These wells are: Bjarni O-82, North Leif I-05, Ogmund E-72 and South Labrador N-79 in the Hopedale Basin; Gilbert F-53, Gjoa G-37 and Ralegh N-18 in the Saglek Basin; and Hellefisk-1, Ikermiut-1 and Kangâmiut-1 off West Greenland (Nøhr-Hansen 2003).

Hiatuses in the younger Palaeogene and Neogene are difficult to determine, largely because sedimentation is dominated by coarse clastic rocks with a low preservation potential for palynomorphs. A hiatus is recognised within the Oligocene, however, on both sides of the Labrador Sea and it extends into the Miocene in several wells. On the western margin, this hiatus seems to primarily represent the Chattian, though it may include part of the Rupelian. In the southern Hopedale Basin, Chattian strata are absent in South Labrador N-79. In Bjarni O-82, however, the thick Rupelian interval is overlain by strata that may be of Chattian age. In Snorri J-90 in the northern Hopedale Basin, Rupelian sediments appear to be directly overlain by Miocene sediments (Fig. 8; Appendix 3.5). The Rupelian is also thick in some of the Saglek Basin wells, such as Gilbert F-53 to the south, and sediments of this age are present in Gjoa G-37 and Hekja O-71 to the north. In Hekja O-71, the thick Rupelian section is overlain by up to 30 m of Chattian sediment, an interval not usually preserved in the region.

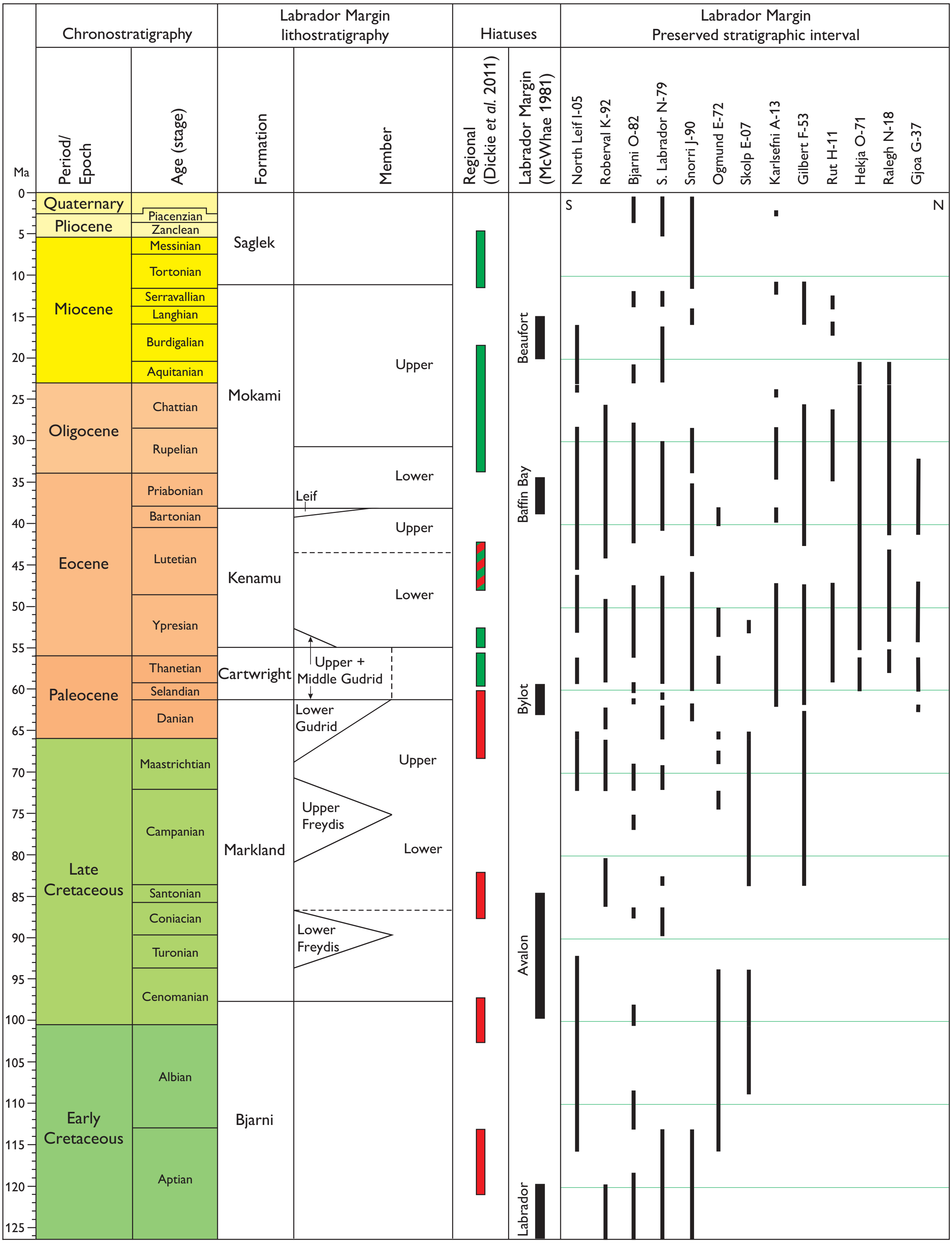
The Oligocene hiatus of the western Labrador Sea probably corresponds to the regional unconformity placed at the top of the Kenamu Formation by Balkwill *et al.* (1990), the Baffin Bay Unconformity (Fig. 6, in pocket, Fig. 8). These authors pointed out that most of the inner and central parts of the northern Labrador and south-eastern Baffin Margins were emergent in the middle to late Oligocene, so that the oldest post-drift rocks are represented by the lower member of the Mokami Formation (Fig. 3).

Off West Greenland, Rolle (1985) recorded Oligocene strata in Hellefisk-1 and possible Oligocene strata in four wells: Ikermiut-1, Kangâmiut-1, Nukik-1 and Nukik-2 (Figs 1–3, 8). However, based on more recent biostratigraphic data, it is most likely that the Oligocene unconformity extends across to the Greenland side, since Piasecki (2003) recorded an Ypresian–Serravallian hiatus in Qulleq-1. The youngest Palaeogene interval found by Nøhr-Hansen (2003) in Hellefisk-1 is of Priabonian age (Figs 3, 8; Appendix 3.19).

This Oligocene unconformity broadly correlates with the cessation of sea-floor spreading in the Rupelian in the northern Labrador Sea and in the Davis Strait, and probably also in Baffin Bay. Srivastava (1978) and Dickie *et al.* (2011) considered that the cessation of sea-floor spreading occurred during the Priabonian (Anomaly 13). However, a more likely cause for the unconformity was the development of the Antarctic Circumpolar Current between 33 and 30 Ma, which marked the onset of Antarctic glaciation. This triggered a drop in sea level that was worldwide (Haq *et al.* 1987; Haq & Al-Qahtani 2005).

Neogene

Unconformities spanning the Palaeogene–Neogene boundary and within the Neogene in the Labrador–Baffin Seaway are difficult to identify and correlate. As noted earlier, McWhae *et al.* (1980) placed the Beaufort Unconformity between the Mokami Formation and the overlying Saglek Formation (Fig. 3); Grant (1980) postulated a regional upper Miocene unconfor-


Chronostratigraphy
Labrador Margin lithostratigraphy
Hiatuses
Labrador Margin Preserved stratigraphic interval
Ma
Period/ Epoch
Age (stage)
Formation
Member
Regional (Dickie et al. 2011)
Labrador Margin (McWhae 1981)
North Leif I-05
Roberval K-92
Bjarni O-82
S. Labrador N-79
Snorri J-90
Ogmund E-72
Skolp E-07
Karlsefni A-13
Gilbert F-53
Rut H-11
Hekja O-71
Ralegh N-18
Gjoa G-37
S
N
0
5
10
15
20
25
30
35
40
45
50
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60
65
70
75
80
85
90
95
100
105
110
115
120
125
Quaternary
Pliocene
Miocene
Oligocene
Eocene
Paleocene
Late Cretaceous
Early Cretaceous
Piacenzian
Zanclean
Messinian
Tortonian
Serravallian
Langhian
Burdigalian
Aquitanian
Chattian
Rupelian
Priabonian
Bartonian
Lutetian
Ypresian
Thanetian
Selandian
Danian
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Aptian
Saglek
Mokami
Kenamu
Cartwright
Markland
Bjarni
Upper
Lower
Leif
Upper
Lower
Upper + Middle Gudrid
Lower Gudrid
Upper
Upper Freydis
Lower
Lower Freydis
Beaufort
Baffin Bay
Bylot
Avalon
Labrador

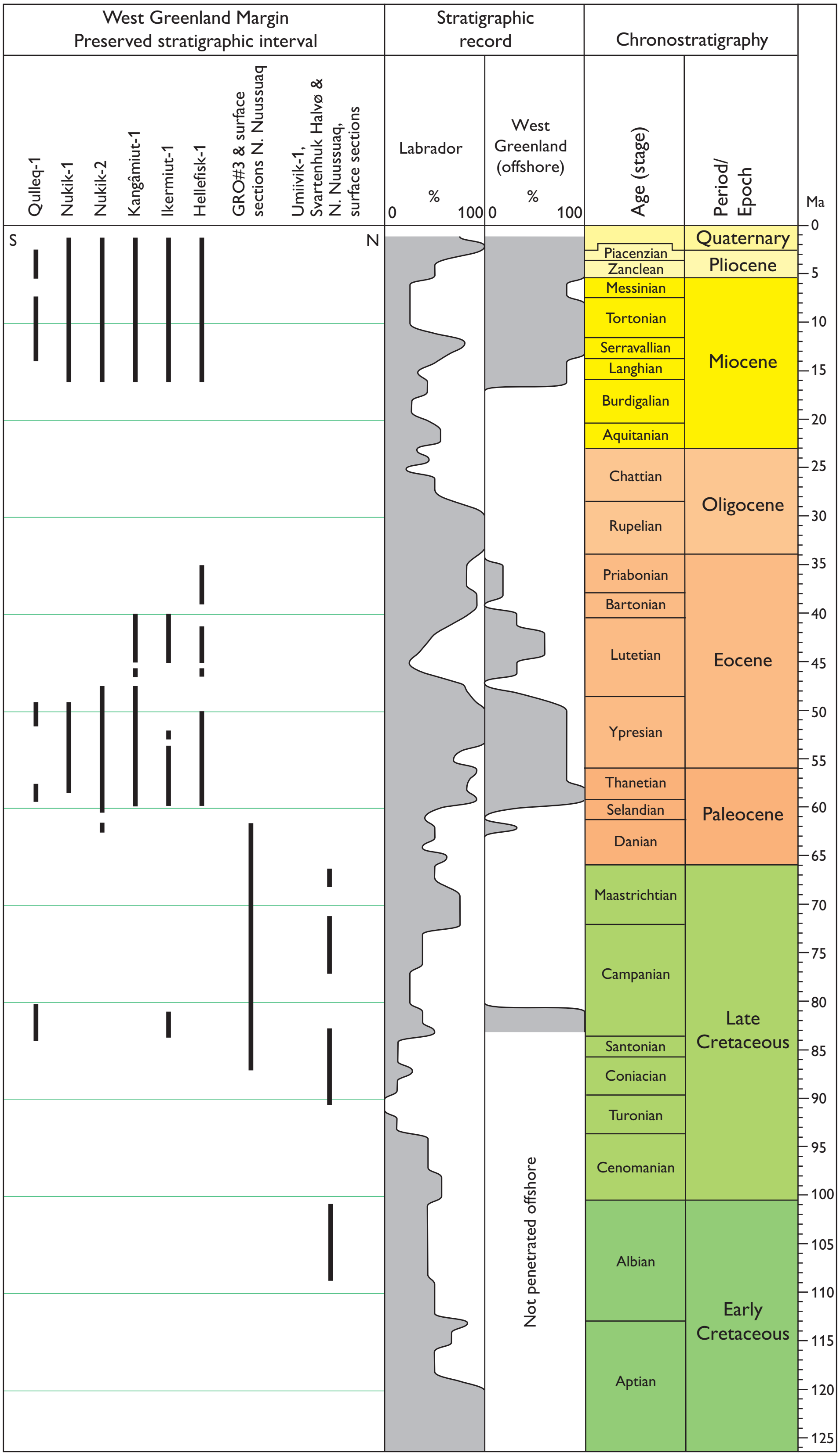

Fig. 9. Schematic representation of the preserved stratigraphic record on the Labrador and Greenland Margins, comparing the preserved record in the sections individually and collectively with the hiatuses linked to unconformities reported in the literature. Dickie *et al.* (2011) recognised a number of unconformities in two or more of three regions – Southwest Greenland Shelf, the Labrador Shelf and the Jeanne d'Arc Basin, offshore Newfoundland (red, all three regions; green, two regions). McWhae (1981) named five unconformities on the Labrador Margin; the hiatuses associated with these unconformities indicated here are estimates by McWhae (1981) based on an unspecified timescale and thus should be considered approximate. The 'cumulative preservation' plots (right) depict schematically the proportion of wells that contain sediments of a specified age, based on one million-year slots; note that these calculations only include wells that extend down to/beyond the relevant stratigraphic level.

mity. In the wells we have examined, a middle to late Miocene hiatus occurs in the Hopedale Basin. For example in Bjarni O-82 (Fig. 8), the Serravallian is overlain by Pliocene–Pleistocene sediments, indicating that all of the upper Miocene is absent. A similar situation seems to exist in South Labrador N-79, where Pliocene–Pleistocene sediments apparently overlie the middle Miocene succession (Fig. 8). Furthermore, in Snorri J-90 in the northern part of the Hopedale Basin, the upper middle Miocene is missing (Fig. 8).

Evidence in the Saglek Basin is more tenuous. In Gilbert F-53, the sparse palynomorph assemblage provides inconclusive evidence, but the thin nature of the Miocene strongly suggests a significant hiatus. Unfortunately, in Gjoa G-37 and Hekja O-71, samples were not available from the upper drilled interval and the uppermost samples analysed are of Rupelian and early Miocene age, respectively.

In offshore West Greenland, Piasecki (2003) recorded middle Miocene as the oldest Neogene interval in the Kangâmiut-1 well. A similar situation may exist in the Nukik-1, Nukik-2, Ikermiut-1 and Hellefisk-1 wells, although no marker species were recorded among the sparse palynomorph assemblages in the samples from the upper part of the Ikermiut-1 and Hellefisk-1 wells.

In summation, there is convincing evidence that some of the Eocene and all of the Oligocene and lower Miocene are missing on the West Greenland Margin, so that middle Miocene sediments directly overlie those of Ypresian to Priabonian age. On the western margin of the seaway, however, there is a middle to late Miocene hiatus, especially in the Hopedale Basin (Fig. 8). This hiatus may be equivalent to the Beaufort Unconformity (Fig. 3) of McWhae *et al.* (1980) and McWhae (1981).

Palaeoenvironmental results

General considerations

The general methodology of palaeoenvironmental interpretation in this study is reviewed in this and the following sections. The initial approach for some wells was to develop palaeoenvironmental plots showing the ratio of miospores to dinocysts, having separated out acritarchs and other organic-walled organisms, such as massullae of *Azolla*. This ratio provides a rough estimate of distance from the shoreline, although it can be misleading because of the dominance of bisaccate pollen far offshore and the general decrease in dinocysts in oligotrophic zones (see below). If there are no dinocysts present it was assumed, perhaps incorrectly, that the sediments were non-marine. Subsequently, the focus of the palaeoecological study switched to fluctuations in dinocyst assemblages and how the palaeoenvironmental determinations compared with previous results in the Labrador–Baffin Seaway region,

The palaeoenvironmental interpretations are based on detailed counts for six wells: Bjarni O-82, Gilbert F-53, Gjoa G-37, Hejka O-71, Snorri J-90 and South Labrador N-79, but are augmented by general observations from other wells. For these six wells, counts of 100 to 200 specimens per sample were made where possible. Dinocyst taxa considered significant are listed in Table 1, and the plots in Appendix 2 include a column highlighting palaeoenvironmental interpretations. The column has five subdivisions: non-marine, marginal marine, inner neritic, outer neritic and open ocean, and the environmental assessment through time is indicated for each well by a curve in this column. Both quantitative and qualitative data have been assessed in developing the palaeoenvironmental curves. For example, the presence of two or three specimens of *Impagidinium* was deemed sufficient to interpret the palaeoenvironment as open ocean (Dale 1996), although as Zonneveld *et al.* (2013) noted, *Impagidinium* is not invariably restricted to open-ocean environments in recent sediments. However, to strengthen the interpretations, occurrences of *Impagidinium* in the Labrador–Baffin Seaway wells were compared with planktonic foraminiferal data.

Palaeoenvironmental curves for the Palaeogene successions in Greenland wells (Hellefisk-1, Ikermiut-1, Kangâmiut-1, Nukik-1 and Nukik-2) published in Rasmussen *et al.* (2003) are included in the present study (Appendices 3.15–3.19). The curves indicate the presence of littoral/lagoonal (transitional), inner nerit-

Table 1. Palaeoenvironmental preferences of dinocyst taxa in the Labrador–Baffin Seaway

Coastal – marginal marine	**Inner neritic**	**Outer neritic**	**Open ocean**
Eocladopyxis	*Areoligera*	*Cerodinium*	*Cannosphaeropsis*
Heteraulacacysta	*Cleistosphaeridium*	*Cleistosphaeridium*	*Impagidinium*
Homotryblium	*Cribroperidinium*	*Cordosphaeridium*	*Nematosphaeropsis*
*Micrhystridium**	*Deflandrea*	*Hystrichokolpoma*	*Pterodinium*
Nyktericysta	*Dinogymnium*	*Hystrichosphaeridium*	
Polysphaeridium	*Glaphyrocysta*	*Operculodinium*	
Tuberculodinium	*Heterosphaeridium*	*Phelodinium*	
Vesperopsis	*Micrhystridium**	*Spiniferites*	
	Phthanoperidinium		
	Wetzeliella		

* Acritarch

ic, middle neritic, outer neritic and upper bathyal palaeoenvironments, and were interpreted from the palynomorph content (mainly dinocysts and their species richness, freshwater algae, fungal spores, miospores, plant tissues) in association with data from other fossils (mainly foraminifera, radiolarians, diatoms, ostracods, gastropods, bivalves and calcareous nannofossils). In general, the palaeoenvironmental signals from different fossil groups show similar trends (Rasmussen *et al.* 2003); the discrepancies that do occur may be due to the fact that most of the samples studied are cuttings.

Use of dinocysts for palaeoenvironmental interpretations can be misleading. Dinocyst assemblages tend to reflect distance from shore rather than water depth, which is why ‘open ocean’ is used in Appendix 2 rather than ‘bathyal’. Since the relationship between water depth and distance from shore is not a simple one – varying for example in relation to shelf width – the curves presented here should be treated with some circumspection. Further caution is needed because, as with the biostratigraphy, the palaeoenvironmental interpretations are based on data from cuttings that can lead to misinterpretation due to downwell contamination. However, the curves, most of which have been reported previously (Williams 2007a–e), do show general trends and agree well with interpretations from, for example, foraminiferal and sedimentological data (Bujak Davies Group 1987; Miller & d’Eon 1987).

Palaeoenvironments and dinocysts: previous studies

Pioneering studies in interpreting palaeoenvironments from dinocyst assemblages were by Gocht (1969) and Downie *et al.* (1971). One early approach involved the ‘gonyaulacacean ratio’, based on an innovative study of the Campanian Bearpaw Formation of Alberta by Harland (1973). This author defined the ratio as the number of species that have a gonyaulacacean affinity divided by the number of species having a peridiniacean affinity. Thus the ratio reflects number of species rather than number of specimens. Harland assumed that when the number of gonyaulacacean species is higher than the number of peridiniacean species, more open-marine conditions prevailed. The interpretations based on this approach were in agreement with the foraminiferal data for the Bearpaw Formation. In our studies, however, it was found that specimen counts were more meaningful than number of species.

Palaeoenvironental studies using dinocysts have expanded significantly in the past thirty years. Important works include those by Köthe (1990), Brinkhuis (1994), Dale (1996), Stover *et al.* (1996), Powell *et al.* (1996), Jaramillo & Oboh-Ikuenobe (1999), Sluijs *et al.* (2005), Sluijs *et al.* (2008), Sluijs & Brinkhuis (2009), Guerstein *et al.* (2008), Lebedeva (2010) and Schreck *et al.* (2012). The comprehensive atlas of the occurrences of modern cyst-forming dinoflagellates by Zonneveld *et al.* (2013) is also very helpful in projecting modern distributions into the past.

From a review of the literature, it is clear that some palaeoenvironments are more clearly interpreted than others from dinocyst assemblages, and some taxa give clearer signals than others. One such signal comes from the late Early Cretaceous ceratiacean cysts with adnate apical archaeopyles – *Nyktericysta* and *Vesperopsis*. MacRae (1996) noted that several studies – including Wightman *et al.* (1987), Bint (1986), Banerjee & Davies (1988) and Leckie & Singh (1991) – had suggested that at least some species of *Nyktericysta* and *Vesperopsis* were specialised for brackish or freshwater environments. Nøhr-Hansen (1992, 2008), Zippi (1998), Dolby *et al.*

(2013) and Pedersen & Nøhr-Hansen (2014) similarly concluded that *Vesperopsis mayi* and *Nyktericysta* (as *Balmula*) *tripenta* and similar ceratiacean taxa seem to be associated with non-marine to marginal marine environments.

In the Cenozoic, some of the most useful dinocyst taxa for indicating marginal marine palaeoenvironments are members of the family Goniodomaceae, including *Homotryblium tenuispinosum* (Brinkhuis 1994) and *Eocladopyxis* (Sluijs *et al.* 2005). Crouch *et al.* (2001, 2003) and Sluijs *et al.* (2005) also noted that abundances of the peridiniacean (wetzelielloidean) *Apectodinium* spp. were common in marginal marine settings in the late Paleocene – early Eocene. Brinkhuis (1994) considered *Areoligera*, *Glaphyrocysta*, *Homotryblium*, *Operculodinium*, *Spiniferites* and *Areosphaeridium* to define inner-shelf palaeoenvironments in the early Cenozoic.

An example of conflicting palaeoenvironmental interpretations involves the findings of Heilmann-Clausen (1994) and Powell *et al.* (1996). Heilmann-Clausen (1994) considered *Areoligera gippingensis* to be indicative of offshore marine enironments. He noted (Heilmann-Clausen 1994, p. 53) that *Areoligera gippingensis* is abundant throughout the latest Selandian – early Thanetian *Alisocysta margarita* zone in Denmark, where "the entire zone occurs in a clearly offshore setting". Powell *et al.* (1996), however, described an *Areoligera*-dominated assemblage (probably equivalent to the *Areoligera gippingensis* complex of this study) from the Thanetian type section of southern England. In their Pegwell Bay section, they noted three intervals where *Areoligera* was 'superabundant' and three where it was 'abundant'. According to Powell *et al.* (1996), such horizons denote restricted high-energy, marginal marine settings typical of a transgressive regime. They believed that the richest samples were close to the most condensed interval or maximum flooding surface. As discussed further below, it appears that assemblages rich in specimens of the *Areoligera gippingensis* complex can give mixed messages.

Downie *et al.* (1971) postulated that their Ypresian *Wetzeliella* association was estuarine. This association was dominated by species of *Wetzeliella* and (perhaps) *Deflandrea*. Dominant taxa included *Apectodinium* (as *Wetzeliella*) *homomorphum*, *Apectodinium (*as *Wetzeliella*) *parvum* and *Deflandrea phosphoritica*. Firth (1996), who studied high-latitude North Atlantic dinocyst assemblages from ODP Hole 913B, found relative abundance peaks of *Deflandrea* spp., together with *Phthanoperidinium* spp., in strata that are primarily diatom- and radiolarian-rich biosiliceous oozes that clearly originated in a deep-water, open-ocean palaeoenvironment. Firth (1996) concluded that these peaks could reflect high palaeoproductivity events. The interpretations of Downie *et al.* (1971) and Firth (1996) demonstrate that similar dinocyst assemblages may reflect conditions such as nutrient enrichment (usually resulting from upwelling) that may occur in a range of marine settings, as is the case today.

More clarity was provided by the studies of Brinkhuis *et al.* (2003) and Sluijs *et al.* (2003), who showed that lithological, geochemical, grain-size and diatom data indicate that high abundances of *Deflandrea* and *Phthanoperidinium* denoted shallow-water palaeoenvironments. Köthe (1990) also concluded that common to abundant occurrences of *Phthanoperidinium* suggest an inner neritic palaeoenvironment. Clearly, the palaeoenvironmental interpretation of dinocyst assemblages is best unravelled with support from other evidence, such as lithological and benthic foraminiferal data.

Harding (1990), Eshet *et al.* (1994), Brinkhuis *et al.* (1998) and van Mourik *et al.* (2001) all suggested that high abundances of *Palaeoperidinium* cysts indicate higher nutrient levels that reflect terrigenous input and therefore palaeoenvironments probably nearer to shore. However, since nutrient enrichment can be related to upwelling processes, as shown later for shelf-edge settings, more than one interpretation is possible for the abundant occurrences of *Palaeoperidinium*.

Oligotrophic palaeoenvironments are commonly associated with mid-shelf settings, where nutrients are low, relative to more nutrient-rich proximal settings, and distal locations where there is upwelling (Sluijs *et al.* 2005). In the Labrador Margin wells, oligotrophic palaeoenvironments can usually be determined from the dramatic drop in numbers of dinocyst specimens, which is commonly accompanied by a marked relative increase in the number of miospores. This is demonstrable in the interval 2020–1450 m in Gilbert F-53 (Appendix 2.4), in which dinocyst specimen counts are extremely low (Williams 2007e) and where the foraminiferal data confirm that the palaeoenvironment was middle neritic (Miller & Helenes 1989c). For example there are nine dinocysts compared to 95 miospores at 1940–1930 m.

It is extremely difficult to determine which dinocyst species are characteristic of outer neritic palaeoenvironments. In their study of early Eocene assemblages, Downie *et al.* (1971) postulated that their *Hystrichosphaeridium* association is indicative of open-sea palaeoenvironments. This association included species of *Achomosphaera*, *Cordosphaeridium*, *Hystrichosphaeridium* and *Spiniferites*. Brinkhuis (1994) came to similar but more detailed conclusions: in his Priabonian outer neritic dinocyst assemblages, he included the taxa *Cleistosphaeridium*, *Spiniferites*, *Areosphaeridium*, *Operculodinium*, *Nematosphaeropsis* and *Cannosphaeropsis*. Other taxa indicating outer neritic palaeoenvironments are species of *Hystrichokolpoma*; this genus, which can also be associated with *Impagidinium*, is suggestive of open-ocean conditions (Williams 2007e). Support for this interpretation is provided by foraminiferal data for the Gilbert F-53 well (Bujak Davies Group 1987).

Open-ocean palaeoenvironments are characterised by the occurrence of *Impagidinium* (Sluijs *et al.* 2005). This conclusion is based on the pioneering study of Wall *et al.* (1977). Fortunately *Impagidinium* occurs in the Late Cretaceous, at least in the Maastrichtian in this study, as well as ranging throughout the Cenozoic. *Hystrichokolpoma*, as discussed above, can also indicate outer neritic to open-ocean palaeoenvironments, just as *Areoligera* (herein *Areoligera gippingensis* complex) abundances seem to do in the Paleocene. This is confirmed by foraminiferal data in the Labrador Margin wells (Miller & Helenes 1989b; Williams 2007e).

Previous palaeoenvironmental interpretations from the Labrador–Baffin Seaway

Published palaeoenvironmental conclusions on the western Labrador Sea wells are based on foraminifera (Gradstein & Williams 1976; Gradstein & Srivastava 1980; Bujak Davies Group 1987; Miller & Helenes 1989a–c; Ainsworth *et al.* 2014), palynomorphs (Gradstein & Williams 1976, Williams 2007a–f) and nannofossils (Crux & Gard 2004). Similar findings for West Greenland utilise foraminiferal, nannofossil and palynological studies of the lower Palaeogene (Rasmussen *et al.* 2003; Sheldon 2003) and dinocyst studies of the Neogene (Piasecki 2003).

Using foramineral and palynological data from wells, Gradstein & Williams (1976) concluded that depositional environments on the Labrador Margin evolved from non-marine in the Early Cretaceous to possibly neritic in the Late Cretaceous – Paleocene, then to bathyal in the Eocene, neritic in the Oligocene–Miocene, and littoral and non-marine in the Pliocene–Pleistocene. An apparent conflict is evident between the palynological and foraminiferal data from the Eocene, where the foraminifera indicate bathyal palaeoenvironments and the dinocysts suggest inner neritic conditions; the most plausible explanation seems to be that the dinocysts were redeposited.

In a reappraisal of the data, Gradstein & Srivastava (1980) defined four depositional palaeoenvironments for Labrador Margin wells, again based on foraminifera and palynomorphs. These were: non-marine; shallow neritic (taken to include marginal marine to inner shelf, with water depths less than 100 m); deep neritic (with water depths ranging from 100–200 m); and bathyal or upper slope (with water depths from 200–1000 m). According to these authors, marine sedimentation started in the middle Late Cretaceous in the Labrador Sea, but the main transgression began during the Maastrichtian, thus coinciding with the onset of sea-floor spreading during Anomaly 32. Neritic to bathyal conditions persisted throughout Paleocene and Eocene times, with the deepest water (bathyal) palaeoenvironments in the Eocene reflecting rapid subsidence at that time. Near the Eocene–Oligocene boundary, at the end of sea-floor spreading, palaeoenvironments changed from deep to shallow marine, the latter conditions persisting through the later Cenozoic. According to Gradstein & Srivastava (1980), the only exception was in Kangâmiut-1 where deeper water environments persisted into the Neogene.

Foraminiferal analyses of cores from Leg 105, Site 645 in Baffin Bay (Srivastava *et. al.* 1987) showed that an upper slope palaeoenvironment persisted there in the Miocene. The dinocysts from the same interval indicated open-marine conditions. Higher in the Miocene, open-marine and neritic dinocyst species occur, probably reflecting redeposition of the latter. At Site 646, palaeoenvironments were generally lower bathyal.

Results and interpretations

Cretaceous

The observations made during this study support earlier findings that non-marine conditions prevailed during the Early Cretaceous on what is today the Labrador Margin (Gradstein & Williams 1976); this interpretation is based on the fact that many assemblages in this part of the section consist exclusively of miospores. Balkwill *et al.* (1990) considered the Bjarni Formation, which they dated as early Barremian to Albian, to represent lacustrine deposits. However, the occasional occurrence of species of *Nyktericysta* and *Vesperopsis* on both sides of the seaway suggests a non-marine to marginal marine setting, as does the presence of *Subtilisphaera* spp. in Bjarni O-82 and *Pseudoceratium* sp. in Roberval K-92. The interval containing these dinocysts was interpreted as non-marine by Miller & d'Eon (1987), but Williams (2007a) interpreted it in part as marginal marine, based on the few dinocysts present.

The overlying rocks contain other Aptian dinocyst species, especially *Tenua hystrix,* which is known only from shallow marine palaeoenvironments. Thus, marine environments extended back to about 120 Ma. Possible evidence for earlier marine conditions in the Davis Strait area are the reworked Late Jurassic dinocysts *Perisseiasphaeridium pannosum* and *Fromea tornatilis* recorded from Qulleq-1 by Nøhr-Hansen *et al.* (2000).

Nyktericysta is present and sometimes common in the Aptian of South Labrador N-79, the Albian–Cenomanian in Ogmund E-72, and North Leif I-05 in the Hopedale Basin (Nøhr-Hansen in Sønderholm *et al.* 2003b; Nøhr-Hansen 2004b; Williams 2007b) and in samples from Nuussuaq and Disko in the Nuussuaq Basin of onshore West Greenland (Nøhr-Hansen 2008; Pedersen & Nøhr-Hansen 2014). These onshore Greenland occurrences accord well with Labrador Sea observations, and suggest that conditions in the entire region fluctuated between shallow marine and lagoonal to lacustrine in the Aptian?/Albian to Cenomanian.

Inner neritic conditions became widespread in the Turonian/Coniacian to Santonian interval. Dinocysts are usually abundant in such settings, especially in the vicinity of discharge from rivers, where nutrients are plentiful. Taxa that appear to indicate inner neritic palaeoenvironments in this interval include *Heterosphaeridium difficile*, *Circulodinium distinctum*, *Chatangiella* and *Gillinia hymenophora*. These conclusions are based on the studies of shallow-water assemblages from Bylot Island (G.L.Williams, unpublished data), in which foraminifera are absent.

More open-ocean, presumably deeper water palaeoenvironments developed in the Campanian and Maastrichtian, as shown in Gilbert F-53 in the Saglek Basin and Bjarni O-82 and South Labrador N-79 in the Hopedale Basin. Foraminiferal data for all three wells indicate that the palaeoenvironments were bathyal (Bujak Davies Group 1987).

Cenozoic

Intervals with occurrences of *Phelodinium kozlowskii* tend to also contain foraminifera that indicate a bathyal palaeoenvironment (Bujak Davies Group 1987); hence, the former may indicate an outer neritic or open-ocean palaeoenvironment. *Phelodinium kozlowskii* occurs in some samples between 3200 and 2740 m in Gilbert F-53, an interval that is of Maastrichtian (3250–3120 m) to Danian (3100–2740 m) age (Williams 2007e). This deeper water interpretation seems to be in conflict with the presence of the hiatus between the Cretaceous and Cenozoic sediments in some of the wells. However, upper Maastrichtian and Danian to Selandian strata, including transitional Cretaceous–Cenozoic strata, occur in Nuussuaq.

Other common dinocyst taxa in the Paleocene are *Alterbidinium* spp., *Areoligera gippingensis*, *Cerodinium diebelii*, *Cerodinium speciosum*, *Glaphyrocysta divaricata*, *Hystrichosphaeridium tubiferum*, *Palaeocystodinium golzowense*, *Palaeoperidinium pyrophorum* and *Trithyrodinium evittii*. The pollen *Pinuspollenites* is also extremely abundant in the Paleocene. That *Palaeoperidinium pyrophorum* is considered to indicate outer neritic to open-ocean palaeoenvironments is based on foraminiferal data (e.g. Gilbert F-53). This interpretation seems at odds, however, with the conclusions of several authors (e.g. Eshet *et al.* 1994; Brinkhuis *et al.* 1998; van Mourik *et al.* 2001), who postulated that high abundances of *Palaeoperidinium* (peridinioid) cysts indicate higher nutrient levels, thus reflecting terrigenous input and a closer proximity to shore. Dale & Fjellså (1994) pointed out that the assumption that peridinioid cysts are invariably heterotrophic is not always warranted and can lead to erroneous interpretations; they also noted that modern heterotrophic dinoflagellates are not restricted to areas of high productivity. In addition, nutrient-rich conditions can develop in various, contrasting settings including inshore areas with abundant terrigenous input and shelf-edge settings with upwelling, so that different interpretations are entirely possible.

The Gilbert F-53 well (3200–2770 m) provides an example in which an abundance of *Palaeoperidinium pyrophorum* is related to an offshore setting rather than to a coastal environment. There is a marked increase in the abundance of this species from 3260 to 2740 m (excluding the interval 2860–2760 m) indicative of increasing trophic resources. Over the same interval, the gonyaulacacean ratio, which is considered to be an indicator of distance from shore, varies from 0.5 to 1.4, suggesting progressively more open-marine conditions. The foraminiferal data from this well indicate that the interval from 3200 to 2740 m represents a bathyal setting (Bujak Davies Group 1987). Miller & Helenes (1989b) interpreted the interval from 3330 to 3230 m as middle to outer neritic, and from 3230 to 2520 m as bathyal, with the interval from 2940 to 2750 m as possibly outer neritic. Similarly, the dinocyst taxa recorded from about 3250 to 2750 m indicate outer-shelf palaeoenvironments; the presence of *Impagidinium* in some samples suggests open-ocean conditions (Dale 1996). During the Danian, the palaeoenvironmental setting of South Labrador N-79 was presumably similar to that of Gilbert F-53; the former well also shows high abundances of *Palaeoperidinium pyrophorum* in association with *Impagidinium*. Thus the abundance of *Palaeoperidinium pyrophorum* in both wells is best explained by high nutrient levels at the shelf edge related to deep-water upwelling, conditions that are ideal for plankton whether autotrophic or heterotrophic.

Several dinocyst groups proliferated during the Palaeogene, an example being the areoligeraceans, especially the genera *Areoligera* and *Glaphyrocysta*. Species of these two genera range through parts of the Late Cretaceous and Palaeogene, and the species *Areoligera gippingensis* and *Glaphyrocysta divaricata* are especially prominent in the Paleocene. The two species are hard to distinguish – we would restrict *Areoligera gippingensis* to specimens with basal ridges at least partially connecting processes in process complexes and *Glaphyrocysta divaricata* to specimens lacking such ridges (see Fensome *et al.* 2016). Most records in the literature understandably just record the complex as *Areoligera gippingensis* or *Areoligera* spp. (although our experience on the Canadian margin is that most specimens belong to *Glaphyrocysta divaricata*). As noted above, we refer to the two species collectively herein as the *Areoligera gippingensis* complex.

Specimens of the *Areoligera gippingensis* complex are among the most common dinocysts in the Paleocene of the Labrador Margin. These forms are abundant in the Danian–Selandian of South Labrador N-79 in the Hopedale Basin, in the Maastrichtian (where they are interpreted as caved) to Thanetian of Gilbert F-53, and in the Selandian–Thanetian of Gjoa G-37 and the Thanetian of Karlsefni A-13 in the Saglek Basin. In these wells, peak abundances of the complex can occur throughout the Paleocene. Similar peaks of this species complex have been observed elsewhere, with contrasting interpretations, for example on the Scotian Margin (Fensome *et al.* 2008), in Denmark (Heilmann-Clausen 1994) and in the type Thanetian of southern England (Powell *et al.* 1996).

Members of the *Areoligera gippingensis* complex are gonyaulacaceans and thus more likely to be the cysts of autotrophic dinoflagellates. Their presence in dominant numbers in wells of the seaway suggests that this was in an area of high nutrient concentrations, presumably but not necessarily related to upwelling. If the complex gravitated towards regions of high productivity, it could have occupied a coastal zone or been near to the shelf margin, as discussed earlier in relation to *Palaeoperidinium pyrophorum*. Independent studies of the intervals containing high abundances of the *Areoligera gippingensis* complex in the Labrador Margin wells (Bjarni O-82 and South Labrador N-79) infer an outer-shelf to bathyal environment (Bujak Davies Group 1987; Miller & d'Eon 1987). It is concluded that high abundances of *Areoligera* and *Glaphyrocysta* can indicate either outermost shelf or innermost shelf settings, the latter related to a transgressive regime. Accordingly such abundances must be treated with care in determining palaeoenvironments, not least since their great abundances would surely have guaranteed their dispersal in currents between environments.

Off West Greenland, the *Areoligera gippingensis* complex is abundant in the predominantly outer neritic Selandian interval in the Kangâmiut-1 and Ikermiut-1 wells (Appendices 3.17 and 3.18 respectively), and present to common in the marginal marine to inner neritic Selandian interval in Hellefisk-1, Nukik-1 and Nukik-2 (Appendices 3.19, 3.15, and 3.16 respectively; Rasmussen *et al.* 2003). Such varied environmental interpretations may also explain the occurrence patterns of the complex on the Canadian side of the seaway.

The interpretation of relatively high abundances of areoligeraceans has been mixed. Sluijs *et al.* (2008) argued that peridinioid dinocysts are less sensitive indicators of proximity to shore than gonyaulacoids; within the gonyaulacoids, these authors suggested that the most reliable indicator for the Paleocene–Eocene interval is the S/A index (*Spiniferites*/*Spiniferites* + *Areoligera*). Sluijs *et al.* (2008) argued that a high relative abundance of *Areoligera* (a low S/A ratio) indicated inner neritic palaeoenvironments, whereas a high relative abundance of *Spiniferites* specimens (a high S/A ratio) indicated outer neritic palaeoenvironments. There are two provisos with this approach: firstly, that *Glaphyrocysta* counts should be included with *Areoligera*; and secondly, that any conclusions based on this approach should, where possible, be supported by planktonic foraminiferal data. Building on the research of Sluijs *et al.* (2008), Sluijs & Brinkhuis (2009) equated the dominance of the *Areoligera* complex (presumably including *Glaphyrocysta*) with inner neritic, high-energy environments and the *Spiniferites* complex with neritic deposits, with relative abundances increasing in outer neritic palaeoenvironments (see also Brinkhuis 1994 and Pross & Brinkhuis 2005). From their study of Paleocene–Eocene assemblages on the New Jersey Shelf, Sluijs & Brinkhuis (2009) concluded that abundant *Areoligera* appears to be consistently related to third-order transgressive systems tracts, indicating rising sea level in a neritic palaeoenvironment.

In debates about the relationship between dinocyst assemblages and palaeoenvironment, one factor missing from the discussion may be evolutionary contingency. The striking acmes of the *Areoligera gippingensis* complex in the Paleocene, especially the Thanetian, may reflect ideal conditions (including climate) for the proliferation of these species at the time of their evolutionary appearance; under such conditions, the species spread widely, possibly as ecological generalists. The species were present still in the early Eocene, but did not dominate assemblages as they had in the Paleocene, possibly due to competition from other 'generalists'. Thus, environmental interpretations of the *Areoligera gippingensis* complex may be specific to particular stages in the evolutionary development of the group, and may change with time.

Open-ocean conditions persisted into the early Eocene, with the foraminifera indicating deep water (Gradstein & Srivastava 1980). There are some differences between the palaeoenvironmental interpretations for the Eocene based on dinocysts and foraminifera: the dinocysts indicate bathyal palaeoenvironments with some neritic excursions, changing to outer to middle neritic in the Priabonian, whereas the foraminifera indicate more consistent bathyal palaeoenvironments changing to outer neritic in the Priabonian (Gradstein & Williams 1976).

Collectively, what were the palaeoenvironmental extremes during the Paleocene–Eocene in the seaway as reflected in the offshore wells? This is best illustrated by comparing the data from Gjoa G-37 (Appendix 2.6), Hekja O-71 (Appendix 2.5) and Ralegh N-18 (not illustrated here). In Gjoa G-37, assemblages from the Paleocene and Eocene suggest predominantly outer neritic palaeoenvironments, with open-ocean interludes, presumably denoting deeper water palaeoenvironments. In contrast, assemblages of the same age in Hekja O-71 and Ralegh N-18 suggest primarily marginal marine to inner neritic palaeoenvironments, with occasional episodes of non-marine deposition. Thus, the lowermost Eocene succession in Ralegh N-18 contains common specimens of the freshwater alga *Pediastrum* (Nøhr-Hansen 2004a) and common *Taurodinium granulatum*, which are assumed to be autochthonous. *Taurodinium granulatum* is also common in Hekja O-71, together with scattered specimens of *Pediastrum*. However, the rare specimens of these taxa in Gjoa G-37 (Nøhr-Hansen in Sønderholm *et al.* 2003b; Nøhr-Hansen 2004a) are inferred to have been transported into the depositional environment. *Taurodinium granulatum* has previously been recorded as "Gen et. sp. Indet" by Hjortkjær (1991) and Piasecki *et al.* (1992) from the syn-volcanic, probably lacustrine Selandian deposits at Assoq and on Disko, West Greenland, and from pre-basaltic Thanetian–?Ypresian lacustrine deposits from the Kangerlussuaq Basin in south-eastern Greenland (Nøhr-Hansen 2012). Thus, the common occurrence of freshwater algae and lacustrine to brackish-water dinocysts in Hekja O-71 and Ralegh N-18 suggests a position close to the Paleocene–Eocene palaeoshoreline. The contrast between the Hekja O-71 and Ralegh N-18 wells on the one hand and the Gjoa G-37 well on the other, is compatible with their relative positions within the basin (Figs 1, 2).

The same pattern has also been recognised in offshore West Greenland wells. Rasmussen *et al.* (2003) showed that *Paralecaniella indentata* is common in the lowermost Thanetian and lowermost Ypresian of Hellefisk-1, Nukik-1 and Nukik-2. Nøhr-Hansen (2004a) recognised an acme of *Paralecaniella indentata* at the same stratigraphic level in Ralegh N-18. *Paralecaniella* appears to be most abundant in marginal marine successions but has a tolerance for inner neritic conditions, presumably in the vicinity of river estuaries or deltas, where there is an influx of freshwater (Elsik 1977; Powell *et al.* 1996). However, Lebedeva (2010) considered that *Paralecaniella* preferred coastal, high-energy marine settings of normal salinity, with sufficient oxygen levels. An alternative explanation is that the specimens were washed in and are thus allochthonous (Rasmussen *et al.* 2003). The common occurrence of the freshwater alga *Pediastrum* at the same stratigraphic level in the outer neritic deposits in Kangâmiut-1 and Ikermiut-1 was interpreted as evidence of redeposition, probably by turbidites (Rasmussen *et al.* 2003).

An intriguing aspect of Labrador Sea – Davis Strait palynomorph assemblages is the common occurrence of *Azolla* in some Ypresian samples – especially in Gjoa G-37, where it occurs with common specimens of the freshwater alga *Pediastrum* between 1890 and 2040 m (Nøhr-Hansen in Sønderholm *et al.* 2003b; Appendix 3.13). The same pattern is seen in the Ypresian of Ralegh N-18 (Appendix 3.12), but only *Pediastrum* is common in the Ypresian of Hekja O-71 (Appendix 3.11; Nøhr-Hansen 2004a). *Azolla* is a small moss-like, freshwater to brackish-water fern famous for its nitrogen-fixing capability (van Kempen *et al.* 2012). Its modern distribution indicates that it prefers much warmer temperatures than occur today in the Labrador–Baffin Seaway and suggests the possibility of extensive freshwater lakes. Massive concentrations of dead *Azolla* accumulating at the bottom of the lakes could be preserved in sediment, and given the right combination of time and temperature, may yield significant hydrocarbon source rocks. The occurrences of *Azolla* in Labrador Sea – Davis Strait wells are restricted to a narrow time interval at the top of the Ypresian. *Azolla* has not been recorded in the offshore West Greenland wells.

Brinkhuis *et al.* (2006) recorded numerous specimens of *Azolla* in a core from the eastern end of the Lomonosov Ridge in the Arctic Ocean; they suggested that the Ypresian records of *Azolla* in the Labrador–Baffin Seaway were potentially derived from natural freshwater overspill from the Arctic Ocean, which they proposed was periodically characterised by fresh surface waters. We consider it difficult, however, to visualise a body of water as large as an ocean with a surface that would be calm for long enough to allow *Azolla* to become established. Even if Brinkhuis *et al.* (2006) are correct in postulating episodic fresh surface waters in the Arctic during the Ypresian, outlets into the Atlantic Ocean would probably have been via shallow seas adjacent to East Greenland, not via the Labrador–Baffin Seaway. This observation is based on paleogeographic maps in Monger *et al.* (2014) and Fensome *et al.* (2014; Fig. 10). *Azolla* occurs in wells off the Canadian margin but has not been found in any wells off West Greenland. This distribution may reflect differential drainage into the seaway, such that large rivers on the Canadian side introduced *Azolla* into the seaway whereas rivers on the Greenland side were too small or non-existent.

The palynomorph data indicate a dramatic change in palaeoenvironments from the early to the middle and late Eocene of the Labrador Margin and western Davis Strait, resulting from, or accentuated by, either a significant drop in sea level or uplift. This ultimately led to inner neritic to marginal marine conditions in the Rupelian. The changes may be related to one or more of three events: the end of the drifting phase (within Anomaly 13, approximately at the Priabonian–Rupelian boundary), the development of the Antarctic Ice Sheet (Zachos *et al.* 2008), or global (eustatic) sea-level fall in the Oligocene (Haq *et al.* 1977, 1987). Throughout the rest of the Oligocene and during the Miocene to early Pliocene interval, the most useful indicator of shifting palaeoenvironments is the miospore/dinocyst ratio. This and other evidence indicate that inner neritic to marginal marine palaeoenvironments prevailed in the vicinity of several wells: Bjarni O-82 (Appendix 2.1), Snorri J-90 (Appendix 2.3), and South Labrador N-79 (Appendix 2.2) in the Hopedale Basin; Gilbert F-53 (Appendix 2.4), and Hekja O-71(Appendix 2.5) in the Saglek Basin (Figs 1, 2). In offshore West Greenland, palynomorphs from the Qulleq-1 well indicate that the middle Miocene succession was deposited in an open-marine palaeoenvironment represented by the most diverse dinocyst assemblages of the entire Neogene; a similar setting is indicated for the upper Miocene to lower Pliocene succession based on the common presence of *Impagidinium* spp. (Piasecki 2003). The peak in dinocyst species richness and abundance corresponds to the end of the middle Miocene climatic optimum (Zachos *et al.* 2001).

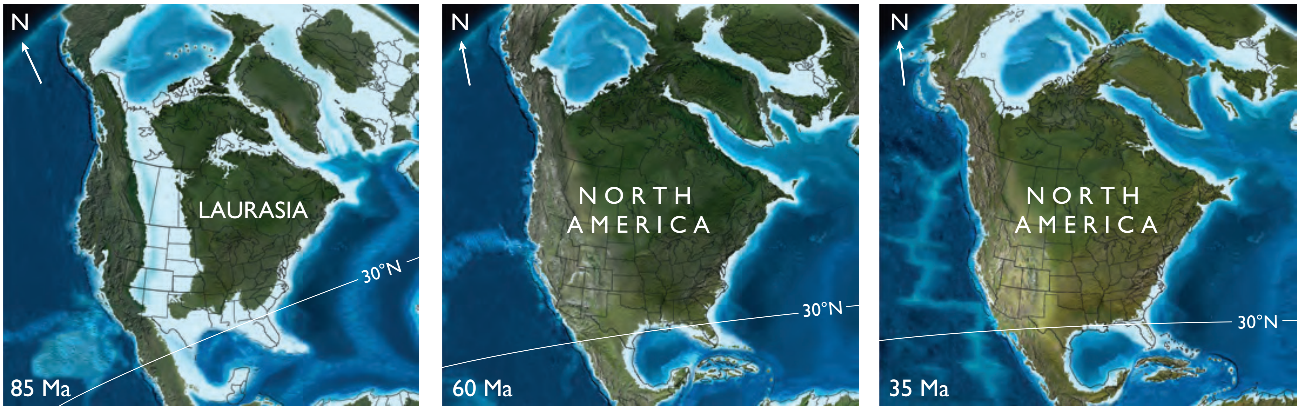

Fig. 10. Palaeogeography of North America for the Late Cretaceous (85 Ma), Paleocene (60 Ma) and Eocene (35 Ma), showing the evolution of the Labrador–Baffin Seaway during that timespan. According to these reconstructions, the seaway was not directly connected with the Arctic basin during the early Cenozoic, which has a major bearing on the source of the *Azolla* specimens found in some wells (see text for discussion). From Monger *et al.* (2014) and Fensome *et al.* (2014); maps courtesy of Ron Blakey.

Palaeogeography, palaeoclimatology and palaeoceanography

During the Cretaceous and Palaeogene, the Labrador Sea region was considerably warmer than it was during the Neogene. Evidence is sparse for the Cretaceous, with exception of the Maastrichtian. The initial findings were by Gradstein & Srivastava (1980), who recognised two principal influxes of warm-temperate planktonic foraminifera – during the Maastrichtian and in the early–middle Eocene. Later research drew attention to the several transient global warming or hyperthermal phases in the late Paleocene and early Eocene, especially the Paleocene–Eocene Thermal Maximum (PETM; Kennett & Stott 1991; Koch *et al.* 1992). Zachos *et al.* (2008) highlighted several other warm phases, including the two-million-year-long Early Eocene Climatic Optimum at 53–51 Ma, the shorter Mid-Eocene Climatic Optimum at around 41 Ma, and the fleeting Eocene Thermal Maximum 2 at around 52.5 Ma. Cooler episodes also occurred in the Eocene, especially towards the end of the epoch, with the onset of Antarctic glaciation at 35 Ma. In the Neogene, a moderate climatic optimum occurred in the middle Miocene.

Early Cretaceous dinocyst assemblages in the Labrador Sea region are too sparse to give any clues to the climatic conditions existing there at that time. The more northerly early Late Cretaceous assemblages show some differences from those on the Scotian Margin and Grand Banks; most notable is the presence of *Heterosphaeridium difficile,* which is common in the Coniacian section in Bjarni O-82 and South Labrador N-79 in the Hopedale Basin, in shallow cored boreholes from western Baffin Bay (MacLean *et al.* 2014), and in upper Turonian – lower Coniacian strata from the Umiivik-1 borehole on Svartenhuk Halvø (Dam *et al.*1998; Figs 1, 2). The available records (e.g. Nøhr-Hansen 1996; Dam *et al.*1998; Pedersen & Nøhr-Hansen 2014; Radmacher *et al.* 2014) and unpublished data (G.L. Williams) from Upper Cretaceous rocks of Bylot Island and Baffin Bay suggest that *Heterosphaeridium difficile* is a high-latitude species. The assemblages also contain many of the species described by Manum & Cookson (1964) from Graham Island, Arctic Canada, who also recorded *Heterosphaeridium difficile*.

Similarities with other dinocyst assemblages can be determined from Lentin & Williams (1980), who described provincialism in Campanian peridinialean dinocysts. These authors defined three assemblages, which they related to climatic belts: the Malloy or tropical–subtropical suite, the Williams or warm-temperate suite and the McIntyre or Boreal suite. Common components of the Malloy suite at generic level include *Andalusiella*, *Cerodinium*, *Lejeunecysta* and *Senegalinium*; the Williams suite is characterised by *Alterbidinium*, *Isabelidinium, Spinidinium*, *Trithyrodinium*, and smaller species of *Chatangiella*. Diagnostic taxa of the McIntyre suite are *Laciniadinium* and the larger taxa of *Chatangiella*. The McIntyre suite is present in Arctic Canada, the Mackenzie Delta, Saskatchewan, Alberta, South Dakota, Wyoming, the northern North Sea (Costa & Davey 1992) and West Greenland (Nøhr-Hansen 1996). Expanding upon the concepts of Lentin & Williams (1980), Mao & Mohr (1992) defined a Helby suite, which included diagnostic dinocyst taxa for the Campanian–Maastrichtian interval in the higher latitudes of the Southern Hemisphere. The Helby suite is characterised by high abundances of the peridinioid dinocyst genera *Isabelidinium*, *Chatangiella* and *Nelsoniella*. As in the McIntyre suite, specimens of *Chatangiella* are large and there are few specimens of *Andalusiella* and *Senegalinium*.

Campanian assemblages on the Labrador Margin seem to fall into the Williams suite, although large *Chatangiella* specimens (characteristic of the McIntyre suite) occasionally occur. Dinocyst assemblages from the Buchan Gulf (Fig.1) on the north-eastern Baffin Margin show McIntyre-suite affinities (MacLean & Williams 1980; Balkwill *et al.* 1990; MacLean *et al.* 2014), but with some elements of the Williams suite. These occurrences indicate that the climate in Baffin Bay during some periods of the Late Cretaceous was warm temperate.

According to Gradstein & Srivastava (1980), the Campanian–Maastrichtian planktonic foraminifera from Nuussuaq show affinities with coeval assemblages from the North Atlantic; this is based on the common occurrence of some poorly preserved taxa. These authors also noted, however, that Late Cretaceous climates were more equable than those of today and that species were cosmopolitan, with no specific high-latitude taxa. Cenomanian to Maastrichtian ammonites have affinities with coeval taxa from the Western Interior Seaway of North America and the Atlantic (Birkelund 1965; Williams & Stelck 1975), thus partially paralleling the distributions shown by the dinocysts.

Maastrichtian strata of the Labrador Margin are characterised by the presence of *Palynodinium grallator* and *Isabelidinium cretaceum*. *Palynodinium grallator* is a ubiquitous species but *Isabelidinium cretaceum* is most abundant at higher latitudes (Askin 1988; Bowman *et al*. 2012). In their study of Southern Ocean ODP sites from Maud Rise and the Georgia Basin, Mohr & Mao (1997) illustrated the taxon *Manumiella cretacea* subsp. *gravida*, which is similar to some of our specimens. Mohr & Mao (1997) considered *Manumiella cretacea* subsp. *gravida* to be an endemic Southern Ocean taxon and interpreted their assemblages to indicate cooler water conditions. Thus, it seems reasonable to assume the same conditions existed in the Labrador Sea at that time.

A similar possible analogy between high southern and northern occurrences has been described by Nøhr-Hansen & Dam (1997) from the uppermost Maastrichtian strata at Nuussuaq, onshore West Greenland. Here, *Palynodinium grallator* occurs with abundant miospores and a peak of *Manumiella* sp. that is very similar to *Manumiella* assemblages described from Seymour Island, Antarctica, by Askin (1988) and which she considered were late Campanian to late Paleocene in age. Askin (1988) erected a Zone 1, characterised by *Isabelidinium cretaceum* and which she considered Campanian. *Isabelidinium cretaceum* did not occur higher in the Seymour Island section, being replaced primarily by *Manumiella* species. The occurrence of *Isabelidinium cretaceum* in the Labrador Sea suggests a mirror-image, high-latitude Northern Hemisphere record. In a recent palynological study of Seymour Island assemblages, Bowman *et al.* (2012) proposed a formal zonation with two late Maastrichtian zones, including two subzones, and one early Danian zone. These authors recognised Zone 1 of Askin (1988), but considered the age to be ?late Maastrichtian. Bowman *et al.* (2012) proposed a South Polar Province for the latest Maastrichtian – earliest Palaeogene, characterised by species of *Manumiella*, *Batiacasphaera reticulata* and *Tanyosphaeridium*. Again, it seems reasonable for us to consider an equivalent Northern Hemisphere province during the same time span, although this may have been somewhat warmer than its southern equivalent because of the proximity of the Arctic Ocean. An almost monospecific assemblage of *Manumiella seelandica* was reported from Seymour Island by Askin & Jacobson (1996) and interpreted to represent marginal marine to shallow-shelf conditions; Habib & Saeedi (2007) considered *Manumiella*-rich assemblages to reflect cooling during regression at the close of the Maastrichtian.

Determination of Palaeogene climates using dinocysts has made considerable advances in recent years (Jaramillo & Oboh-Ikuenobe 1999; Sluijs *et al.* 2005; Sluijs *et al*. 2008; Sluijs & Brinkhuis 2009). We build on these earlier studies, incorporating taxa that seem to be endemic to mid- or high latitudes, as noted above and as Zonneveld *et al.* (2013) has shown for modern environments. In the Danian, the dinocyst *Trithyrodinium* is common to abundant in the following wells: Bjarni O-82, North Leif I-05, Ogmund E-72 and South Labrador N-79 in the Hopedale Basin (Figs 1, 2); Gilbert F-53 and Skolp E-07 in the Saglek Basin (Figs 1, 2). Lentin & Williams (1980) included *Trithyrodinium* in the Williams suite for the Campanian. Nøhr-Hansen & Dam (1997) and Nøhr-Hansen *et al.* (2002) recorded abundant *Trithyrodinium evittii* pulses just above the Cretaceous–Paleocene boundary at Nuussuaq. Smit & Brinkhuis (1996) and Nøhr-Hansen & Dam (1999) have shown that this species preferred lower latitudes in the Late Cretaceous but later migrated to higher latitudes, suggesting increasing sea-surface temperatures at high latitudes in the early Danian. The abundance of *Trithyrodinium* in higher latitudes was confirmed by Nøhr-Hansen *et al.* (2002), who defined an early Danian *Trithyrodinium evittii* Zone for the succession in the Nuussuaq Basin, by Bowman *et al.* (2012), who defined an Early Danian *Trithyrodinium evittii* Zone for rocks on Seymour Island, and by Willumsen & Vajda (2010) in a study of New Zealand dinocyst assemblages. Gradstein & Srivastava (1980) found that the foraminifera of the Labrador Margin and Nuussuaq reflected Atlantic water-mass incursions and that these are supported by mollusc, echinoid and coral faunas on Nuussuaq. Gradstein & Srivastava (1980) considered these observations to indicate temperate (warmer) climatic conditions in the Labrador Sea region during the Danian; such observations are in accordance with the idea that *Trithyrodinium* testifies to more temperate conditions in the Labrador–Baffin Seaway during the Danian.

One species that seems to occur consistently in higher latitude samples is *Palaeocystodinium bulliforme*, first described from the Paleocene of Bylot Island by Ioannides (1986). In wells encountering Selandian sediments, such as in Bjarni O-82 and South Labrador N-79 in the Hopedale Basin and Gilbert F-53 and Hekja O-71 in the Saglek Basin (Figs 1, 2), *Palaeocystodinium bulliforme* is common. It is also common in middle to late Danian and ?early Selandian successions in the Nuussuaq Basin (Nøhr-Hansen *et al.* 2002) and occurs in Danian? and Selandian sediments on Bylot

Island (G.L. Williams, unpublished data). *Palaeocystodinium bulliforme* is also present in Selandian strata in warmer climes farther south, being restricted to the Selandian in Morocco (H. Slimani, personal communication 2015) and having its LO in the uppermost Selandian on the Scotian Margin (Fensome *et al.* 2008). The variation in ranges between regions may be indicative of its origination in more northerly latitudes.

The existence of warm climatic conditions in the Ypresian and more temperate conditions in the middle Eocene (Sluijs *et al.* 2008; Zachos *et al.* 2008; Schoon *et al.* 2013) had an impact on the Labrador–Baffin Seaway, as demonstrated by the presence of nannofossils recovered from the Kangâmiut-1 well (Sheldon 2003). Further evidence for a warm interlude is provided by the influx of the dinocyst *Apectodinium homomorphum* close to the Paleocene–Eocene boundary in Hekja O-71, Hellefisk-1, North Leif I-05, Ogmund E-72 and South Labrador N-79. Bujak & Brinkhuis (1998) considered *Apectodinium homomorphum* to be a warmer water species. These findings were confirmed in studies of stable isotope and biogeochemical palaeotemperature indicators (Sluijs *et al.* 2006; Zachos *et al.* 2006; Schoon *et al.* 2013). Crouch *et al.* (2001) showed that the earliest appearance of *Apectodinium*-dominated assemblages seems to be synchronous on a global scale. One *Apectodinium* peak occurred during the Paleocene–Eocene Thermal Maximum (PETM) at 55 Ma, which lasted for about 220 000 years. This peak can be correlated with a negative carbon-isotope excursion (CIE), a benthic foraminifera extinction event and the calcareous nannofossil zonation (Crouch *et al.* 2001). According to these authors, the *Apectodinium* influx reflects higher sea-surface temperatures and a major increase in marginal marine surface-water productivity. Based on the studies of Iakovleva *et al.* (2001), Crouch *et al.* (2003), Sluijs *et al.* (2008) and others, a marked decline in *Apectodinium* abundances towards the end of the PETM may record a corresponding temperature decrease and/or a global regression. It is generally agreed that a maximum flooding surface, defining the culmination of a global transgression, partially coincides with the PETM, although the onset of sea-level rise is thought to have predated the PETM by a few thousand years. In the Labrador–Baffin Seaway, *Apectodinium* spp. are common to abundant in the uppermost Thanetian in Nukik-2 (Appendix 3.16), Kangâmiut-1 (Appendix 3.17), Ikermiut-1 (Appendix 3.18), Hekja O-71 (Appendix 3.11), Ralegh N-18 (Appendix 3.12), Gjoa G-37 (Appendix 3.13), North Leif I-05 (Appendix 3.1), Ogmund E-72 (Appendix 3.6) and South Labrador N-79 (Appendix 3.4).

Several dinocyst taxa indicate warm-water conditions in the Ypresian; examples are species of *Homotryblium*, which are common in parts of the Ypresian section in the following wells: Bjarni O-82 (Appendix 3.3), North Leif I-05 (Appendix 3.1) and Snorri J-90 (Appendix 3.5) in the Hopedale Basin; Gilbert F-53 (Appendix 3.9) in the Saglek Basin; and Kangâmiut-1 (Appendix 3.17) and Nukik-1 (Appendix 3.15) in offshore West Greenland (Figs1, 2). *Homotryblium* is a warm-water genus commonly assumed to favour restricted settings with increased salinity, and thus characterising inshore, lagoonal palaeoenvironments (Brinkhuis 1992, 1994; de Verteuil & Norris 1996). However, in a study of early Oligocene dinocyst assemblages from the Upper Rhine Graben of Germany, Pross & Schmiedl (2002) developed a model proposing different settings for what they termed the *Homotryblium* assemblage. They found that the *Homotryblium* assemblage predominated in nearshore palaeoenvironments where salinity was increased. In these palaeoenvironments, dinocyst species richness was lower. To explain these fluctuations, Pross & Schmiedl (2002) postulated that dominance of the *Homotryblium* assemblage was related to relatively dry periods with reduced runoff and potentially strong evaporation, leading to high salinity conditions in nearshore palaeoenvironments. According to Zonneveld *et al.* (2013), the related modern species *Polysphaeridium zoharyi* occupies coastal, fully marine, subtropical to tropical regions, which may be characterised by high productivity and high surface-water salinities. Specimens of *Homotryblium* are common to abundant in the 1890–1930 m interval in Gjoa G-37. The presence of the freshwater fern *Azolla* in Hekja O-71, Ralegh N-18 and Gjoa G-37 (Appendices 3.11 to 3.13) provides further evidence for a warm, humid climate around the Ypresian–Lutetian boundary.

Counts for *Homotryblium* and *Polysphaeridium* in the Ypresian and their absence from middle Eocene and younger rocks indicate that climatic warming was fleeting in the Labrador Sea. Further confirmation is provided by the position of the LO of *Diphyes colligerum* at the Lutetian–Bartonian boundary in the Labrador–Baffin Seaway. According to Brinkhuis & Biffi (1993) and Bujak & Mudge (1994) this species was temperature-sensitive, preferring warmer water palaeoenvironments, explaining its occurrence in the Rupelian in Italy. Dinocyst species richness takes a dramatic plunge in Labrador Margin wells in the middle Eocene. Consequently, the numbers of species and specimens decline throughout the remainder of the Cenozoic, and the remaining taxa are either ubiquitous or higher-latitude indicators. Much of this decline, which was probably related to the general cooling trends during the transition from a Greenhouse to an Icehouse world (Zachos *et al.* 2001, 2008), mirrors the global decline in dinocyst species richness during the Cenozoic, as shown by MacRae *et al.* (1996).

Dinocyst assemblages from the Eocene–Oligocene strata of ODP Site 647A in the southern Labrador Sea (Figs 1, 2) provide some clues to Palaeogene oceanic conditions. From a study of ODP assemblages, Head & Norris (1989) concluded that evidence existed for a proto-Gulf Stream in the middle Eocene. The ODP assemblages included taxa known only from the southwestern Atlantic, eastern United States, Norwegian Sea, Belgium and Australia. Such a distribution could be best explained by the pattern of oceanic currents. A cooling trend in the late Eocene – Oligocene is indicated by an influx of colder-water taxa, including *Gelatia inflata, Svalbardella* and protoperidiniaceans (Head & Norris 1989). This cooling trend in the late Eocene – early Oligocene is also a characteristic of high latitudes in the Southern Hemisphere (Guerstein *et al.* 2008, 2010; Houben *et al.* 2013) and probably reflects cooling conditions in the Oligocene, resulting from a reduction in atmospheric pCO_2, which allowed development of a permanent ice sheet in Antarctica (Hren *et al.* 2013).

The relative decline in dinocyst species richness in Labrador Margin wells is accompanied, especially in the Oligocene and Neogene, by a drop in angiosperm pollen species richness (Williams 1986). However, conifer pollen in the Neogene, primarily *Pinuspollenites*, are common. General trends suggest rapid and widespread cooling for the Labrador Sea, triggered in part by fluctuations in oceanic-circulation patterns. At ODP Site 646, also in the Labrador Sea (Figs 1, 2), the late Miocene – early Pliocene dinocyst associations reflect predominantly temperate to cool surface waters, with *Impagidinium pallidum* and diverse protoperidiniaceans (Head *et al.* 1989a). Zonneveld *et al.* (2013) noted that *Impagidinium pallidum* is primarily restricted to higher latitudes with high concentrations in Arctic and Antarctic regions, whereas of the two species of *Protoperidinium*, *P. americanum* is a coastal sub–polar to tropical form whereas *P. monospinum* is characteristically found in “full marine, tropical to equatorial upwelling areas of NW Africa” (Zonneveld *et al.* 2013, p. 131). These observations could indicate mixing of warm-temperate and Arctic water in the Labrador Sea, with the West Greenland Current already in place – a situation not dissimilar to present-day conditions.

According to de Vernal & Mudie (1989a), the early Miocene assemblages at ODP Site 645 in Baffin Bay (Figs 1, 2) seem to indicate cool-temperate surface waters. De Vernal & Mudie (1989a, b) found that similar conditions persisted into the Pliocene–Pleistocene at both Site 646 and Site 647 (Figs 1, 2). There was a marked drop in species richness in the middle and late Miocene, however, accompanied by an increase in terrigenous debris. Head *et al.* (1989b) related these changes to the onset of colder-water conditions and the establishment of circulation patterns in Baffin Bay similar to those of today. However, *Dapsilidinium pastielsii*, one of the species recorded by these authors, was considered to be a warmer water species by Head & Westphal (1999), who noted that its latitudinal occurrences contracted in the late Miocene and Pliocene; they attributed this to the cooling of the North Atlantic in the late Miocene and the evolution of the cold Labrador Current. The persistence of *Dapsilidinium pastielsii* into the middle Miocene is probably a reflection of the Mid-Miocene Climatic Optimum (Zachos *et al.* 2008).

Piasecki (2003) concluded that the dinocyst assemblages in Qulleq-1 on the West Greenland Margin (Figs 1, 2; Appendix 3.14) were comparable to North Atlantic assemblages, but had higher latitude elements. The Serravallian samples reflected warmer water, signifying the Mid-Miocene Climatic Optimum. In contrast, the Pliocene was marked by depleted dinocyst counts reflecting the progressively deteriorating climate.

Schreck *et al.* (2012, 2013), in their study of the dinocyst assemblages from an almost continuous middle Miocene through Pliocene section in ODP Site 907A in the Iceland Sea, recorded high marine productivity in the middle Miocene, with a diminution toward the impoverished assemblages of the late Pliocene. We conclude that the proto-East Greenland Current was well developed by about 9 Ma. The establishment at around 4.5 Ma of the modern East Greenland Current, which would presumably have accelerated the influence and impact of the Labrador Current, may explain the low abundance and species richness of the dinocyst assemblages.

De Vernal & Mudie (1989a) determined that the Pliocene–Pleistocene dinocysts at Site 645 (Figs 1, 2) included Boreal and cool-temperate taxa. These data suggest that the major cooling occurred relatively late in the Cenozoic history of Baffin Bay. The waning influence of the Gulf Stream and the development of the Labrador Current were important events in the evolution of the Labrador Sea. Based on foraminiferal data from a study of DSDP Sites 111 and 112, Poore & Berggren (1974) considered the cut-off of the Gulf Stream to have occurred in the middle–late Pliocene.

Conclusions

A new biostratigraphic framework has been developed for the Aptian (Lower Cretaceous) to Pliocene–Pleistocene of the Labrador–Baffin Seaway. This framework is based on 187 bioevents for taxa of dinocysts, miospores, fungal spores and *Azolla*; these define 106 bioevent horizons, mostly last occurrences, but including some local and regional peak- or common-occurrence events. Also incorporated are additional data from previous studies by Piasecki (2003) and Pedersen & Nøhr-Hansen (2014). Most events are concentrated in the Campanian to Rupelian interval. Integration of the palynological data from wells on both margins of the Seaway provides the first broad biostratigraphic correlation of Mesozoic–Cenozoic strata of the region.

Detailed biostratigraphic evidence has confirmed the following hiatuses: pre-Aptian in the Hopedale Basin; pre-Albian in the Saglek Basin; Albian–Turonian in some wells of the Hopedale Basin; Turonian–Santonian/Campanian in some areas; pre-Campanian and late Campanian–Thanetian on the Greenland Margin; late Maastrichtian and Danian in some wells of the Hopedale Basin and in the Saglek Basin; Selandian in part in the Hopedale Basin, in total in the Saglek Basin and in two wells on the West Greenland Margin; late Ypresian and/or Lutetian on both sides of the seaway; Oligocene to middle Miocene of considerable variability on both margins, with all of the Oligocene and the lower Miocene missing in all the West Greenland Margin wells; middle to late Miocene on the western side (Figs 7–9). On the Canadian margin, these hiatuses can be matched in part with the five recognised regional unconformities of McWhae (1981) as follows: the pre-Aptian–Albian hiatus of this study is presumed to correlate with the Labrador Unconformity; the Aptian/Albian–Turonian hiatus represents the Avalon Unconformity; the Bylot Unconformity is represented by the Maastrichtian–Selandian hiatus and the 'base-Tertiary unconformity' in the Jeanne d'Arc Basin (Sinclair 1988); the Oligocene to middle Miocene hiatus of this study may be equivalent to the Baffin Bay Unconformity but we regard it as resulting from the late Oligocene drop in sea level, which is not mentioned by McWhae *et al.* (1980); and finally the middle to late Miocene hiatus described here matches the proposed age of the Beaufort Unconformity. McWhae (1981) only recognised these five unconformities and restricted them to specific ages. This does not fully match our findings since we recognise seven significant hiatuses which furthermore are of greater duration than indicated by McWhae (1981). The intra-Selandian and the Lutetian hiatuses documented here are not readily correlated with the regional unconformities of McWhae (1981), but may match additional seismic unconformities reported by Dickie *et al.* (2011).

On the West Greenland Margin, the hiatuses are fewer and only partly conform to those on the Canadian margin. The absence of a pre-Santonian section in part reflects the depth of the wells, since seismic data indicate that older strata are present. An apparent unconformity separating the Appat seismic sequence from the overlying Kangeq seismic sequence, probably equates with the Avalon Unconformity. The late Campanian to Selandian hiatus in two wells and the absence of the Danian and most or all of the Selandian in the other four wells represent the Bylot Unconformity. Thus it appears that the Bylot Unconformity is equivalent to the 'base-Tertiary unconformity' recognised by Dalhoff *et al.* (2003). Alternatively, following Dickie *et al.* (2011), the Bylot Unconformity could be restricted to the Selandian. The intra-Selandian hiatus recognised here, however, demonstrates the difficulty of identifying the Bylot Unconformity *sensu stricto*. On the West Greenland margin, Dalhoff *et al.* (2003) also mapped a Mid Eocene Unconformity, which we consider equivalent to our Lutetian hiatus. In three of the wells, the overlying sediments are middle Miocene in age. In two other wells the Bartonian is overlain by middle Miocene sediments and in one the Priabonian is overlain by middle Miocene sediments. These hiatuses could be regarded as correlating with the Baffin Bay Unconformity, but the time spans are significantly greater than that recorded by McWhae (1981) on the Canadian margin, and they are likely to represent composite unconformities.

Palynomorph assemblages show that most of the Aptian and Albian sediments on the present-day Labrador Margin were deposited in marginal marine to lagoonal palaeoenvironments, punctuated by a shallow marine episode in the Aptian. A marine transgression starting in the Cenomanian–Turonian led to the most offshore, presumably deepest water palaeoenvironments in the Campanian – late Maastrichian, although this conclusion seems to conflict with the hiatus between the Cretaceous and Cenozoic sediments in many wells, especially on the West Greenland Margin. However, the Cretaceous–Palaeogene boundary and upper Maastrichtian and Danian–Selandian strata occur in the Nuussuaq Basin (Nøhr-Hansen & Dam 1997; Dam *et al.* 2009). Outer neritic to open-ocean conditions persisted throughout the Paleocene and Ypresian and into the Lutetian, an interval corresponding to a time of sea-floor spreading in the Labrador–Baffin Seaway. The onset of shallowing, probably in the late Lutetian, continued through the Priabonian and into the Rupelian, when marginal marine to inner neritic palaeoenvironments predominated. Throughout the rest of the Oligocene and in the Neogene, inner neritic palaeoenvironments alternated with marginal marine conditions.

Dinocysts indicate that climatic conditions in the Labrador–Baffin Seaway region, which had been relatively temperate in the Cretaceous, varied dramatically in the Cenozoic. The Palaeogene was a time of increasingly warmer climate, a thermal maximum being reached around the Paleocene–Eocene boundary, reflecting the global thermal event at this time. Warm to hot conditions prevailed throughout the Ypresian, but began to cool in the Lutetian and cooling accelerated in the Priabonian and Rupelian, a trend observed globally (Zachos *et al.* 2008). Temperatures generally declined throughout the Neogene, reaching a low in the Pleistocene.

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Appendix I

Names of taxa used in text with authorships

References are not included in the current reference list (unless otherwise used in text) but can be found as follows:

^ reference in Pierce (1961)
# reference in Singh (1971)
† reference in Jansonius & Hills (1976 and updates)
> reference in Dörhöfer (1977)
†† reference in Singh (1983)
** reference in Fensome *et al.* (1990)
^^ reference in Zonneveld *et al.* (2013)
* reference in Fensome *et al.* (2016)
§ reference in *http://botany.si.edu/ing/*
*** reference in *http://fossilworks.org*
All others can be found in *http://dinoflaj.smu.ca/wiki/*

Citations are listed as they are given in these sources. Hence the order of references from the same author(s) in the same year (e.g. Eisenack 1954b in the first dinocyst below) follows that given in these sources and thus may not match that given in the companion taxonomic bulletin (Fensome *et al.* 2016) which has its own internally consistent reference list.

Dinocysts

Achilleodinium biformoides (Eisenack 1954b) Eaton 1976
Achomosphaera Evitt 1963
Achomosphaera grallaeformis (Brosius 1963) Davey & Williams 1969
Alisocysta circumtabulata (Drugg 1967) Stover & Evitt 1978
Alisocysta margarita (Harland 1979a) Harland 1979a
Alterbidinium (Lentin & Williams 1985) Fensome *et al.* 2016 *
Alterbidinium acutulum (Wilson 1967b) Lentin & Williams 1985
Alterbidinium biaperturum (McIntyre 1975) Fensome *et al.* 2016 *
Alterbidinium? *bicellulum* (Islam 1983b) Lentin & Williams 1985
Alterbidinium ioannidesii Pearce 2010
Alterbidinium varium Kirsch 1991
Andalusiella Riegel 1974
Apectodinium (Costa & Downie 1976) Lentin & Williams 1977b
Apectodinium homomorphum (Deflandre & Cookson 1955) Lentin & Williams 1977b
Apectodinium hyperacanthum (Cookson & Eisenack 1965b) Lentin & Williams 1977b
Apectodinium parvum (Alberti 1961, p. 8–9) Lentin & Williams 1977b
Apteodinium australiense (Deflandre & Cookson 1955) Williams 1978
Apteodinium spiridoides Benedek 1972
Areoligera Lejeune-Carpentier 1938a
Areoligera gippingensis Jolley 1992
Areoligera semicirculata (Morgenroth 1966b) Stover & Evitt 1978 (now *Licracysta semicirculata*)
Areosphaeridium Eaton 1971
Areosphaeridium diktyoplokum (Klumpp 1953) Eaton 1971
Arvalidinium scheii (Manum 1963) Lentin & Vozzhennikova 1990

Atopodinium haromense Thomas & Cox 1988
Axiodinium augustum (Harland 1979c) Williams *et al.* 2015
Balmula tripenta Bint 1986 (now *Nyktericysta tripenta*)
Barssidinium evangelineae Lentin *et al.* 1994
Barssidinium graminosum Lentin *et al.* 1994
Batiacasphaera reticulata (Davey 1969b) Davey 1979d
Batioladinium jaegeri (Alberti 1961) Brideaux 1975
Callaiosphaeridium asymmetricum (Deflandre & Courteville 1939) Davey & Williams 1966b
Cannosphaeropsis Wetzel 1933b
Cannosphaeropsis passio de Verteuil & Norris 1996a
Cauveridinium membraniphorum (Cookson & Eisenack 1962b) Masure in Fauconnier & Masure 2004
Cerbia tabulata (Davey & Verdier 1974) Below 1981a
Cerebrocysta bartonensis Bujak in Bujak *et al.* 1980
Cerebrocysta magna Bujak 1994
Cerebrocysta poulsenii de Verteuil & Norris 1996a
Cerodinium Vozzhennikova 1963
Cerodinium diebelii (Alberti 1959b) Lentin & Williams 1987
Cerodinium glabrum (Gocht 1969) Fensome *et al.* 2009
Cerodinium kangiliense Nøhr-Hansen & Heilmann-Clausen 2001
Cerodinium pannuceum (Stanley 1965) Lentin & Williams 1987
Cerodinium speciosum (Alberti 1959b) Lentin & Williams 1987
Cerodinium speciosum subsp. *glabrum* (Gocht 1969) Lentin & Williams 1987 (now *Cerodinium glabrum*)
Charlesdowniea columna (Michoux 1988) Lentin & Vozzhennikova 1990 (now *Piladinium columnum*)
Chatangiella (Vozzhennikova 1967) Fensome *et al.* 2016 *
Chatangiella decorosa (McIntyre 1975) Lentin & Williams 1976
Chatangiella ditissima (McIntyre 1975) Lentin & Williams 1976
Chatangiella madura Lentin & Williams 1976
Chatangiella mcintyrei Nøhr-Hansen 1996
Chiropteridium galea (Maier 1959) Sarjeant 1983
Chiropteridium gilbertii Fensome *et al.* 2016 *
Chlamydophorella nyei Cookson & Eisenack 1958
Chytroeisphaeridia hadra Fensome *et al.* 2016 *
Circulodinium distinctum (Deflandre & Cookson 1955) Jansonius 1986
Cleistosphaeridium Davey *et al.* 1966
Cleistosphaeridium ancyreum (Cookson & Eisenack 1965a) Eaton *et al.* 2001
Cleistosphaeridium diversispinosum Davey *et al.* 1966
Cleistosphaeridium palmatum Fensome *et al.* 2016 *
Cleistosphaeridium placacanthum (Deflandre & Cookson 1955) Eaton *et al.* 2001
Cleistosphaeridium polypes (Cookson & Eisenack 1962b) Davey 1969a (now *Kiokansium unituberculatum*)
Cleistosphaeridium polypetellum (Islam 1983c) Stover &Williams 1995
Cordosphaeridium Eisenack 1963b
Cordosphaeridium cantharellus (Brosius 1963) Gocht 1969
Cordosphaeridium delimurum Fensome *et al.* 2009
Cordosphaeridium fibrospinosum Davey & Williams 1966b
Cordosphaeridium funiculatum Morgenroth 1966a
Cordosphaeridium gracile (Eisenack 1954b) Davey & Williams 1966b
Cordosphaeridium minimum (Morgenroth 1966a) Benedek 1972 (now *Minisphaeridium latirictum*)
Cribroperidinium Neale & Sarjeant 1962
Cribroperidinium giuseppei (Morgenroth 1966a) Helenes 1984
Cyclonepheliium attadalicum Cookson & Eisenack 1962b
Dapsilidinium pastielsii (Davey & Williams 1966b) Bujak *et al.* 1980

Dapsilidinium pseudocolligerum (Stover 1977) Bujak *et al.* 1980
Dapsilidinium pseudoinsertum Fensome *et al.* 2016 *
Deflandrea Eisenack 1938b
Deflandrea galeata (Lejeune-Carpentier 1942) Lentin & Williams 1973
Deflandrea majae (Schiøler 1993) Fensome *et al.* 2016 *
Deflandrea oebisfeldensis Alberti 1959b
Deflandrea phosphoritica Eisenack 1938b
Dinogymnium Evitt *et al.* 1967
Dinogymnium longicorne (Vozzhennikova 1967) Harland 1973
Dinogymnium sibiricum (Vozzhennikova 1967) Lentin & Williams 1973
Diphyes brevispinum Bujak 1994
Diphyes colligerum (Deflandre & Cookson 1955) Cookson 1965a
Diphyes ficusoides Islam 1983b
Disphaerogena carposphaeropsis Wetzel 1933b
Eatonicysta furensis (Heilmann-Clausen in Heilmann-Clausen & Costa 1989) Stover & Williams 1995
Eatonicysta ursulae (Morgenroth 1966a) Stover & Evitt 1978
Edwardsiella sexispinosa Versteegh & Zevenboom in Versteegh 1995
Endoceratium dettmanniae (Cookson & Hughes 1964) Stover & Evitt 1978
Enneadocysta magna Fensome *et al.* 2007
Eocladopyxis Morgenroth 1966a
Eocladopyxis peniculata Morgenroth 1966a
Evittosphaerula? *foraminosa* Fensome *et al.* 2016 *
Fibrocysta bipolaris (Cookson & Eisenack 1965b) Stover & Evitt 1978
Gelatia inflata Bujak 1984
Geonettia de Verteuil & Norris 1996b
Gillinia hymenophora Cookson & Eisenack 1960a
Ginginodinium? *flexidentatum* Fensome *et al.* 2016 *
Glaphyrocysta Stover & Evitt 1978
Glaphyrocysta divaricata (Williams & Downie 1966c) Stover & Evitt 1978
Glaphyrocysta exuberans (Deflandre & Cookson 1955 ex Eaton 1976) Stover & Evitt 1978
Glaphyrocysta retiintexta (Cookson 1965a) Stover & Evitt 1978
Glaphyrocysta spineta (Eaton 1976) Stover & Evitt 1978
Glaphyrocysta texta (Bujak 1976) Stover & Evitt 1978
Glaphyrocysta vicina (Eaton 1976) Stover & Evitt 1978
Gonyaulacysta fastigiata Duxbury 1977
Gonyaulacysta pectinigera (Gocht 1970b) Fensome 1979
Habibacysta tectata Head *et al.* 1989b
Hapsocysta? *benteae* Nøhr-Hansen 1993
Heteraulacacysta Drugg & Loeblich Jr. 1967
Heteraulacacysta porosa Bujak in Bujak *et al.* 1980
*Heterosphaeridium C*ookson & Eisenack 1968
Heterosphaeridium bellii Radmacher *et al.* 2014
Heterosphaeridium difficile (Manum & Cookson 1964) Ioannides 1986
Heterosphaeridium heteracanthum (Deflandre & Cookson 1955) Eisenack & Kjellström 1972
Homotryblium Davey & Williams 1966b
Homotryblium abbreviatum Eaton 1976
Homotryblium tenuispinosum Davey & Williams 1966b
Hurlandsia rugara (Piasecki 1984) Lister & Batten 1988a
Hystrichokolpoma Klumpp 1953
Hystrichokolpoma bulbosum (Ehrenberg 1838) Morgenroth 1968
Hystrichokolpoma rigaudiae Deflandre & Cookson 1955

Hystrichosphaeridium Deflandre 1937b
Hystrichosphaeridium quadratum Fensome *et al.* 2016 *
Hystrichosphaeridium tubiferum (Ehrenberg 1838) Deflandre 1937b
Hystrichosphaeropsis perforata Schiøler 1993
Hystrichosphaeropsis quasicribrata (Wetzel 1961) Gocht 1976
Impagidinium Stover & Evitt 1978
Impagidinium dispertitum (Cookson & Eisenack 1965a) Stover & Evitt 1978
Impagidinium victorianum (Cookson & Eisenack 1965a) Stover & Evitt 1978
Impagidinium pallidum Bujak 1984
Impletosphaeridium apodastum Fensome *et al.* 2016 *
Invertocysta lacrymosa Edwards 1984
Isabelidinium Lentin & Williams 1977a
Isabelidinium cooksoniae (Alberti 1959b) Lentin & Williams 1977a
Isabelidinium cretaceum (Cookson 1956) Lentin & Williams 1977a
Isabelidinium magnum (Davey 1970) Stover & Evitt 1978
Isabelidinium microarmum (McIntyre 1975) Lentin & Williams 1977a
Kiokansium unituberculatum (Tasch in Tasch *et al.* 1964) Stover & Evitt 1978
Kiokansium williamsii Singh 1983
Kleithriasphaeridium mantellii (Davey & Williams 1966b) Fensome *et al.* 2016 *
Labyrinthodinium truncatum Piasecki 1980
Laciniadinium McIntyre 1975
Laciniadinium arcticum (Manum & Cookson 1964) Lentin & Williams 1980
Lejeunecysta Artzner and Dörhöfer 1978
Lentinia serrata Bujak in Bujak *et al.* 1980
Licracysta corymbus Fensome *et al.* 2007
Licracysta? *semicirculata* (Morgenroth 1966b) Fensome *et al.* 2007
Lingulodinium Wall 1967
Lithodinia Eisenack 1935
Manumiella Bujak & Davies 1983
Manumiella cretacea subsp. *gravida* (Mao Shaozhi & Mohr 1992) Lentin & Williams 1993
Manumiella seelandica (Lange 1969) Bujak & Davies 1983
Mendicodinium Morgenroth 1970
Microdinium ornatum Cookson & Eisenack 1960a
Minisphaeridium latirictum (Davey & Williams 1966b) Fensome *et al.* 2009
Nelchinopsis kostromiensis (Vozzhennikova 1967) Wiggins 1972
Nelsoniella Cookson & Eisenack 1960a
Nematosphaeropsis Deflandre & Cookson 1955
Nyktericysta Bint 1986
Nyktericysta arachnion Bint 1986
Nyktericysta davisii Bint 1986
Nyktericysta dictyophora He Chengquan *et al.* 1992
Nyktericysta tripenta (Bint 1986) Fensome *et al.* 2009
Odontochitina ancala Bint 1986
Odontochitina costata Alberti 1961
Odontochitina operculata (Wetzel 1933a) Deflandre & Cookson 1955
Odontochitina porifera Cookson 1956
Oligosphaeridium albertense (Pocock 1962) Davey & Williams 1969
Oligosphaeridium totum Brideaux 1971
Operculodinium Wall 1967
Operculodinium centrocarpum (Deflandre & Cookson 1955) Wall 1967
Operculodinium giganteum Wall 1967

Operculodinium janduchenei Head *et al*. 1989b
Operculodinium piaseckii Strauss & Lund 1992
Palaeocystodinium australinum (Cookson 1965b) Lentin & Williams 1976
Palaeocystodinium bulliforme Ioannides 1986
Palaeocystodinium golzowense Alberti 1961
Palaeohystrichophora infusorioides Deflandre 1935
Palaeoperidinium Deflandre 1934 ex Sarjeant 1967b
Palaeoperidinium pyrophorum (Ehrenberg 1838 ex Wetzel 1933a) Sarjeant 1967b
Palynodinium grallator Gocht 1970a
Perisseiasphaeridium pannosum Davey & Williams 1966b
Petalodinium condylos (Williams & Downie 1966b) Williams *et al*. 2015
Phelodinium Stover & Evitt 1978
Phelodinium kozlowskii (Górka 1963) Lindgren 1984
Phthanoperidinium Drugg & Loeblich Jr. 1967
Phthanoperidinium alectrolophum Eaton 1976
Phthanoperidinium coreoides (Benedek 1972) Lentin & Williams 1976
Phthanoperidinium geminatum Bujak in Bujak *et al*. 1980
Phthanoperidinium levimurum Bujak in Bujak *et al*. 1980
Phthanoperidinium multispinum Bujak in Bujak *et al.* 1980
Phthanoperidinium regale Bujak 1994
Phthanoperidinium stockmansii (de Coninck 1975) Lentin & Williams 1977b
Piladinium columna (Michoux 1988) Williams *et al*. 2015
Polysphaeridium Davey & Williams 1966b
Polysphaeridium zoharyi (Rossignol 1962) Bujak *et al*. 1980
Protoperidinium Bergh 1881a
Protoperidinium americanum (Paulsen 1907) Zonneveld & Dale 1994 ^^
Protoperidinium monospinum (Gran & Braarud 1930) Balech 1974 ^^
Pseudoceratium Gocht 1957
Pseudoceratium interiorense Bint 1986
Pterodinium Eisenack 1958a
Pyrophacus Stein 1883
Raphidodinium fucatum Deflandre 1936b
Reticulatosphaera actinocoronata (Benedek 1972) Bujak & Matsuoka 1986
Rhombodinium draco Gocht 1955
Rhombodinium porosum Bujak 1979
Scalenodinium scalenum Fensome *et al.* 2016 *
Schematophora speciosa Deflandre & Cookson 1955
Scriniodinium obscurum Manum & Cookson 1964 (now *Spongodinium obscurum*)
Selenopemphix brevispinosa Head *et al*. 1989c
Selenopemphix nephroides Benedek 1972
Senegalinium Jain & Millepied 1973
Senegalinium iterlaaense Nøhr-Hansen & Heilmann-Clausen 2001
Senoniasphaera inornata (Drugg 1970b) Stover & Evitt 1978
Senoniasphaera microreticulata Brideaux & McIntyre 1975
Senoniasphaera protrusa Clarke & Verdier 1967
Senoniasphaera rotundata Clarke & Verdier 1967
Simplicidinium insolitum (Eaton 1976) Fensome *et al.* 2016 *
Sirmiodinium grossii Alberti 1961
Sophismatia tenuivirgula (Williams & Downie 1966b) Williams *et al*. 2015
Spinidinium Cookson & Eisenack 1962b
Spinidinium densispinatum Stanley 1965

Spinidinium echinoideum (Cookson & Eisenack 1960a) Lentin & Williams 1976
Spiniferites Mantell 1850
Spiniferites ovatus Matsuoka 1983b
Spiniferites pseudofurcatus (Klumpp 1953) Sarjeant 1970
Spiniferites scabrosus (Clarke & Verdier 1967) Lentin & Williams 1975
Spiniferites solidago de Verteuil & Norris 1996a (=*Achomosphaera grallaeformis* (Brosius 1963) Davey & Williams 1969)
Spongodinium delitiense (Ehrenberg 1838) Deflandre 1936b
Spongodinium grossum (Manum & Cookson 1964) Fensome *et al.* 2016 *
Spongodinium obscurum (Manum & Cookson 1964) Fensome *et al.* 2016 *
Stichodinium lineidentatum (Deflandre & Cookson 1955) Williams *et al.* 2015
Stiphrosphaeridium dictyophorum (Cookson & Eisenack 1958) Lentin & Williams 1985
Subtilisphaera Jain & Millepied 1973
Subtilisphaera perlucida (Alberti 1959b) Jain & Millepied 1973
Surculosphaeridium longifurcatum (Firtion 1952) Davey *et al.* 1966
Svalbardella Manum 1960
Systematophora ancyrea Cookson & Eisenack 1965a (now *Cleistosphaeridium ancyreum*)
Talladinium pellis Fensome *et al.* 2016 *
Tanyosphaeridium Davey & Williams 1966b
Tanyosphaeridium xanthiopyxides (Wetzel 1933b ex Deflandre 1937b) Stover & Evitt 1978
Taurodinium granulatum Fensome *et al.* 2016 *
Tenua hystrix Eisenack 1958a
Thalassiphora fenestrata Liengjarern *et al.* 1980
Trichodinium castanea Deflandre 1935 ex Clarke & Verdier 1967
Trinovantedinium Reid 1977
Trithyrodinium Drugg 1967
Trithyrodinium? *conservatum* Fensome *et al.* 2016 *
Trithyrodinium evittii Drugg 1967
Trithyrodinium quinqueangulare Marheinecke 1992
Trithyrodinium suspectum (Manum & Cookson 1964) Davey 1969b
Tuberculodinium Wall 1967
Tuberculodinium vancampoae (Rossignol 1962) Wall 1967
Vesperopsis Bint 1986
Vesperopsis longicornis (Batten & Lister 1988) Harding 1990b
Vesperopsis mayi Bint 1986
Vesperopsis nebulosa Bint 1986
Wallodinium luna (Cookson Eisenack 1960a) Lentin & Williams 1973
Wetzeliella Eisenack 1938b emend. Williams, Damassa, Fensome & Guerstein in Fensome *et al.* 2009
Wetzeliella homomorpha Deflandre & Cookson 1955 (now *Apectodinium homomorphum*)
Wetzeliella parva Alberti 1961 (now *Apectodinium parvum*)
Xenascus ceratioides (Deflandre 1937b) Lentin & Williams 1973
Xenascus sarjeantii (Corradini 1973) Stover & Evitt 1978

Acritarchs and algae

Cymatiosphaera invaginata Head *et al.* 1989a **
Fromea nicosia Jansonius 1989 *
Fromea quadrangularis Fensome *et al.* 2016 *
Fromea tornatilis (Drugg 1978) Lentin & Williams 1981
Micrhystridium Deflandre 1937b
Microsphaeridium ancistroides Benedek 1972
Paralecaniella indentata (Deflandre & Cookson 1955) Cookson & Eisenack 1970b

Pediastrum Meyen 1829 *
Tetraporina Naumova 1939

Plant microfossils

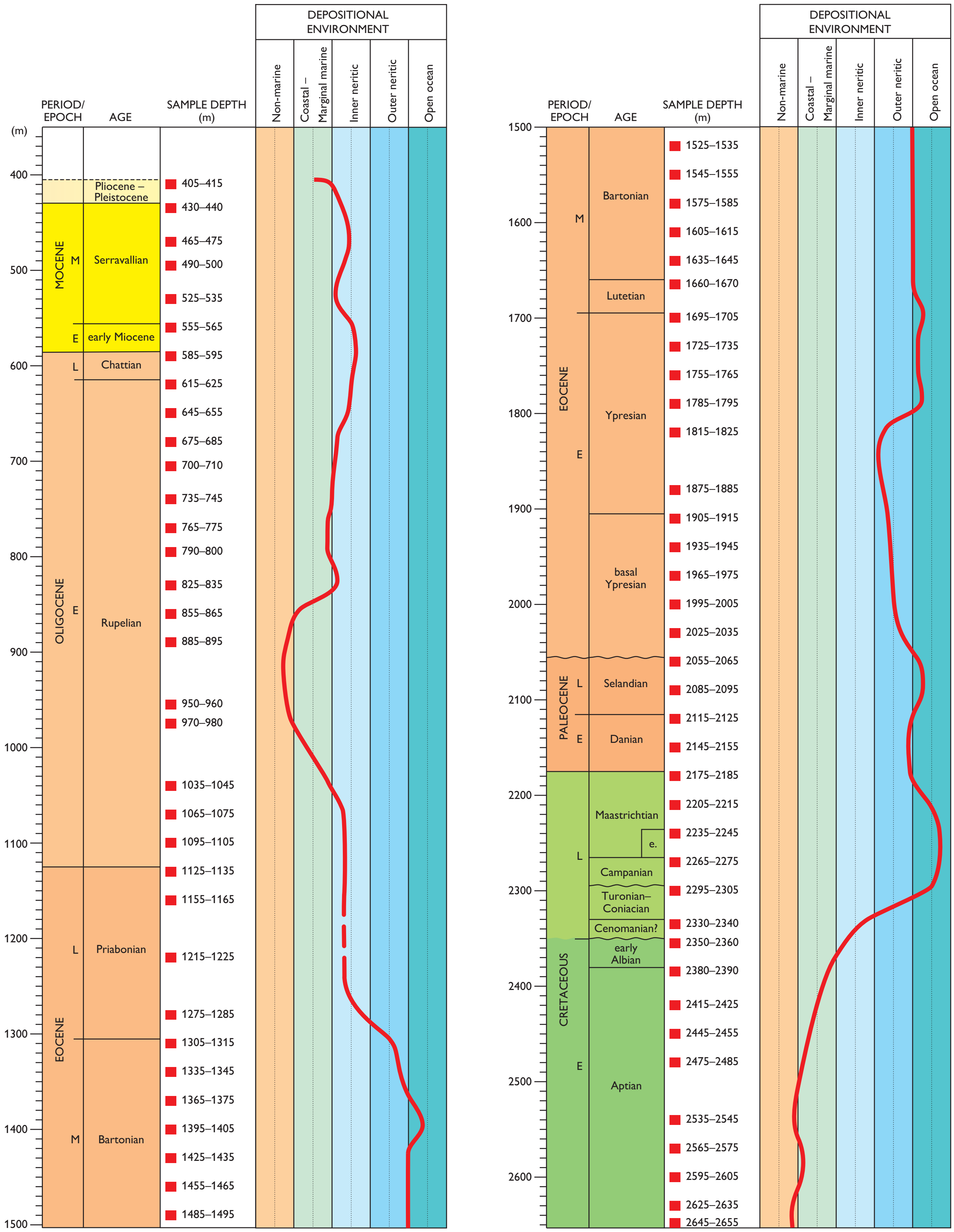
Afropollis Doyle *et al.* 1982 *
Alisporites grandis (Cookson 1953) Dettmann 1963 #
Appendicisporites jansonii Pocock 1962 #
Aquilapollenites Rouse 1957 *
Artemisia Linneaus 1753 §
Azolla Lamarck *in* Lamarck *et al.* 1783
Balmeisporites holodictyus Cookson & Dettmann 1958 †
Bombacacidites Couper 1960 †
Callialasporites dampieri (Balme 1957) Dev 1961 *
Callialasporites obrutus Norris 1969 *
Caryapollenites Raatz 1938 ex Potonié 1960 *
Cerebropollenites mesozoicus (Couper 1958) Nilsson 1958 *
Cicatricosisporites australiensis (Cookson 1953) Potonié 1956 #
Cicatricosisporites minutaestriatus (Bolkhovitina 1961) Pocock 1964 *
Cicatricosisporites ornatus Srivastava 1972 *
Cicatricosisporites reticicatricosus Döring 1965a >
Cicatricososporites eocenicus (Selling 1944) Jansonius & Hills 1976 *
Compositoipollenites Potonié 1951 ex Potonié 1960 *
Contignisporites glebulentus Dettmann 1963 #
Corsinipollenites oculusnoctis (Thiergart 1940) Nakoman 1965 *
Extratriporopollenites Pflug *in* Thomson & Pflug 1952 ex Pflug in Thomson & Pflug 1953 *
Graminidites Cookson 1947 ex Potonié 1960 *
Klukisporites areolatus Singh 1971 #
Osmundacidites wellmannii Couper 1953 *
Parvisaccites amplus Brenner 1963 *
Parvisaccites radiatus Couper 1958 *
Periporopollenites Pflug & Thomson in Thomson & Pflug 1953 *
Pilosisporites verus Delcourt & Sprumont 1955 ***
Pinus Linnaeus 1753 §
Pinuspollenites Raatz 1938 ex Potonié 1958 †
Pistillipollenites macgregorii Rouse 1962 *
Plicatella bifurcata (Singh 1964) Dörhöfer 1977 >
Quercoidites Potonié *et al.* 1950 ex Potonié 1960 *
Rugubivesiculites Pierce 1961 ^
Rugubivesiculites convolutus Pierce 1961 †
Rugubivesiculites multiplex Pierce 1961 ^
Rugubivesiculites multisaccus Singh 1983 ††
Rugubivesiculites reductus Pierce 1961 ^
Rugubivesiculites rugosus Pierce 1961 ^
Taraxacum Wiggers 1780 §
Tiliaepollenites crassipites (Wodehouse 1933) Fensome *et al.* 2016 *
Tsugaepollenites igniculus Potonié 1931 * (now *Zonalapollenites igniculus*)
Wodehouseia spinata Stanley 1961 *
Zlivisporis Pacltová 1961 *
Zonalapollenites igniculus (Potonié 1931) Thomson & Pflug 1953 *

Appendix 2

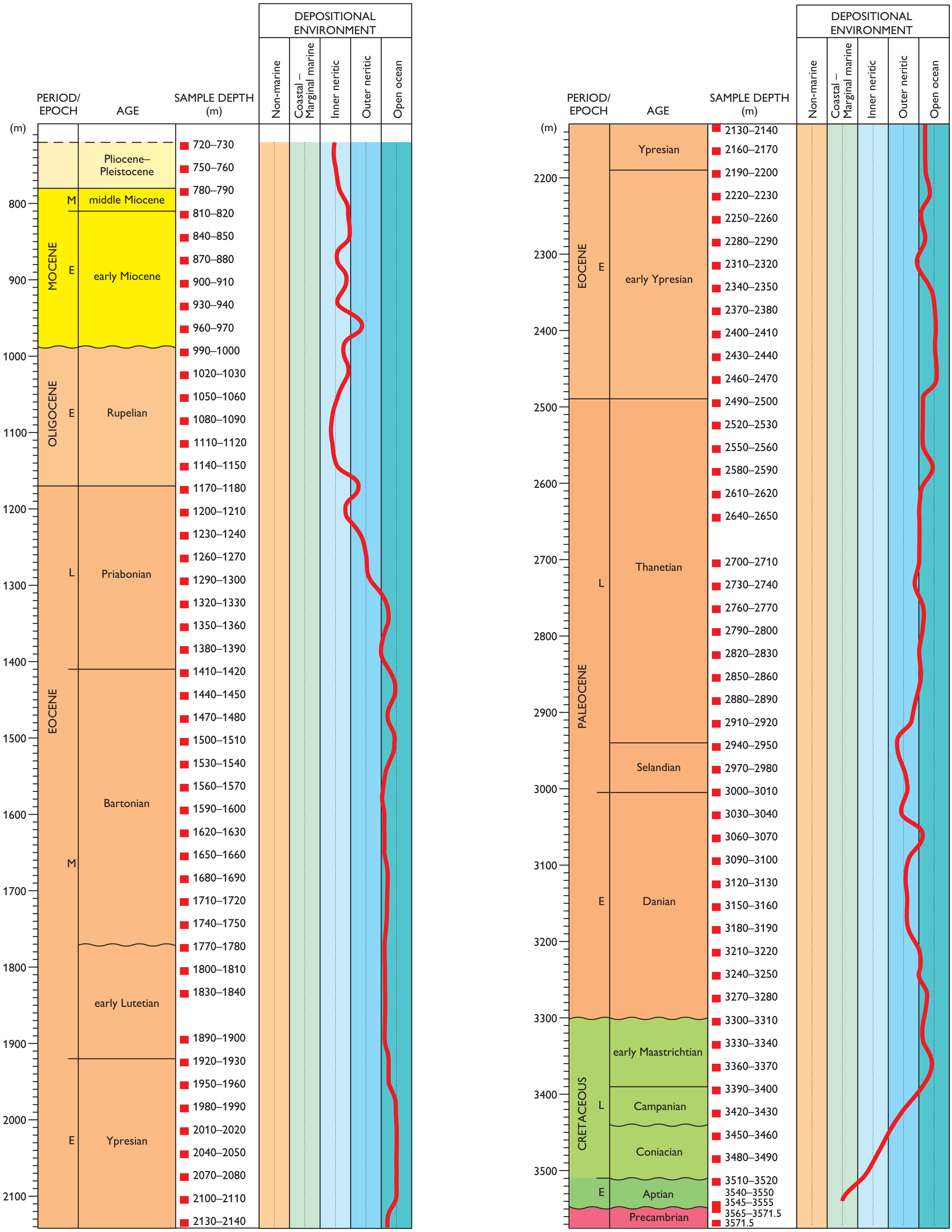
Palaeoenvironmental analysis of six wells on the Canadian margin (for location, see Fig. 1), based on palaeoecological interpretation of palynological data (by Graham L. Williams).

Legend for Appendices 2.1–2.6

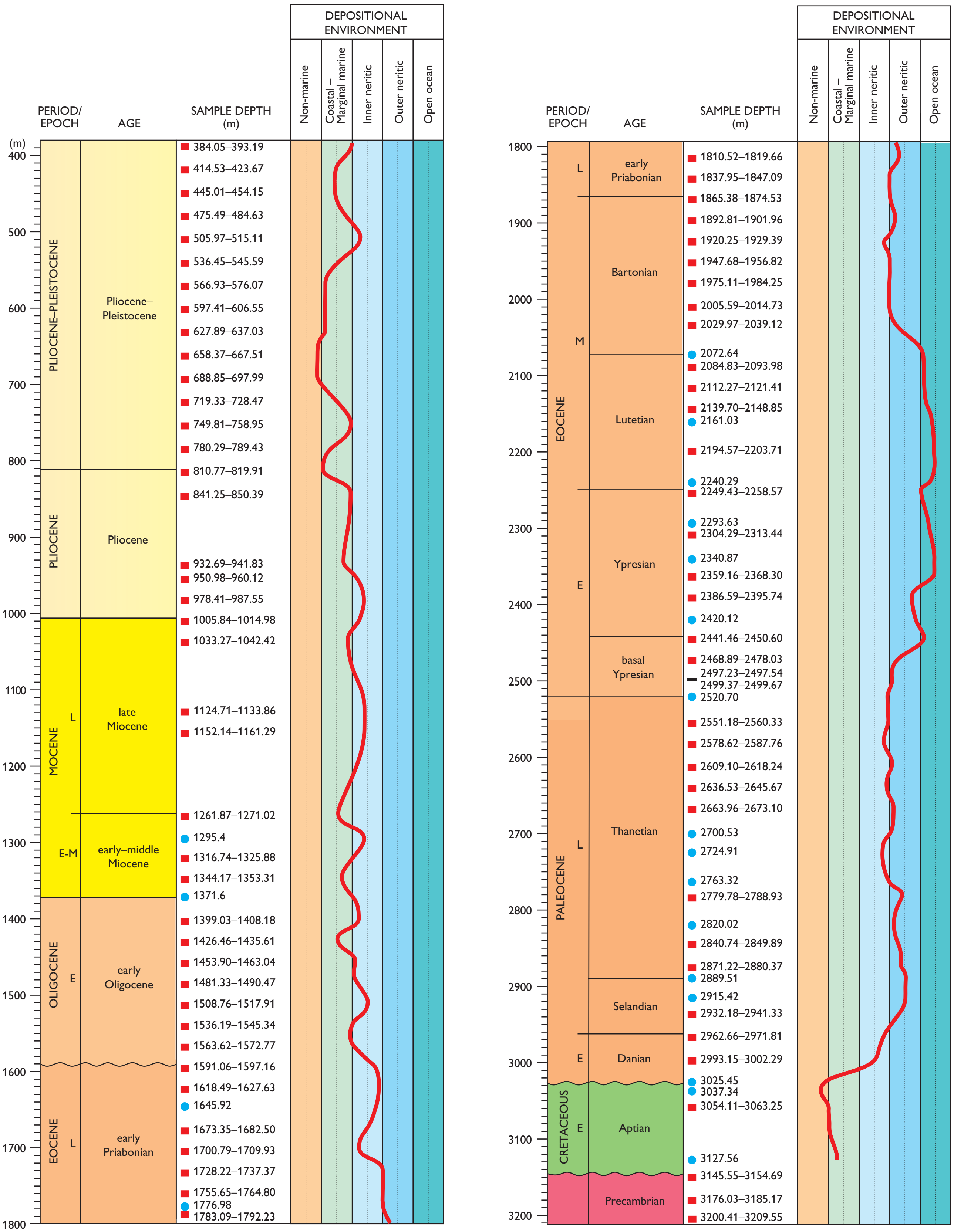
- 🟥 Cuttings sample
- ● Cuttings sample (secondary suite)
- ◂ Side-wall core (SWC)



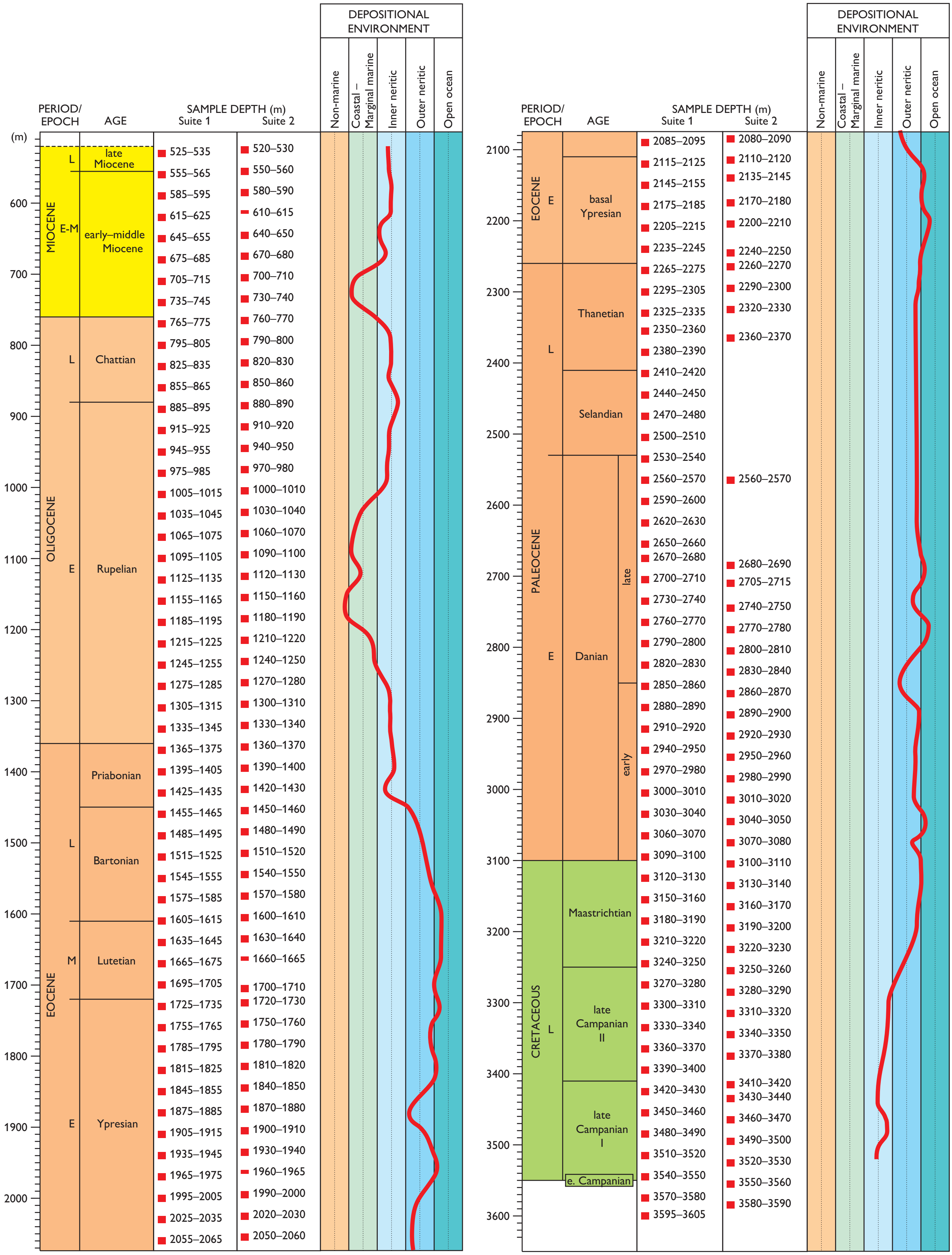
Appendix 2.1. Stratigraphy and palaeoenvironmental interpretation of the Bjarni O-82 well. Kelly Bushing height: 12.0 m above sea level. Water depth: 144 m. Total depth: 2650.0 m.



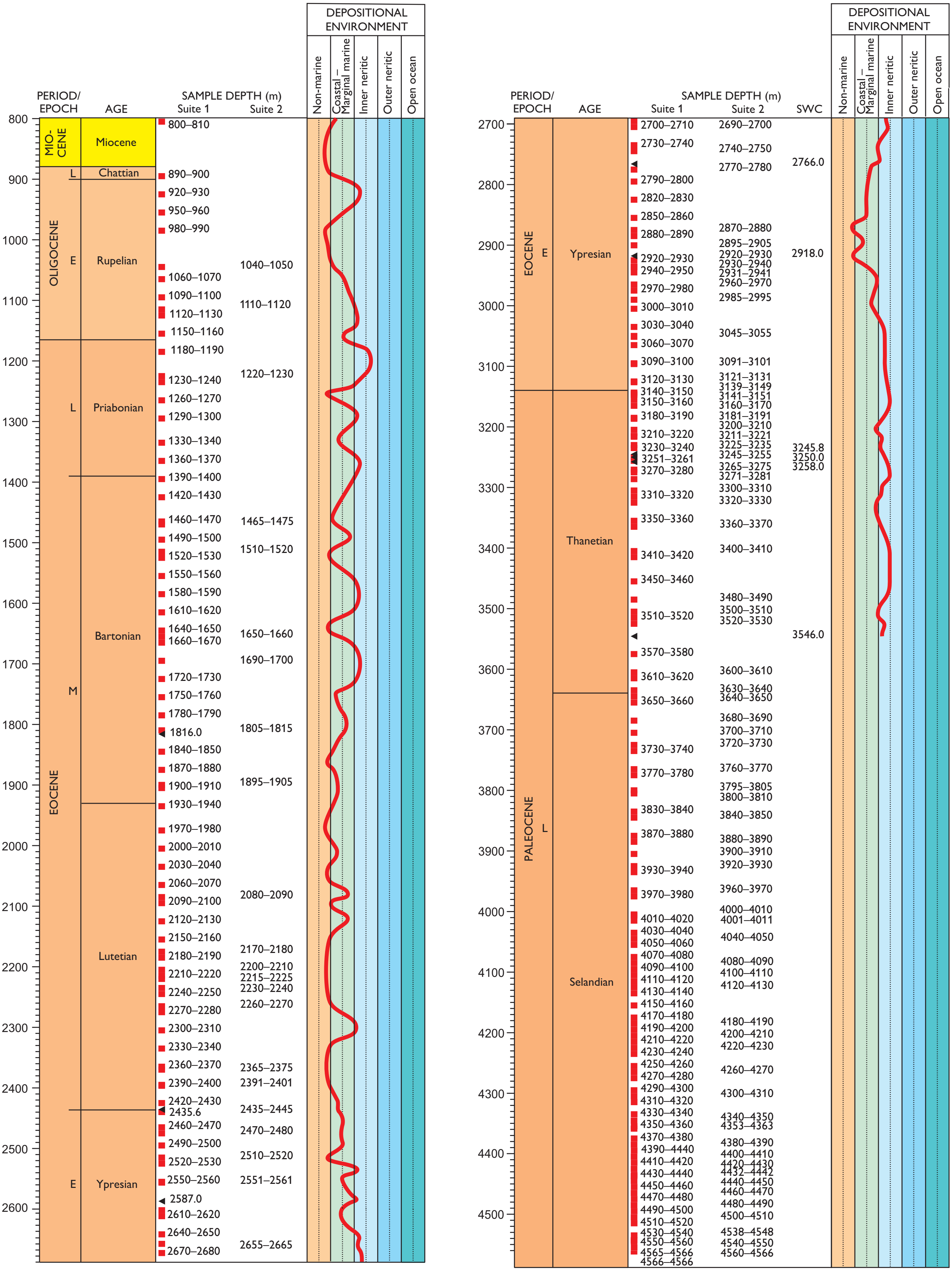
Appendix 2.2. Stratigraphy and palaeoenvironmental interpretation of the South Labrador N-79 well. Kelly Bushing height: 11.3 m above sea level. Water depth: 449.9 m. Total depth: 3571.5 m.



Appendix 2.3. Stratigraphy and palaeoenvironmental interpretation of the Snorri J-90 well. Kelly Bushing height: 11.3 m above sea level. Water depth: 140.8 m. Total depth: 3209.8 m.

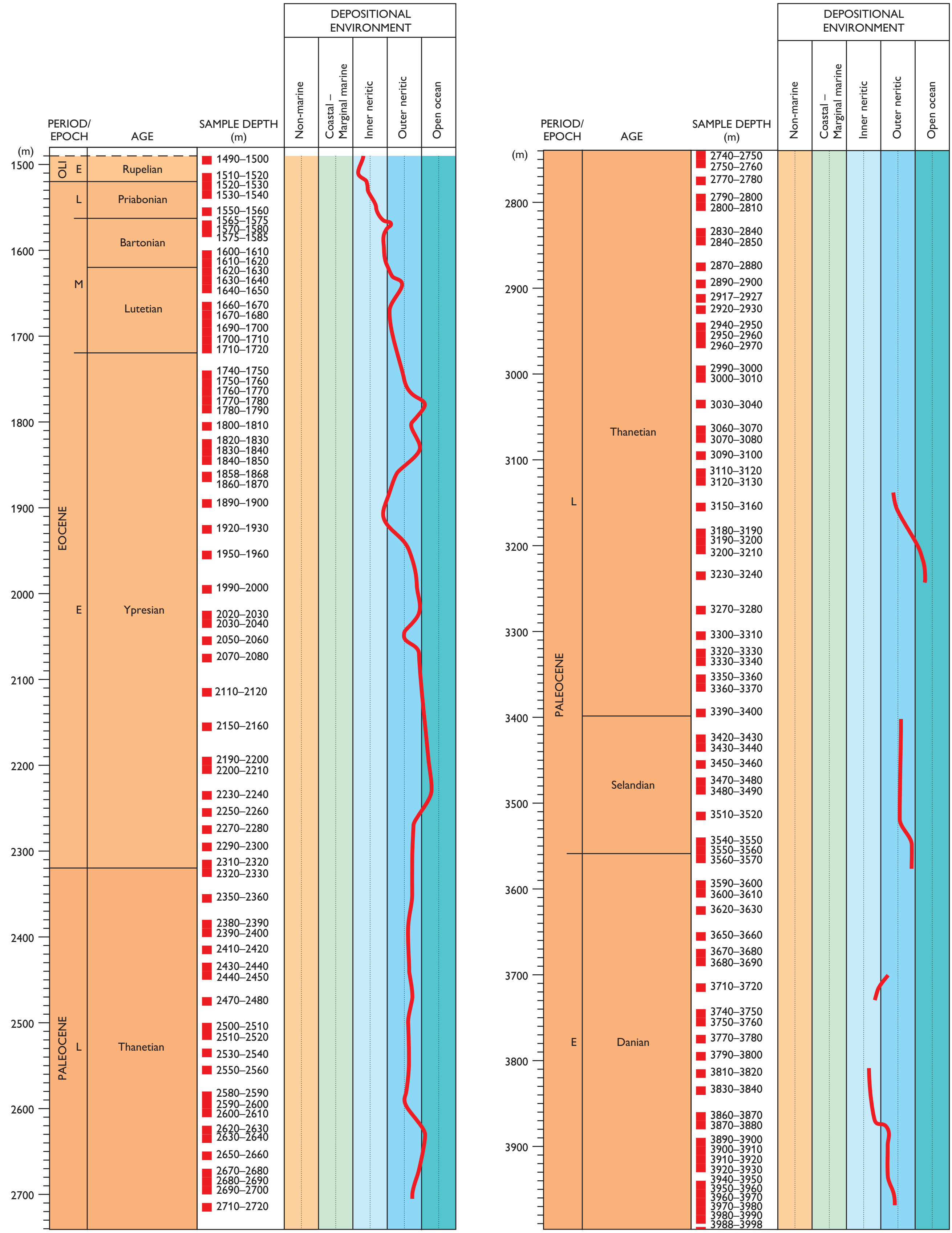


Appendix 2.4. Stratigraphy and palaeoenvironmental interpretation of the Gilbert F-53 well. Kelly Bushing height: 12.1 m above sea level. Water depth: 183 m. Total depth: 3608.0 m.



Appendix 2.5. Stratigraphy and palaeoenvironmental interpretation of the Hekja O-71 well. Kelly Bushing height: 12.5 m above sea level. Water depth: 350.8 m. Total depth: 4566.0 m.

]



Appendix 2.6. Stratigraphy and palaeoenvironmental interpretation of the Gjoa G-37 well. Kelly Bushing height: 24.0 m above sea level. Water depth: 1000 m. Total depth: 3998 m.

Appendix 3

Appendices 3.1–3.19 are located in pockets attached to the inside covers

Palynological event summary charts for the 19 wells used in this study, in order from south to north (for well locations, see Fig. 1). Although the information included varies from chart to chart, wireline logs, a simplified lithology log, lithostratigraphic units, palynological events and chronostratigraphic subdivisions are included for all wells. Charts of wells analysed by Henrik Nøhr-Hansen (Hellefisk-1, Ikermiut-1, Kangâmiut-1, Nukik-1, Nukik-2, Qulleq-1, North Leif I-05, Ogmund E-72, Skolp E-07, Hekja O-71, Ralegh N-18 and Gjoa G-37) include, in addition to palynological events, a biostratigraphic zonation for the Aptian–Albian to Priabonian of the West Greenland and Labrador Margins of the Labrador Sea; this zonation was published by Nøhr-Hansen in Sønderholm *et al.* (2003b), Nøhr-Hansen *et al.* (2000, 2002) and Nøhr-Hansen (2003, 2004a, b). Some of the well charts listed above also show dinocyst species diversity, *Azolla* abundances and palaeoenvironmental interpretations for the Palaeogene (after Rasmussen *et al.* 2003). Plots generated by Graham L. Williams and Robert A. Fensome (Bjarni O-82, Gilbert F-53, Karlsefni A-13, Roberval K-92, Rut H-11, Snorri J-90 and South Labrador N-79) show events and ages only; a biozonation was not developed. **KB**: Kelly Bushing.

De Nationale Geologiske Undersøgelser for Danmark og Grønland (GEUS)

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