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Introduction

In the 1970s and early 1980s, there was extensive exploration for hydrocarbons on the Labrador Shelf and in the Davis Strait area, with about thirty wells being drilled. All the drilling was focussed within one of two basins, the Hopedale to the south and the Saglek to the north. The wells included Total Eastcan et al. Roberval K-92 and Petro-Canada et al. Roberval C-02, which were drilled in 1978-82 and 1980, respectively in the Hopedale Basin (the location of all the wells is shown in Figure 1). Roberval C-02 was drilled above a horst of Precambrian gneiss, and Roberval K-92 was drilled on the side of the same horst. In Roberval C-02, total depth was 2823.2 metres, and in Roberval K-92, total depth was 3874 metres. Water depths at Roberval K-92 and C-02 were 268.5 and 276 metres, respectively. Both encountered oil and gas but were not tested.

Roberval C-02 and K-92 are only about 1800 metres apart, providing an ideal example of replicate sections and the opportunity to test the consistency of the palynomorph events recognized in Nøhr-Hansen et al. (in press). In that paper, the authors recognized 167 last occurrences and 18 local/regional peak/common-occurrence events for fossil dinoflagellates (dinocysts), miospores, fungal spores and the freshwater fern *Azolla* in wells drilled in the Labrador-Baffin Seaway. The study was based on the analysis of samples from 19 offshore wells, six from the West Greenland Margin, seven from the Saglek Basin and 6 from the Hopedale Basin. Although Nøhr-Hansen et al. (in press) included some data from Roberval K-92 there was no information on Roberval C-02, so that the biostratigraphy of the two closely spaced wells could not be compared.

My study of the two wells is based primarily on the palynological analysis of cuttings samples. In Roberval C-02, the 77 cuttings samples generally represented ten-metre composites over 30 metre intervals, and in Roberval K-92, the 171 cuttings samples were grouped into two intervals of five metres approximately every thirty metres. There were eight conventional core samples from cores 1 and 2 in Roberval K-92. The four samples processed from Core 2 were from 3101 m, 3099.93 metres, 3097.76 metres, 3096.35 metres and 3095 metres. Core 1 yielded three samples from 3016.75 metres, 3015.4 metres and 3014 metres.

Methodology

Figures 2 and 6 provide summaries of my biostratigraphic conclusions for the two wells: The results are based on the analysis of the palynomorph groups defined above, lithostratigraphy and well logs. I also provide a series of bioevents, each generally representing the Last Occurrence (the highest or youngest occurrence of a taxon in a well or surface section – commonly denoted by the acronym LO). First Occurrences (FOs) are not reliable indicators when deriving data from cuttings, so I included only those derived from the conventional cores from Roberval K-92 in Figure 2. Figures 3 and **7** provide the supporting data for my interpretations of the

paleoenvironments of the wells. I also show stratigraphic ranges based on both cuttings and core samples in Figures 4 and 5 for Roberval C-02 and Figures 8-11 for Roberval K-92. Plates 1-7 illustrate specimens from the Roberval C-02 well: plates 8-12 illustrate specimens from the Roberval K-92 well.

Age interpretations for the two wells are based primarily on the known stratigraphic ranges of dinocysts in European sections (Powell, 1992; Bujak et al., 1980; Bujak, 1994; Williams et al., 1999, 2004) and from older wells and coreholes from offshore eastern Canada and onshore and offshore western Greenland (Williams, 1975; Williams and Brideaux, 1975; Williams and Bujak, 1977; Barss et al., 1979; Williams et al., 1990; Sónderholm et al., 2003; Nøhr-Hansen 2003, 2004; Nøhr-Hansen et al., in press; and Fensome et al., in press). Throughout this study, I have adhered to the time scale proposed by Gradstein et al. (2012). This has been also used in the transposing of ages given for individual dinocyst species but derived from other sources.

Processing of the samples from the two wells was undertaken by three laboratories. These were: Global Geolab in Medicine Hat, Alberta; the Geological Survey of Canada (Calgary); and the Geological Survey of Canada (Atlantic). Global Geolab, processed all the samples from Roberval C-02 and the conventional cores from Roberval K-92. The two Survey laboratories processed 30 metre intervals from Roberval K-92. Global Geolab screened samples through 150 μ m and 10 μ m screens to concentrate the cuttings, then adhered to standard oxidation processing. After oxidation, part of each sample was screened through +45 μ m and +20 μ m sieves. Subsequently three slides were made representing the +45 μ m and +20 μ m fractions, plus one unscreened. Counts were based on the unscreened fraction. The GSC processing varied in the nature of the sieving. GSC (Atlantic) used a +30 μ m sieve only and prepared two slides, one of the +30 μ m fraction and one of the -30 μ m fraction. A similar processing technique was followed at GSC Calgary, differing only in that lab providing an unsieved slide, which facilitated counts. All slides used elvacite as the mounting medium.

Roberval C-02

Biostratigraphy

According to Moir (1989), in Roberval C-02 the lowermost 20 metres (2823 to 2803 metres) were Precambrian gneiss. However, two palynological samples, one from 2820 metres and one from 2805 metres contain the dinocyst *Tenua* cf. *hystrix* (recorded as *Cerbia* cf. *tabulata* in some wells). This taxon has been recorded from the Campanian of other Labrador Shelf wells including South Labrador N-79 and Roberval K-92, so its LO appears to have some validity as an index marker for this stage. Further evidence for the presence of Campanian sediments is the LO of *Trithyrodinium suspectum* at 2680 metres. Nøhr-Hansen et al. (in press) placed the LO of this species in the upper part of the Campanian. From the occurrences of these two taxa, I am

assuming that the Precambrian is unconformably overlain by Campanian sediments, which extend from 2805 metres to about 2680 metres.

One especially good index species for the early Maastrichtian is common in the sample from 2655 metres and has its LO in the sample at 2635 metres. This is *Isabelidinium cretaceum*, which has been recorded from several Labrador Shelf wells (Nøhr-Hansen et al., in press). Askin (1988) — in a study of dinocysts from the Campanian to Paleocene of Seymour and adjacent islands, Antarctica — defined a Zone 1, which was characterized by *Isabelidinium cretaceum*. She considered the zone to be late Campanian. Bowman et al. (2012), based on updated data, cited the age to be questionable late Maastrichtian but recognized two younger Maastrichtian zones. Thus, the LO of *Isabelidinium cretaceum* can be considered as early late Maastrichtian is missing in the Labrador–Baffin Seaway. In the Labrador Shelf wells, I consider the LO of the species to equate approximately with the top of the early Maastrichtian. Other species having their LOs in the interval 2680-2635 metres are *Impagidinium cf. victorianum* and *Spongodinium delitiense*. Nøhr-Hansen et al. (in press) placed the LO of *Impagidinium cf. victorianum* delitiense ranges up into the Danian.

The sample at 2590 metres is marked by the LO of the dinocyst taxa *Cerodinium glabrum*, *Hystrichosphaeridium tubiferum* subsp. *brevispinum* and *Tanyosphaeridium xanthiopyxides*. Since all three species occur in the Danian and I did not record any species having their LOs in the late Maastrichtian, I consider this an indication that upper Maastrichtian sediments are either condensed or absent in Roberval C-02.

Two key marker species for the Danian are Phelodinium kozlowskii and Cerodinium diebelii. Phelodinium kozlowskii has it's LO at 2525 metres and Cerodinium diebelii has it's LO at 2500 metres, which I consider to equate with the top of the Danian. Nøhr-Hansen et al. (in press) place the LO of Phelodinium kozlowskii within the Danian and the LO of Cerodinium diebelii at the Danian–Selandian boundary; the latter is based on agreement with the findings at three other Labrador Shelf wells, Bjarni O-82 (Williams 2007a), South Labrador N-79 (Williams 2007b) and Snorri J-90 (Williams 2007c). This is in slight conflict with Williams et al. (2004), who gave the LO of Cerodinium diebelii at about 60 Ma in Northern Hemisphere mid-latitudes, within the early Selandian. This discrepancy could possibly be explained if we assume that the species evolve in higher northern latitudes and later migrated south to warmer seas. Cerodinium diebelii has been recorded from the Selandian in Nukik- 2 (Nøhr-Hansen 2003), but this may represent reworking. Placing the top of the Danian at 2500 metres means that this stage extends from 2590 to 2500 metres. Other species having their LOs in this interval are Achomosphaera ramulifera, Areoligeran gippingensis, Hystrichosphaeridium quadratum, Hystrichosphaeridium salpingophorum, Oligosphaeridium complex, Palaeocystodinium bulliforme, Palaeoperidinium pyrophorum and Spiniferella sp.

I am dating the interval 2475 to 2230 metres as Thanetian, based on the LO of the pollen *Caryapollenites inelegans* and *Caryapollenites veripites* in the sample at 2230 metres and *Caryapollenites imparalis* at 2260 metres. Nichols and Ott (1978) noted that the three pollen species were restricted to the Paleocene in the Wind River Basin of Wyoming. Also having it's LO in the sample at 2230 metres is the dinocyst *Apectodinium parvum*. Powell (1992) considered this species to have a stratigraphic range of late Thanetian to early Ypresian. And Nøhr-Hansen et al. (in press) consider the LO of *Apectodinium parvum* to be immediately above the Thanetian–Ypresian boundary. However, the pollen data clearly indicate that the interval 2475-2230 metres is Thanetian. One surprise is the apparent absence of Selandian sediments in Roberval C-02. An excellent Selandian marker is *Palaeocystodinium bulliforme*, but this species occurs in the sample at 2560 metres, below the LO of *Cerodinium diebelii*.

The overlying interval from 2200 to 2170 metres contains the dinocysts *Petalodinium condylos* and *Scalenodinium scalenum*, both of which Nøhr-Hansen et al. (in press) considered to have LOs in the early Ypresian. Supporting evidence for considering the LO of *Petalodinium condylos* to mark the top of the early Ypresian is found in Bujak (1994), who plotted the consistent occurrence of the species within the nannofossil NP12 Zone. Other dinocyst species having their LOs in this interval are *Achilleodinium biformoides*, *Areoligera gippingensis*, *Glaphyrocysta divaricata*, *Cordosphaeridium gracile*, *Eocladopyxis peniculata* and *Hystrichokolpoma granulatum*. According to Nøhr-Hansen et al. (in press), several of these species have their LOs in the Ypresian in the Labrador-Baffin Seaway wells.

Dinocyst richness reaches a peak in the interval 2145 to 2080 metres, with species having their LOs including Axiodinium simile, Diphyes brevispinum, Diphyes ficusoides, Dracodinium solidum, Ginginodinium flexidentatum, Heteraulacacysta pustulosa, Piladinium columna and Piladinium edwardsii. Michoux (1988) described Piladinium (as Charlesdowniea) columna from upper Ypresian rocks of southwestern 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. For the Norwegian – Greenland Sea Basin, 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 very close to our findings. According to Nøhr-Hansen et al. (in press), 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). The stratigraphic range of *Piladinium edwardsii* seems to closely parallel that of *Piladinium columna*, which is not surprising considering the similarity of the morphology.

Another species with a restricted stratigraphic range is *Ginginodinium? flexidentatum*, which appears to equate with *Trinovantedinium* #LA of Bujak–Davies Group (1987). These authors

defined a *Trinovantedinium* #LA Zone that they considered to be late Ypresian, based on foraminiferal data in the South Labrador N-79 well on the Labrador Shelf. *Ginginodinium? flexidentatum* is present in the Ypresian of several wells, both on the eastern and western margins of the Labrador–Baffin Seaway. The wells 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 (Figure 1)

Taken collectively, the assemblages in the interval 2145-2080 metres indicate an age of late Ypresian, thus according with the findings of Nøhr-Hansen et al. (in press). The thinness of the section compared to in Roberval K-92, where it is 230 metres thick, is presumably explained by the closeness of the Roberval C-02 well to the basement horst.

What I consider to be Lutetian, from 2055 to 2025 metres is also attenuated, indicating that some of the sediments of this age are either missing or condensed. The Lutetian age is based on the presence of the dinocyst *Diphyes colligerum* in the sample from 2025 metres. 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 Greenland–Norwegian 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 (2004), who recorded the LO of *Diphyes colligerum* at the top of the Ypresian in North Leif I-05. Other dinocyst species having their LOs in the interval 2055-2025 metres. are *Cleistosphaeridium palmatum*, *Glaphyrocysta ordinata* and *Heteraulacacysta campanula*. Also having it's LO in this interval is a distinctive but undescribed species of *Glaphyrocysta*, which may be a useful marker for the Lutetian.

The dinocyst assemblages from the interval 1995 to 1665 metres are less diverse than lower in the well, although there are some age-restricted taxa. The most significant is *Chiropteridium gilbertii*, described by Fensome et al. (in press), whose LO occurs at 1665 metres. According to Nøhr-Hansen et al. (in press), the LO of this species is in the Bartonian. *Chiropteridium gilbertii* occurs only in wells on the Labrador Shelf (Williams, 2007d; under the informal name *Hystrichokolpoma "gilbertii*").

I have picked the top of the overlying Priabonian at 1450 metres on the LO of the dinocyst *Glapyrocysta* cf. *ordinata*. This unusual form has not been recorded from other wells on the Labrador Shelf but its morphology is strikingly similar to species found only in the Eocene, especially of the Grand Banks of Newfoundland (Williams & Brideaux, 1975). Possible corroborating evidence is the occurrences of *Lentinia serrata* in the sample at 1425 metres. The LO of *Lentinia serrata* appears to define the top of the Priabonian in some Grand Banks wells (e.g. Williams, 2003a, b). Support for the LO of *Lentinia serrata* being used to determine the top of the Priabonian is provided by Williams et al. (2004), who placed it 0.2 million years above the Priabonian-Rupelian boundary. *Lentinia serrata* is found in the GilbertF-53, North Leif I-05, Ralegh N-18 and South Labrador N-79 wells on the Canadian margin. However, *Lentinia*

serrata occurs in several samples above 1425 metres, although these occurrences could represent reworking, which is a major problem in Roberval C-02.

Another potentially useful species as a marker for the top of the Priabonian is *Lingulodinium funginum*, which is present at 1450 metres. This species appears to be restricted to the Eocene in several other wells on the Labrador Shelf and may be a good stratigraphic marker in the region, although it is found in much younger sediments elsewhere. Possibly its restricted range on the Labrador Shelf reflects climatic control. Thus the assemblages, assuming that I am correct in regards to the presence of reworked specimens, indicate a Priabonian age for the interval 1635 m to 1425 m.

In Roberval C-02, samples from the interval 1425 to 735 metres contain a very mixed dinocyst assemblage, many of the specimens being reworked. Such species include *Aptea polymorpha*, *Chatangiella verrucosa*, *Chatangiella victoriensis*, *Deflandrea oebisfeldensis*, *Florentinia mantellii*, *Glaphyrocysta divaricata*, *Heterosphaeridium difficile*, *Odontochitina costata*, *Ovoidinium verrucosum* and *Spongiodinium delitiense*. Of these, most are from the Late Cretaceous but some are Paleogene in age. *Ovoidinium verrucosum* consistently occurs throughout the well and I consider it as a contaminant from the drilling mud.

Even though the samples contain such a diverse dinocyst assemblage, I think it safe to assume that the presence of several specimens of *Phthanoperidinium coreoides* in the sample at 735 metres as indicative of a Rupelian age. According to Nøhr-Hansen et al. (in press), the LO of *Phthanoperidium coreoides* occurs within the Rupelian in Labrador Shelf wells. Thus, the Rupelian can be taken as extending from 1425 to at least 735 metres. Other species with LOs in this interval include: *Cleistosphaeridium diversispinosum, Cordosphaeridium fibrospinosum, Glaphyrocysta* (as *Cyclonephelium*) sp. A of Williams and Brideaux 1975, *Membranophoridium aspinatum* and *Trithyrodinium conservatum*. This interval includes the miospores *Corsinipollenites oculusnoctis* and *Zlivisporites*. Nøhr-Hansen et al. (in press) consider the miospore *Corsinipollenites oculusnoctis* to have its LO in the Bartonian. However, Williams (1986) placed the LO of this species, as *Jussiaea* sp., in the Early Oligocene (Rupelian). My analyses of the samples from Roberval C-02 agrees with extending the LO of *Corsinipollenites oculusnoctis* in agreement with Williams's findings.

My recognition of Chattian sediments in Roberval C-02 is based on the LOs of the two dinocyst species, *Chiropteridium galea* in the sample at 615 metres and *Deflandrea phosphoritica* in the sample at 705 metres. Williams et al. (2004) considered that both species extended into the early Aquitanian in northern mid-latitudes, but Nøhr-Hansen et al. (in press) found that their LOs equated with the top of the Chattian. Thus the Chattian extends from 705 to 615 metres in this well. Other species having their LOs in this interval are *Batiacasphaera micropapillata*, *Cordosphaeridium cantharellus*, *Cousteaudinium aubryae*, and *Minisphaeridium latirictum*.

The topmost sample in the well at 555 metres contains the spore *Osmundacidites wellmannii*, which Nøhr-Hansen et al. (in press) considered to have an LO in the Burdigalian. From this sparse data, I can only conclude that the sample is Aquitanian-Burdigalian in age.

In Roberval C-02, there appear to be three major hiatuses: the first is between the early Maastrichtian and the Danian; the second is between the Danian and the Thanetian; and the third is within the Lutetian. Of the three, the oldest can be related to one of the regional unconformities recognized in the Labrador Shelf and more northerly areas by McWhae et al. (1980) and McWhae (1981). This is the Bylot Unconformity, which I also consider to equate with the base Tertiary unconformity of Sinclair (1988)

A major hiatus with Thanetian sediments directly overlying Danian sediments is not restricted to Roberval C-02, having been recognize in several Labrador Shelf wells, including Gjoa G-37 in the Saglek Basin and Bjarni 0-82, North Leif I-05, Snorri J-90 and South Labrador N-79 in the Hopedale Basin. On the West Greenland Margin, Danian sediments in the Nukik-2 well are overlain by upper Selandian sediments (Nøhr-Hansen et al., in press). 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.

The third hiatus within the Lutetian also occurs in several wells on both sides of the Labrador Sea, in which parts of the middle Eocene are marked by a hiatus or condensed section: this represents the Mid-Eocene Unconformity of Dalhoff et al. (2003) (Fig. 7). These wells include: 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; Nøhr-Hansen et al., in press).

Paleoenvironments

Modelling basin evolution and interpreting the history of potential source rocks are dependent in large part on paleoenvironmental input. However, the capability for such studies in the Labrador-Baffin Seaway has been weakened by the decline in micropaleontological specialities involved in these studies on wells of offshore eastern Canada. Previously foraminiferal studies were key to providing this information, but these studies are no longer being undertaken. Consequently, it has become necessary to refine palynological analyses so that paleoenvironmental conclusions can be drawn; however, these would be much more meaningful if done in conjunction with studies of the benthic foraminifera.

There are several concerns when utilizing palynomorphs as paleoenvironmental parameters. The first, which applies to all the microfossil groups, is that most of the samples available from the offshore wells are cuttings. Thus, qualitative and quantitative data may be misleading. Because of caving and contamination from drilling mud, the major concern is to determine which

specimens are in place. For qualitative analyses, we rely on LOs or last occurrences going down the hole, still a potentially dangerous practice but to date no one has come up with a better approach. Quantitative analyses are more speculative. However, it is not necessary to count everything at the species levels, as individual genera or morphologic groupings often show the more obvious trends. Thus for dinocysts, the gonyaulacacean/peridiniacean/ceratiacean ratio, as used by Lister and Batten (1988), is one possible option.

One major advantage of palynomorphs is the diversity of paleoenvironments they denote. Spores and pollen yield information on terrestrial paleoenvironments, whereas dinocysts provide a key to the aqueous domains from fresh water to open ocean. But there are caveats. One is that dinocysts represent the encysted stage of the motile dinoflagellate, which is a planktonic organism. Consequently, it has been widely accepted that dinocyst distribution patterns exhibit a minimal relationship to water depths. In a literal sense this is correct. But dinoflagellates and hence the corresponding dinocysts do show distinct environmental preferences, especially when related to salinity and/or nutrient availability. Thus some dinocysts are restricted to (or more abundant in) non-marine, lagoonal, coastal, inshore, offshore or open-ocean settings. This means that it is feasible to make paleoenvironmental interpretations. For example, open ocean can be equated with a deeper water or bathyal environment.

The concept of developing a sophisticated paleoenvironmental model for dinocyst genera and species is not new, as demonstrated by the pioneering research, based on qualitative and quantitative data, of Gocht (1969), Downie et al. (1971) and Köthe (1990). The early results soon highlighted the importance of quantitative data to obtain reproducible and predictive results. Thus the model presented by Brinkhuis (1992, 1994), which represented a major advancement in dinocyst paleoenvironmental studies, must be keyed to quantitative studies.

In his study of the Priabonian, Brinkhuis (1992, 1994) illustrated lateral changes in dinocyst assemblages across a transect from lagoonal to open ocean environments. I have used the modified version of this model, as presented in Sluijs et al. (2005) plus my own observations on Labrador Shelf wells, in my paleoenvironmental interpretations for the Roberval C-02 well and, where possible, duplicate it here. Because of the relative sparseness of dinocysts in some assemblages, however, I have had difficulty in interpreting all the paleoenvironmental settings.

A plot showing the relative percentages of dinocysts, miospores, acritarchs and other organicwalled microfossils is given in Figure 3. This plot reveals the dominance of miospores throughout the section, with values commonly exceeding 75% and sometimes attaining 100%. Some of the samples don't contain dinocysts but may have significant percentages of acritarchs. Samples can encompass several dinocyst taxa but these are not reflected in the counts. The explanation for this apparent anomaly is that the counts are undertaken on unsieved fractions of each sample. Sieving, a routine procedure, concentrates the dinocysts, which are generally larger than the miospores with the exception of the bisaccates. Allowing for the above concerns, what conclusions can be drawn from the quantitative data? The dominance of the miospores could indicate one of three possibilities: that the section is predominantly non marine, middle neritic or open ocean. The presence of what I consider in situ acritarchs and dinocysts and the high degree of reworked dinocysts indicate to me that most if not all of the section is marine and much of it middle neritic. From 2805 to 2635 metres, which is Campanian and Maastrichtian in age, specimens of *Impagidinium* cf. *victorianum* are found in most of the samples. Based on these occurrences I consider the paleoenvironment during deposition of the interval 2805-2635 metres in Roberval C-02 to represent a time of deeper water, open ocean deposition. This suggests a rapid marine transgression with a corresponding sudden rise in sea level, supported by the top of the Precambrian gneiss being at 2803.5 metres. Obviously, those specimens of *Lingulodinium* cf. *victorianum* below 2805 metres represent caved specimens.

Impagidinium is one of the few dinocyst genera, which appear to be restricted to open ocean, deeper water environments. Wall et al. (1977) were the first to recognize that *Impagidinium* species (then included in *Leptodinium*) were indicative of oceanic realm environments. Brinkhuis (1992, 1994) incorporated this concept into his Priabonian model and Dale (1996) confirmed the validity of *Impagidinium* dominance among organic-walled dinocysts in the oceanic realm. The *Impagidinium* signal has been used to indicate open water or deeper water paleoenvironments in studies of other Labrador Sea wells (Nøhr-Hansen et al., in press), for example South Labrador N-79 (personal observations).

Paleoenvironmental interpretations for Roberval C-02 have been published by Doeven and McIntyre (1980) and Miller and d'Eon (1987). The interpretations by Doeven and McIntyre are based on benthic foraminifera and palynomorphs: Miller and d'Eon (1987) relied on lithologic analyses. Doeven and McIntyre (1980) interpreted the following paleoenvironments: 2803.5 to 2175 metres, slope; 2175-1830 metres, middle to deep neritic; 1830-1275 metres, shallow to middle neritic; and 1275-530 metres, shallow neritic. Miller and d'Eon (1987) considered 2803-2793 metres as shelf; 2793-2483 metres as bathyal; 2483-2352 metres as outer shelf to bathyal; 2352-2196 metres as outer shelf turbidite fan; 2196-1690 metres as bathyal; 1690-1392 metres as outer shelf to bathyal; 1392-703 metres as inner to middle shelf; and 703-550 metres as inner shelf.

In Roberval C-02, I found specimens of *Impagidinium* as high as 2115 metres supporting the interpretation of open ocean conditions extending into the Ypresian. This agrees closely with the interpretations of Doeven and McIntyre (1980) and Miller and d'Eon (1987), respectively. Supporting evidence for the open ocean setting may be the high abundances of miospores in the samples between 2475 and 2230 metres. One unexplained anomaly is the major influx of small acritarchs in the sample at 2170 metres. This must indicate a change in the paleoenvironment, perhaps denoting an influx of nutrients resulting from the site being closer to the shelf edge

Impagidinium also occurs at 1690 metres and 1610 metres, suggesting that open oceanic conditions prevailed in the vicinity of Roberval C-02 into the Bartonian. Lower down in the well, there are additional peaks in abundances of small acritarchs at 1755 metres and 1695 metres, which I interpret as indicating that at that time the location of the sediments in the well were in shelfal water depths. Doeven and McIntyre (1980) interpreted the sediments between 2175 and 1830 metres as being representative of middle to deep neritic paleoenvironments. However, Miller & d'Eon (1987) considered the sediments from 2196 to 1690 metres to have been deposited in a bathyal setting. There are few dinocysts in this section but the abundant acritarchs may support the interpretation of Doeven and McIntyre (1980).

Palynomorph assemblages from 1635 to 555 metres, the highest sample in Roberval C-02, are dominated by pollen; in one sample at 1360 metres the percentage is 100%. Such a dominance of pollen can be explained either by the location of the well being very close to shore or far offshore in an open ocean setting. The degree of reworking in some of the samples between 1055 and 555 metres leads me to favour interpreting the paleoenvironment as middle to shallow neritic, with shallowing upwards.

Correlation of Palynology and Lithostratigraphy

The lithostratigraphic interpretations for Roberval C-02 (Figure 2) are derived from Moir (1987) and the Canada-Newfoundland and Labrador Offshore Petroleum Board (CNLOPB; 2008). According to both papers, the Precambrian gneiss is unconformably overlain by the Markland Formation, which extends from 2803 to 2483 metres in the well. The Markland, erected by McWhae et al. (1980), is shale with occasional siltstone and sandstone and thin dolomitic beds. These authors gave an age for the formation of Cenomanian-Turonian to Danian, based on foraminifera.

From palynological studies, Williams et al. (1985) considered the Markland to be Albian-Cenomanian to Paleocene. In Roberval C-02, the age is Campanian to Danian, which fits nicely with my interpretation that there appears to be a hiatus between the Danian and the Thanetian.

Overlying the Markland according to Moir (1987) is the Gudrid Formation, which extends from 2483 to 2196 metres. This unit was named as the Gudrid Sand Member of the Cartwright Formation by Umpleby (1979), who characterized it as a quartz- and feldspar-rich sandstone. McWhae et al. (1980) elevated the Gudrid to formation status. But later authors, including the CNLOPB (2008) treated it as two members, the lower and upper of the Markland Formation. Thus, in Roberval C-02, the CNLOPB recognized the Lower Gudrid Member between 2483 and 2352 metres and the Upper Gudrid Member between 2352 and 2196 metres. Fortunately, both Moir (1987) and the CNLOPB (2008) placed the top of the Gudrid Member and the Upper Gudrid Member respectively at 2196 metres. Subsequent workers, such as Dickie et al. (2011), have reverted back to using the term Gudrid Formation.

Umpleby (1979) defined the Gudrid Member as consisting of quartzose and feldspathic sandstones deposited as part of a deep-sea fan sequence on the outer continental shelf, slope and rise. This generally agrees with the findings of Doeven and McIntyre (1980), Miller and d'Eon (1987) and this study in Roberval C-02 in that the paleoenvironment during deposition of the Gudrid was bathyal. McWhae et al. (1980) assigned a Paleocene to early Eocene age to the Gudrid Member. Based upon a palynological study, Barss et al. (1979) dated the type section in the Gudrid H-55 well as late Paleocene to early Eocene. In Roberval C-02, I determined the age as Thanetian to Ypresian, which shows close agreement with previous studies.

Sequentially overlying the Gudrid Member of the Cartwright Formation are the Kenamu, Mokami and Saglek formations. The Kenamu contains a sandstone unit, the Leif Member, which has potential as a reservoir rock. In Roberval C-02, the Kenamu extends from the top of the Gudrid at 2196 metres to 1690 metres, according to Moir (1987) and the CNLOPB (2008). The Kenamu was defined by McWhae et al. (1980) as an Eocene shale, siltstone, and sandstone sequence, which is in part glauconitic and calcareous: these sediments were deposited in outer shelf to upper slope environments. Moir (1987) and the CNLOPB (2008) considered the interval 1732-1690 metres in Roberval C-02 to be assignable to the Leif Member. I have dated the Kenamu Formation as Early Ypresian to Bartonian and the Leif Member as Bartonian. According to Barss et al. (1979), the palynomorphs in the interval designated as the type section of the Leif Member indicate a middle to late Eocene age. The environment of deposition for the Kenamu was presumably outer shelf to bathyal. But the Leif is somewhat of a puzzle, since the equivalent of the unit in Herjolf M-92 contains coal. Lynn Dafoe (pers. comm.) considers the Leif to be a deltaic/shoreface complex.

Moir (1987) and the CNLOPB (2008) assigned the interval 1690-701 metres to the Mokami Formation and the interval 701-375 metres to the Saglek Formation. McWhae et al. (1980) defined the Mokami as a predominantly claystone and soft shale unit, possibly Late Eocene to Middle Miocene in age and deposited in a neritic paleoenvironment. In Roberval C-02, the Mokami is Bartonian to Chattian and was deposited in a shelfal environment, shallowing upwards.

The youngest lithologic unit in Roberval C-02 is the Saglek Formation, which extends from 701 to 375 metres (Moir, 1987; Canada-Newfoundland and Labrador Offshore Petroleum Board, 2008). Umpleby (1979) erected the Saglek Formation for a sequence of poorly sorted, fine- to coarse-grained or conglomeritic clastics with abundant pelecypod fragments, lignite and glauconite. Originally the age of the formation was Eocene to Miocene. In their redefinition, McWhae et al. (1980) included only the uppermost pre-Quaternary part of the Saglek Formation, however, and dated it as mid-Late Miocene to Pliocene. However, my ages suggest that the Saglek could be as old as Chattian in its lowermost part.

Summary

Roberval C-02 was drilled to test the hydrocarbon potential of the Paleozoic carbonates (Petro Canada et al. 1980). But unfortunately the well bottomed in Precambrian gneiss, failing to encounter any Paleozoic rocks. Unconformably overlying the gneiss is a sequence of late Cretaceous and Tertiary sediments, including the Gudrid Formation and the Leif Member of the Kenamu Formation. Age control is based primarily on dinocysts but the spores and pollen are useful, especially when determining paleoenvironments.

Significant aspects of the Roberval C-02 sequences are the major unconformity between the Precambrian gneiss and the Campanian and the three hiatuses, which are as follows: between the early Maastrichtian and the Danian; between the Danian and the Thanetian; and within the Lutetian. All of these hiatuses have been observed in several wells in the Labrador-Baffin Seaway (Nøhr-Hansen et al., in press). The oldest can be related to one of the regional unconformities recognized in the Labrador Shelf and more northerly areas by McWhae et al. (1980) and McWhae (1981). This is the Bylot Unconformity, which I equate with the base Tertiary unconformity of Sinclair (1988). The major hiatus with Thanetian sediments directly overlying Danian sediments has been recognized in wells in both the Saglek and the Hopedale basins. Dalhoff et al. (2003) proposed a Mid-Eocene Unconformity, which he recognized in the wells of offshore West Greenland. This would equate with the third hiatus within the Lutetian in Roberval C-02 and other Labrador Shelf wells.

Sequentially overlying the attenuated Lutetian are sediments assignable to the remaining stages of the Paleogene. The youngest sediments, which are of Neogene age, appear to be Aquitainian-Burdigalian.

Paleoenvironments in Roberval C-02 ranged from open ocean, that is probably bathyal during most of the Campanian-Maastrichtian and into the Eocene to shelfal in the Bartonian and later, with shallowing upwards.

Palynomorph concentrations, especially those of dinocysts, show considerable variation. Recovery from the late Cretaceous and Paleocene is fair, but does not match that of the Eocene, especially for the dinocysts. Recovery of dinocysts from the Oligocene and Miocene sediments is poor; however, miospores are common, especially the angiosperms and gymnosperms.

Roberval K-92

Biostratigraphy

At total depth of 3874 metres (Moir 1989; Canada-Newfoundland and Labrador Offshore Petroleum Board, 2008; Ainsworth et al., 2014), Roberval K-92 was in Paleozoic dolomite, which extends up to 3544 metres. Based on the palynomorphs, Barss (1981) dated the interval 3870.3 to 3578.7 metres as Pennsylvanian (Westphalian D). Ainsworth et al. (2014) recognized an unconformity at 3544 metres, where the Paleozoic is overlain by Lower Cretaceous rocks. In my study, I analyzed composite 10 metre cuttings samples taken every 30 metres over the interval 3220-635 metres. I also examined samples taken from three of the conventional cores: five from Core 2 covering the interval 3125-3095 metres and two from Core 1 covering the interval 3017-3014 metres.

Miospores and dinocysts recovered from the interval 3220-3090 metres indicate that the age is Aptian. Age diagnostic taxa, based on my findings in other wells and verified in Nøhr-Hansen et al. (in press), include the miospore *Callialasporites* sp. and the dinocysts *Tenua hystrix*, *Cerbia tabulata* and *Pseudoceratium anaphrissa*. *Tenua hystrix*, is the taxonomic senior synonym of *Cerbia tabulata* (see Fensome et al., in press). *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.

The dinocyst *Odontochitina porifera* occurs in the cuttings sample at 3070 metres, indicating an age of early Santonian. Support for this age is provided by the LO of this species, which Stover et al. (1996) placed in the early Santonian, although other authors (Costa and Davey 1992; Williams et al., 2004) have extended its range into the Campanian. According to Nøhr-Hansen et al. (in press) *Odontochitina porifera* is present in some Labrador Shelf wells but not in the two West Greenland wells containing Cretaceous rocks: Qulleq-1 and Ikermiut-1.

I consider the interval 3060-3040 metres to be Campanian, based on the presence of the dinocyst *Raphidodinium fucatum*. This accords with the findings of Williams et al. (2004) and Nøhr-Hansen et al. (in press), who placed the LO of the species in the late Campanian. Other dinocysts with their LOs in this interval are *Tenua* cf. *hystrix* and *Cerodinium kangiliense*. *Tenua* cf. *hystrix* seems to be a reliable Campanian index species in some of the Labrador Shelf wells, including Roberval C-02. A conventional core sample at 3016.75 metres contains the taxa *Palaeoperidiniu pyrophorum, Impagidinium, Hystrichosphaeridium salpingophorum, Coronifera oceanica, Spiniferites ramosus, Circulodinium distinctum, Hystrichosphaeridium quadratum, Manumiella selandicum, Isabelidinium cretaceum, Hystrichosphaeridium bowerbankii, Canningia sp., Odontochitina costata, Heterosphaeridium difficile, Adnatosphaeridium sp. Ioannides 1987, Kleithriasphaeridium loffrense, Cerbia tabulata, Spiniferella sp., Aquilapollenites sp., Laciniadinium williamsii and Microdinium ornatum. Based on the presence of <i>Palaeoperidinium pyrophorum* and *Heterosphaeridium difficile*, I interpret the assemblage as early Campanian and indicative of an open ocean paleoenvironment.

From 3010 to 2860 metres appears to be early Maastrichtian. *Isabelidinium cretaceum* is common at 2880-2890 metres. As noted in my discussion of the biostratigraphy of Roberval C-02, the LO of *Isabelidinium cretaceum* extends just into the late Maastrichtian, so I use it as a

marker for the top of the early Maastrichtian in the Labrador Shelf wells. Other species having their LOs in the interval 3010-2860 metres are Laciniadinium arcticum, Disphaerogena carposphaeropsis, Hystrichosphaeridium bowerbankii, Impagidinium cf. victorianum, Isabelidinium belfastense, Oligosphaeridium pulcherrimum, Spiniferella cornuta and Spiniferites scabrosus. The LOs of Impagidinium cf. victorianum and Spiniferites scabrosus are at 2860 metres. Nøhr-Hansen et al. (in press) placed the LO of both species at approximately the top of the early Maastrichtian. Confirmation of the Maastrichtian age for the LO of Impagidinium cf. victorianum comes from combined palynological and micropaleontological analyses of South Labrador N-79 by Bujak–Davies Group (1987). In an interval designated as Maastrichtian, based on foraminiferal data, they recognized an early Maastrichtian subzone for a taxon they identified as Impagidinium #LL. The taxon is probably conspecific with the species we have identified as Impagidinium cf. victorianum and the species Nøhr-Hansen (1996) identified from the upper Maastrichtian in the Nuussuaq Basin as Impagidinium sp. cf. I dispertitum. This provides good supporting evidence for my assumption that the lower Maastrichtian extends to 2860 metres. From palynological analyses, Bujak Davies Group (1987) assigned the interval 2950-2810 metres to the Maastrichtian. However, they did not subdivide the stage.

A cuttings sample from 2850-2840 metres contains the dinocyst *Palynodinium grallator*. Nøhr-Hansen in Sønderholm et al. (2003) defined a *Palynodinium grallator* interval for the uppermost Maastrichtian. This was characterized by the LOs of *Palynodinium grallator* and the pollen *Wodehouseia spinata*. Williams et al. (2004) placed the FO of *Palynodinium grallator* in northern mid-latitudes at the Maastrichtian–Danian boundary and it's LO in southern mid-latitudes within the earliest Danian. One specimen of *Palynodinium* in the sample from 2830 metres suggests that the latest Maastrichtian extends from 2850-2830 metres. *Cerodinium diebelii* also has it's LO in this sample. If the lower Maastrichtian top is at 2860 metres and the uppermost Maastrichtian extends from 2850 to 2830 metres, this indicates to me that part of the upper Maastrichtian is missing in Roberval K-92.

I consider from 2810 metres to 2690 metres to be early Danian. Dinocyst species with their LOs in this interval include *Hafniasphaera hyalospinosa*, *Palaeocystodinium lidiae*, *Phelodinium kozlowskii*, *Spongodinium delitiense*, *Tanyosphaeridium xanthiopyxides* and *Trithryodinium evittii*. According to Nøhr-Hansen et al. (2004) the presence of this stage is indicated by the LOs of the dinocyst species *Cerodinium diebelii*, *Phelodinium kozlowskii*, *Senoniasphaera inornata*, *Spongodinium delitiense*, *Tanyosphaeridium xanthiopxides* and *Trithryodinium evittii*, According to Williams et al. (2004), the LO of *Spongodinium delitiense* is at about 64 Ma in Northern Hemisphere mid-latitudes. In North Leif I-05, Nøhr-Hansen (2004) and in Ogmund E-72 and Skolp E-07, Nøhr-Hansen in Sønderholm et al. (2003) recognised the presence of the lower Danian *Trithyrodinium evittii* Zone (Nøhr-Hansen et al. 2002), indicating a late Danian – Thanetian hiatus in North Leif I-05 and Ogmund E-72 and a late Danian – Ypresian unconformaty/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. Nøhr-Hansen et al. (2004)

placed the LO of *Spongodinium delitiense*, *Tanyosphaeridium xanthiopxides* and *Trithyrodinium evitti* approximately at the top of the early Danian. Thus I regard lower Danian sediments extending to 2690 metres.

Apparently, immediately overlying the lower Danian are Thanetian sediments, which extend to 2480 metres. I picked the top of the Thanetian on the presence of *Cerodinium glabrum* and *Cerodinium speciosum*. Both *Cerodinium glabrum* and *Cerodinium speciosum* have their LOs at the Thanetian–Ypresian boundary. Gradstein and Williams (1976) and the Bujak-Davies Group (1987) both defined a *Cerodinium speciosum* Zone, which they considered to be late Paleocene. And Nøhr-Hansen (2004) in his study of the North Leif I-05 well, considered the LO of *Cerodinium glabrum* (as *Cerodinium speciosum* subsp. *glabrum*) to be in the late Thanetian. Another species with its LO in the Thanetian of Roberval K-92 is *Deflandrea leptodermata*

Since I consider from 2810 to 2690 metres to be early Danian and from 2600 to 2480 metres to be Thanetian, it would appear that the Selandian is absent or greatly attenuated. This is somewhat at variance with Ainsworth et al. (2014), who dated the interval 2850-2700 metres as Selandian. However, the sample at 2700-2690 metres must be considered Danian, since it contains the species *Phelodinium kozlowskii* and *Spongodinium delitiense*.

The Ypresian extends from 2470 to 2240 metres and contains diverse dinocyst assemblages. The two wetzelielloideans species *Piladinium columna* and *Petalodinium condylos* occur in the sample at 2250-2240 metres and, as noted in my discussion of the biostratigraphy of Roberval K-92, both are good Ypresian markers

Other stratigraphically useful species in the Ypresian of Roberval K-92 are: *Areoligera gippingensis* and *Deflandrea oebisfeldensis* at 2460-2450 metres; *Cordosphaeridium gracile* and *Eocladopyxis peniculata* at 2440 metres; *Diphyes brevispinum* and *Homotryblium abbreviatum* at 2400-2390 metres; *Lentinia wetzelii, Heteraulacacysta pustulosa, Piladinium edwardsii* and *Schemotophora speciosa* at 2340-2330 metres; *Dapsilidinium simplex* and *Hystrichokolpoma globulus* at 2310-2300 metres; *Ginginodinium? flexidentatum* at 2280-2270 metres; and *Homotryblium tenuispinosum* at 2250-2240 metres. Ainsworth et al. (2014) assigned the interval 2320-2140 metres to the Ypresian. I cannot see any good index markers denoting the top of the Ypresian between 2240 and 2140 metres, although there are a few specimens of *Apectodinium* in the sample at 2220-2210 metres and these may justify a slight upward modification to the Ypresian-Lutetian boundary.

The Lutetian section in Roberval K-92, which extends from 2200 to 1970 metres, is attenuated as in Roberval C-02. Index species with their LOs in the Lutetian include *Alterbidinium bicellulum*, *Cleistosphaeridium ancyreum*, *Hystrichokolpoma salacium*, *Sophismatia tenuivirgula* and *Trrithyrodinium? conservatum*, Although dinocysts are sparse in this interval, there is a marked increase in the wetzelielloideans.

A dinocyst species that has been demonstrated to have a consistent LO in the Bartonian is *Chiropteridium gilbertii*. This species occurs only in wells on the Labrador Shelf (Williams 2007d) under the informal name *Hystrichokolpoma "gilbertii*". In Roberval K-92, it has its LO in the sample at 1800-1790 metres, which I am taking as the top of the stage. Ainsworth et al. (2014) considered the interval 2130-1820 metres to be Lutetian-Bartonian, which shows close agreement with my findings.

Determining the top of the Priabonian is difficult because of the reworking of older Paleogene dinocysts in Roberval K-92. However, the occurrence of *Hemiplacophora semilunifera* in the sample from 1635-1625 metres is probably a good marker for the stage. Williams et al. (2004) placed the LO of this species at 35.4 Ma, that is within the Priabonian, in southern high latitudes. Another species that may have significance is *Rhombodinium porosum*, which occurs in the sample at 1605-1595 metres. Nøhr-Hansen et al. (in press), following Bujak (1994) considered this species to have its LO at the top of the Bartonian. But Williams et al. (2004) placed its LO at 33.7 Ma, which is in the late Priabonian. Based on the above, I am placing the top of the Priabonian at 1595.

Bujak Davies (1987) designated the interval 2670-1625 metres as Eocene, subdividing it into early (2670-2210 metres), middle (2110-1910 metres), middle to late (1890 to 1625 metres), and late Eocene to early Oligocene (1605 to 1475 metres).

The Rupelian, which is surprisingly thick, extends from 1595 to 880 metres, but determining the top of this stage is difficult because dinocysts are rare to absent throughout; accordingly, I am picking its top on the presence of the miospore *Zlivisporites* and the dinocyst *Phthanoperidinium amoenum* at 880 metres. Ainsworth et al. (2014) placed the top of the Rupelian at 990 metres but the only evidence I see is the occurrence of single specimens of *Lentinia serrata* at 1005-995 metres. Single specimens of *Lentinia serrata* occur in several of the samples, including that at 1005-995 metres, which contains two specimens. Nøhr-Hansen et al. (in press) consider the LO of the two species of *Lentinia* to coincide with the top of the Priabonian, with which I generally agree. But the single occurrences of the two species in samples and the ghost-like appearance of specimens lead me to presume that they are reworked.

Immediately above the Rupelian section are about 250 metres of Chattian sediments, which extend from 855 metres to the uppermost sample at 635 metres. This sample contains the dinocyst *Chiropteridium galea*. Nøhr-Hansen et al. (in press) recognized the top of the Chattian on the LOs of two dinocyst species *Chiropteridium galea* and *Deflandrea phosphoritica*. However, Williams et al. (2004) placed the LOs of these species within the Aquitanian in Northern Hemisphere mid latitudes. I follow Nøhr-Hansen et al. (in press). Other dinocyst species considered to be in place in this interval include *Apteodinium australiense*, *Cleistosphaeridium diversispinosum*, *Cordosphaeridium cantharellus* and *Deflandrea phosphoritica*. In Roberval K-92, Ainsworth et al. (2014) dated the interval 980 to 750 metres as Chattian; thus, their base is somewhat higher than mine.

Paleoenvironments

As for Roberval C-02, I include a plot showing the relative percentages of dinocysts, miospores, acritarchs and other organic-walled dinocysts in Roberval K-92 (Figure 7). This plot reveals the dominance of dinocysts in the lower part of the section that is Aptian to early Danian in age. In the upper part of the section, the miospores predominate and palynomorph assemblages are sparse, with percentages of the former commonly exceeding 85% and sometimes attaining 100%. At some horizons, there are significant percentages of acritarchs. Samples can contain several dinocyst taxa but these are not reflected in the counts. The explanation for this apparent anomaly is that the counts are undertaken on unsieved fractions of each sample. Sieving, a routine procedure, concentrates the dinocysts, which are generally larger than the miospores with the exception of the bisaccates.

Dominance of dinocysts usually indicates shelfal conditions unless species richness is extremely low, whereas dominance of miospores can reflect predominantly non marine, middle neritic or open-ocean paleoenvironments. The presence of what I consider in-situ acritarchs and dinocysts and the high degree of reworked dinocysts indicate to me that most of the section is marine, but there is significant shallowing higher up in the section.

Paleoenvironmental interpretations for Roberval K-92 have been published by Robertson Research (1979), Total C.F.P. (1980), Miller and d'Eon (1987), Bujak Davies Group (1987) and Ainsworth et al. (2014). The interpretations by Robertson Research (1979), Total C.F.P. (1980), Bujak Davies Group (1987) and Ainsworth et al. (2014) are all based on benthic foraminifera, whereas Miller and d'Eon (1987) relied on lithologic analyses. Robertson Research (1979) interpreted the following paleoenvironments: questionable shallow marine (3874-3544 metres); marginal marine (3544-3070 metres); shallow to open marine (3070-2679 metres); transitional (2679-2488 metres); shallow to open marine (2488 to 2030 metres); and shallow marine (1386 to 702 metres). Total C.F.P. (1980) postulated several episodes of outer ramp to bathyal deposition, including between 3090 and 2653 metres and 1750 and 1690 metres. Miller and d'Eon (1987), primarily based on cuttings samples, recorded predominantly bathyal deposition from 3010 to 1595 metres, with successively above outer to inner shelf settings. Bujak Davies Group (1987) and Ainsworth et al. (2014) have a somewhat similar interpretation to the above. The latter authors considered the sediments deposited between 3080 and 1720 metres to be bathyal and those between 1710 and 650 metres to vary between bathyal and inner neritic.

The palynomorphs show some agreement with the above interpretations. In my analyses of the conventional core samples from the interval 3101 to 3095 metres in Roberval K-92, I recovered miospores but no dinocysts, indicating that the palaeoenvironment was non-marine. However, the cuttings sample from 3190-3180 metres contains the dinocyst *Vesperopsis*, which indicates lagoonal to marginal marine conditions. Further evidence of a marine-influenced environment is

found in the cuttings samples at 3160, 3100-3090 and 3070 metres, which contain dinocysts indicative of inner shelf environments.

My observations support earlier findings that non-marine conditions generally 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. But there were marine interludes, as shown by the presence of the dinocysts in the cuttings from Roberval K-92.

From 3070 to 1820 metres, dinocysts are common in most samples but rarely outnumber the miospores, or in some cases the acritachs, except in samples at 3070 metres, 3040 metres and 1820 metres. However, *Impagidinium* cf. *victorianum* and other species of the genus occur throughout the interval 3042-2180 metres, indicating that open ocean or deeper water conditions existed during the time of deposition of this interval. Further evidence for deep-water deposition is the presence of *Impagidinium* at 1655 and 1625 metres. The interval 2150-1700 metres is dominated by miospores, with high counts of acritarchs at 1830-1820 metres. This could indicate deep-water paleoenvironments but I have no dinocyst evidence to substantiate this. There is a paucity of dinocysts from 1690 to the uppermost sample at 635 metres, making difficult any interpretation of the paleoenvironment. However, from the poor assemblages, the high degree of reworking, and the low numbers of dinocysts I would postulate either a mid or inner neritic paleoenvironment. Based solely on the paucity of the dinocyst assemblages I would consider it indicative of an oligotrophic zone, which is usually found in a mid-shelf setting.

Correlation of Palynology and Lithostratigraphy

Roberval K-92 encountered Westphalian dolomite from 3544 metres to total depth of 3874 metres (Figure 6). Unconformably overlying the dolomite is the Lower Cretaceous Alexis Formation, which Moir (1989) considered to extend from 3544 to 3197 metres. Umpleby (1979) erected the Alexis for a repeating sequence of red and green weathered basalt flows, alternating with fresher amygdaloidal basalt and minor, thin quartzose sandstones and red silty claystones. According to McWhae and Michel (1975), the volcanic suite is Neocomian-Aptian. I have determined an Aptian age for the interval 3220-3090 metres, which falls within that stipulated by McWhae and Michel (1975).

Moir (1989) included the interval 3197-3080 metres in the Bjarni Formation and designated from 3187 to 3080 metres as the Snorri Member of the Bjarni Formation. I shall follow the Canada and Newfoundland and Labrador Offshore Petroleum Board (2008) and Ainsworth et al. (2014), who did not recognize the Snorri Member and who both put the top of the Bjarni Formation at 3080 metres. The Bjarni consists of coarse-grained sandstones, with fine-grained sandstones, conglomerates, carbonaceous shales and thin coal seams: it is an excellent reservoir rock. Barss

et al. (1979) dated the formation as Neocomian to Albian-Cenomanian. In Roberval K-92, I considered the Bjarni to be Aptian in age.

Overlying the Bjarni is the Markland Formation, which extends from 3080 to 2679 metres, according to both Moir (1989) and the CNLOPB (2008). (Lithologic and biostratigraphic details of the Markland are given in the section on Roberval C-02). From my analyses, the age of the Markland is Santonian to early Danian in Roberval K-92, which is somewhat more restricted than the Cenomanian-Turonian to Danian age given by McWhae et al. (1980).

According to Moir (1989), overlying the Markland Formation is the Gudrid Formation (Upper), which extends from 2679 to 2356 metres (see my discussion of this unit in the section under Roberval C-02). However, the CNLOPB (2008) includes this interval in the Cartwright Formation, although it does recognize the Lower and Upper Gudrid members in the intervals 2679-2468 and 2464-2356 metres, respectively. The Cartwright Formation is predominantly a claystone with siltstone and thin distal carbonate and sandstone turbidites. Umpleby (1979) considered the formation to be deposited in a marginal to shallow marine environment but McWhae et al. (1980) interpreted the paleoenvironments as outer shelf to bathyal. Barss et al. (1979) in a palynological study dated the type section in the Gudrid H-55 well as Maastrichtian to early Paleocene. In Roberval K-92, I determined the age to be Thanetian to Ypresian: this shows close agreement for the age of the Gudrid Formation, the lateral equivalent of the Cartwright, in the Roberval C-02 well.

As in Roberval C-02l, the overlying sequences are, in order of deposition, the Kenamu, Mokami and Saglek formations. I have described the lithology and ages of these formations under the section on the Roberval C-02. Therefore this discussion will be abbreviated. One difference in Roberval K-92 is that Moir (1989) did not recognize the Leif Member of the Kenamu Formation. However, the Canada-Newfoundland and Labrador Offshore Petroleum Board (2008) identified this unit between 2014 and 1815 metres. In Roberval K-92 the Kenamu extends from the top of the Gudrid at 2356 metres to 1815 metres, according to Moir (1989) and from 2355 to 1815 metres according to the Canada-Newfoundland and Labrador Offshore Petroleum Board (2008). In Roberval K-92, I consider the Kenamu Formation to be Ypresian to Bartonian and the Leif Member to be Lutetian-Bartonian, but predominantly the latter. As noted above, according to Barss et al. (1979) the palynomorphs in the interval designated as the type section of the Leif Member indicate a middle to late Eocene age.

Moir (1989) and the Canada-Newfoundland and Labrador Offshore Petroleum Board (2008) assigned the intervals 1815-726 and 1815-725 metres respectively to the Mokami Formation and the intervals 726-340 and 725-340 metres respectively to the Saglek Formation. In Roberval K-92, the Mokami is Bartonian to Chattian and was deposited in a shelfal environment, shallowing upwards.

The youngest lithologic unit in the well is the Saglek Formation, which extends from 726 to 340 metres, according to Moir (1989) and from 725 to 340 metres, according to the Canada-Newfoundland and Labrador Offshore Petroleum Board (2008). Originally the age of the formation was Eocene to Miocene. In their redefinition, however, McWhae et al. (1980) dated it as mid-Late Miocene to Pliocene. The Chattian age I determined in Roberval K-92 is somewhat older than would be expected and may reflect either problems with the lithostratigraphic picks or the age determinations.

Summary

Roberval K-92 was drilled to test the hydrocarbon potential of Paleozoic dolomites (Total Eastcan et al., 1979), which had proved so productive at Gudrid H-55, located about 5 kilometres to the northwest. The well was successful in encountering the dolomites, but these were waterbearing. However, a hydrocarbon-bearing reservoir with a high probability for oil was encountered in the Bjarni Formation. Unconformably overlying the Paleozoic dolomites is a sequence of Cretaceous and Tertiary sediments, including the Bjarni and Gudrid formations and the Leif Member of the Kenamu Formation, all potential reservoir rocks. Age control is based primarily on dinocysts but the spores and pollen are useful, especially when determining ages in the Early Cretaceous and the paleoenvironments.

Roberval K-92 has one major unconformity between the Westphalian dolomite and the Early Cretaceous Alexis Formation and three hiatuses, which are as follows: between the Aptian and the Santonian; between the Danian and the Thanetian; and within the Lutetian. All of these hiatuses have been observed in several wells in the Labrador-Baffin Seaway (Nøhr-Hansen et al. in press). The oldest can be related to the Labrador Unconformity one of the regional unconformities recognized on the Labrador Shelf and more northerly areas by McWhae et al. (1980) and McWhae (1981). Another regional unconformity is the Avalon Unconformity, which separates the Bjarni Formation from the overlying Markland Formation. McWhae (1981) considered the age of the Avalon Unconformity to range from 100 to 85 Ma — but did not specify the time scale. The major hiatus with Thanetian sediments directly overlying Danian sediments has been recognized in wells in both the Saglek and the Hopedale basins. Dalhoff et al. (2003) proposed a Mid-Eocene Unconformity, which he recognized in the wells of offshore West Greenland. This would equate with the third hiatus within the Lutetian in Roberval K-92 and other Labrador Shelf wells. Sequentially overlying the attenuated Lutetian are sediments assignable to the remaining stages of the Paleogene.

Paleoenvironments in Roberval K-92 ranged from terrestrial to marginal marine in the Early Cretaceous, to open ocean, that is probably bathyal, during most of the Campanian-Maastrichtian and into the Eocene, to shelfal in later Eocene. Neritic conditions prevailed into the Chattian.

Palynomorph concentrations, especially those of dinocysts, show considerable variation. Recovery from the Aptian, late Cretaceous and Paleocene is fair, but does not match that of the Eocene, especially the dinocysts. Recovery of dinocysts from the Oligocene and Miocene sediments is poor; however, miospores are common, especially the angiosperms and gymnosperms. Preservation of the palynomorphs is variable.

Comparison of the two wells

The benefits of undertaking palynological analyses on replicate wells has been proven in the study of the Roberval C-02 and K-92 wells, even though the Lower Cretaceous and Santonian sections in the former well were absent in the latter. Comparison of the Paleocene and Ypresian sections showed remarkable similarities in the ranges of index species, generally conforming to the stratigraphic ranges shown in the events chart of Nøhr-Hansen et al. (in press). In the Late Cretaceous, *Tenua* cf. *hystrix* was present in the Campanian of both wells, as were *Impagidinium* cf. *victorianum* and *Isabelidinium cretaceum* in the early Maastrichtian. The Danian in both wells contained the species *Cerodinium diebelii*, *Palaeoperidinium pyrophorum* and *Phelodinium kozlowskii*. There is considerable variation in the Thanetian, which I think reflects differences in processing of the samples, since those from Roberval C-02 are dominated by small miospores.

Where the closest agreement is seen is in the Ypresian. In both wells, *Eocladopyxis peniculata* and *Scalenodinium scalenum* appear to be early Ypresian, with Roberval K-92 also containing *Areoligera gippingensis* and *Deflandrea oebisfeldensis* The early Ypresian in Roberval C-02 has another species that according to Nøhr-Hansen et al. (in press) denotes this age in the Labrador-Baffin Seaway and this is *Petalodinium condylos*. Ypresian samples in both wells contain *Piladinium columnum, Ginginodinium fleximorphum, Heteraulacacysta pustulosa* and *Diphyes brevispinum*.

Correlating the younger Tertiary is not so easy. In the Lutetian, there are no species that have their LOs in this stage and that are found in both wells. However, the Bartonian is characterized in both wells by the LO of *Chiropteridium gilbertii*, which according to Nøhr-Hansen et al. (in press) has it's LO in that stage. The Priabonian is marked by the LOs of some *Phthanoperidinium* species, but these differ between the two wells.

Separating out the reworked and in-situ palynomorphs in the Oligocene-Miocene is difficult. But *Lentinia serrata* occurs in the Rupelian of both Roberval C-02 and K-92, although it is rare in the former well. Another taxon common to both wells in this stage is the miospore *Zlivisporites*. The Chattian is distinguished on the presence of *Chiropteridium galea*, a worldwide marker and one found throughout the Labrador-Bafffin Seaway according to Nøhr-Hansen et al. (in press).

One of the enigmas of the assemblages in Roberval C-02 and Roberval K-92 is the rarity of the fresh-water 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 ca. 49 Ma and the termination at about 48.3 Ma. Assuming that the time scale is that of Gradstein *et al.* (2004), the termination is just above the Ypresian–Lutetian boundary, which is at 48.6 Ma. However, neither of the two Roberval wells contains even moderate numbers of *Azolla*. Some other wells, all in the northern Saglek Basin, had more notable relative abundances: these are Hekja O-71, Ralegh N-18 and Gjoa G-37 (Nøhr-Hansen et al., in press). But even in these wells, *Azolla* was not recorded in high concentrations, and was surely transported in rather than growing in situ.

In summation, although my study of these two closely spaced wells has been a revelation, I could have obtained more pertinent information if the techniques for processing the samples had been identical. My recommendation is that Roberval K-92 be resampled and the samples processed as for Roberval C-02. That should provide us with detailed biostratigraphic and paleoenvironmental control, which could be extended to other wells. The first and most obvious would be Gudrid H-55. Ultimately following such an approach, we could develop a model for the Mesozoic-Cenozoic evolution of the Labrador Shelf that could, in part, be extended into Baffin Bay.

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Achilleodinium biformoides (Eisenack 1954) Eaton 1976 Achomosphaera ramulifera (Deflandre 1937b) Evitt 1963 Adnatosphaeridium sp. Ioannides 1987 Alterbidinium? bicellulum (Islam 1983a) Lentin & Williams 1985 Apectodinium parvum (Alberti 1961) Lentin & Williams 1977b Aptea polymorpha Eisenack 1938 Apteodinium australiense (Deflandre & Cookson 1955) Williams 1978 Aquilapollenites Rouse 1957 Areoligera gippingensis Jolley 1992 "Axiodinium simile" Azolla Lamarck in Lamarck et al. 1783 Batiacasphaera micropapillata Stover 197 Callialasporites Dev 1961 Canningia Cookson & Eisenack 1960b Caryapollenites imparalis Nichols & Ott 1978 Caryapollenites inelegans Nichols & Ott 1978 Caryapollenites veripites (Wilson & Webster 1946) Nichols & Ott 1978 Cerbia tabulata (Davey & Verdier 1974) Below 1981a Cerodinium diebelii. (Alberti 1959) Lentin & Williams 1987 Cerodinium glabrum (Gocht 1969) Fensome et al. 2009 Cerodinium kangiliense Nøhr-Hansen & Heilmann-Clausen 2001 Cerodinium speciosum (Alberti 1959) Lentin & Williams 1987 Chatangiella verrucosa (Manum 1963) Lentin & Williams 1978

Chatangiella victoriensis (Cookson & Manum 1964) Lentin & Williams 1976 Chiropteridium galea (Maier 1959) Sarjeant 1983 Chiropteridium gilbertii Fensome et al. in press Circulodinium distinctum Deflandre & Cookson 1955) Jansonius 1986 Cleistosphaeridium ancyreum (Cookson & Eisenack 1965a) Eaton et al. 2001 Cleistosphaeridium diversispinosum Davey et al. 1966 *Cleistosphaeridium palmatum* Fensome et al. in press Cordosphaeridium cantharellus (Brosius 1963) Gocht 1969 Cordosphaeridium fibrospinosum Davey & Williams 1966b Cordosphaeridium gracile (Eisenack 1954) Davey & Williams 1966b Coronifera oceanica Cookson & Eisenack 1958 Corsinipollenites oculusnoctis (Thiergart 1940) Nakoman 1965 Cousteaudinium aubryae de Verteuil & Norris 1996a Cyclonepheliium (now Circulodinium) attadalicum Cookson & Eisenack 1962b Dapsilidinium simplex (White 1842) Bujak et al. 1980 Deflandrea leptodermata Cookson & Eisenack 1965a Deflandrea oebisfeldensis Alberti 1959 Deflandrea phosphoritica Eisenack 1938 Diphyes brevispinum Bujak 1994 Diphyes colligerum (Deflandre & Cookson 1955) Cookson 1965a Diphyes ficusoides Islam 1983b Disphaerogena carposphaeropsis Wetzel 1933b Dracodinium solidum Gocht 1955 Eocladopyxis peniculata Morgenroth 1966a Florentinia mantellii (Davey & Williams 1966b) Davey & Verdier 1973

Ginginodinium? flexidentatum Fensome et al. in press Glaphyrocysta (as Cyclonephelium) sp. A of Williams & Brideaux 1975, Glaphyrocysta divaricata (Williams & Downie 1966b) Stover & Evitt 1978 Glaphyrocysta ordinata (Williams & Downie 1966b) Stover & Evitt 1978 Hafniasphaera hyalospinosa Hansen 1977 Hemiplacophora semilunifera Cookson & Eisenack 1965a Heteraulacacysta campanula Drugg & Loeblich Jr. 1967 Heteraulacacysta pustulosa Jan du Chêne & Adediran 1985 Heterosphaeridium difficile (Manum & Cookson 1963) Ioannides 1986 Homotryblium abbreviatum Eaton 1976 Homotryblium tenuispinosum Davey & Williams 1966b Hystrichokolpoma globulus Michoux 1985 Hystrichokolpoma granulatum Eaton 1976 Hystrichokolpoma salacium Eaton 1976 Hystrichosphaeridium bowerbanki Davey & Williams 1966b Hystrichosphaeridium quadratum Fensome et al. in press Hystrichosphaeridium salpingophorum Deflandre 1935 ex Deflandre 1937b Hystrichosphaeridium tubiferum subsp. brevispinum (Davey & Williams 1966b) Lentin & Williams 1973 Impagidinium Stover & Evitt 1978 Impagidinium dispertitum (Cookson & Eisenack 1965a) Stover & Evitt 1978 Impagidinium victorianum (Cookson & Eisenack 1965a) Stover & Evitt 1978 Isabelidinium belfastense (Cookson & Eisenack 1961a) Lentin & Williams 1977a Isabelidinium cretaceum (Cookson 1956) Lentin & Williams 1977a Jussiaea

Kleithriasphaeridium loffrense Davey & Verdier 1976 Laciniadinium arcticum (Manum & Cookson 1964) Lentin & Williams 1980 Laciniadinium williamsii Ioannides 1986 Lentinia serrata Bujak in Bujak et al. 1980 Lentinia wetzelii (Morgenroth 1966a) Bujak in Bujak et al. 1980 Lingulodinium funginum (Morgenroth 1966a) Islam 1983a Manumiella selandicum (Lange 1969) Bujak & Davies 1983 Membranophoridium aspinatum Gerlach 1961 Microdinium ornatum Cookson & Eisenack 1960a Minisphaeridium latirictum (Davey & Williams 1966b) Fensome et al. 2009 Odontochitina costata Alberti 1961 Odontochitina porifera Cookson 1956 Oligosphaeridium complex (White 1842) Davey & Williams 1966b Oligosphaeridium pulcherrimum (Deflandre & Cookson 1955) Davey & Williams 1966b Osmundacidites wellmannii Couper 1953 Ovoidinium verrucosum (Cookson & Hughes 1964) Davey 1970 Palaeocystodinium bulliforme Ioannides 1986 Palaeocystodinium lidiae (Gorka 1963) Davey 1969b Palaeoperidinium pyrophorum (Ehrenberg 1838 ex Wetzel 1933a) Sarjeant 1967 Palynodinium grallator Gocht 1970 Petalodinium condylos (Williams & Downie 1966a) Williams et al. 2015 Phelodinium kozlowskii (Gorka 1963) Lindgren 1984 Phthanoperidinium amoenum Drugg & Loeblich Jr. 1967 Phthanoperidinium coreoides (Benedek 1972) Lentin & Williams 1976 Piladinium columna (Michoux 1988) Williams et al. 2015

Piladinium edwardsii (Wilson 1967b) Williams et al. 2015 Pseudoceratium anaphrissa (Sarjeant 1966c) Bint 1986 Raphidodinium fucatum Deflandre 1936 Rhombodinium porosum Bujak 1979 Scalenodinium scalenum Fensome et al. in press Schematophora speciose Deflandre & Cookson 1955 Senoniasphaera inornata (Drugg 1970) Stover & Evitt 1978 Sophismatia tenuivirgula (Williams & Downie 1966a) Williams et al. 2015 Spiniferella cornuta (Gerlach 1961) Stover & Hardenbol 1994 Spiniferella sp. Spiniferites ramosus (Ehrenberg 1838) Mantell 1854 Spiniferites scabrosus (Clarke & Verdier 1967) Lentin & Williams 1975 Spongiodinium delitiense (Ehrenberg 1838) Deflandre 1936 Tanyosphaeridium xanthiopyxides (Wetzel 1933b ex Deflandre 1937) Stover & Evitt 1978 Tenua cf. hystrix Tenua hystrix, Eisenack 1958 Trithyrodinium? conservatum Fensome et al. in press Trithyrodinium evittii Drugg 1967 Trithyrodinium suspectum (Manum & Cookson 1964) Davey 1969b Vesperopsis Bint 1986 Zlivisporites Pacltová 1961



Figure 1. Map of Labrador Sea showing the location of the Roberval C-02 and Roberval K-92 wells.

Figure Captions

Figure 2. Well log, lithology, and formation and biostratigraphic picks for the Roberval C-02 well. The information other than my age determinations is taken from the BASIN database.

Figure 3. Relative abundances of miospores, bisaccates, others (*Palambages, Pediastrum*, etc.), acritarchs and dinocysts in the Roberval C-02 well. These data are the basis for the paleoenvironmental conclusions that I draw about this well.

Figure 4. Plot showing the stratigraphic ranges and abundances of dinocysts in Roberval C-02.

Figure 5. Plot showing the stratigraphic ranges and relative abundances of miospores in Roberval C-02.

Figure 6. Well log, lithology, and formation and biostratigraphic picks for the Roberval K-92 well. The information other than my age determinations is taken from the BASIN database.

Figure 7. Relative abundances of miospores, bisaccates, others (*Palambages, Pediastrum*, etc.), acritarchs and dinocysts in the Roberval K-92 well. These data are the basis for the paleoenvironmental conclusions that I draw about this well.

Figure 8. Plot showing the stratigraphic ranges and abundances of dinocysts in Roberval K-92, as determined from my analysis of the samples processed at GSC Calgary.

Figure 9. Plot showing the stratigraphic ranges and relative abundances of dinocysts in Roberval K-92, as determined from my analysis of the samples processed at GSC Atlantic.

Figure 10. Plot showing the stratigraphic ranges and abundances of miospores in Roberval K-92, as determined from my analyses of the samples processed at GSC Calgary.

Figure 11. Plot showing the stratigraphic ranges and relative abundances of miospores in Roberval K-92, as determined from my analysis of the samples processed at GSC Atlantic.

Dinocysts from the Roberval C-02 well. Scale bar represents 30 microns

- 1. Achomosphaera ramulifera. 2805 metres. R3331-76+30.
- 2. Adnatosphaeridium multispinosum. 2200 metres. R3331-56 +30.
- 3. Adnatosphaeridium sp. 1085 metres. R3331-19 uns.
- 4. Alisogymnium sp. 1085 metres. R3331-19 +30.
- 5. Apectodinium astra. 2475 metres. R3331-65 +30.
- 6. Apectodinium homomorphum. A2475 metres. R3331-65 +30.
- 7. Apectodinium parvum. 2200 metres. R3331-56 +30.
- 8. Apectodinium quinquelatum. 2500 metres. P3331-66 +30. P3331-66 +30.
- 9. Areoligera cf. medusettiformis. 2560 metres. R3331-68 +30.
- 10. Areoligera gippingensis. 2200 metres. R3331-56 +30.
- 11. Batiacasphaera micropapillata. 615 metres. R3331-3 uns.
- 12. Batiacasphaera micropapillata. 645 metres. R3331-4 uns.
- 13. Canningia sp. 735 metres. R3331-7 +30.
- 14. Cerebrocysta magna. 2055 metres. R3331-51 +30.
- 15. Cerebrocysta sp. 2295 metres. R3331-59 uns.
- 16. Chatangiella tripartita. 765 metres. R3331-8+30.
- 17. Chiropteridium gilbertii. 1665 metres. R3331-38+30.
- 18. Chiropteridium gilbertii. 1665 metres. R3331-38 +30
- 19. Chytroeisphaeridia hadra. 2145 metres. R3331-54 +30
- 20. Cleistosphaeridium ancyreum. 2170 metres. R3331-55 +30

Roberval C-02

Plate 1



Dinocysts from the Roberval C-02 well. Scale bar represents 30 microns

- 1. *Cleistosphaeridium ancyreum*. 2170 metres. R3331-55 +30.
- 2. Cleistosphaeridium diversispinosum. 1425 metres. R3331-30 +30.
- 3. Cleistosphaeridium palmatum. 2500 metres. P3331-66 +30.
- 4. *Cleistosphaeridium polypetellum*. 2170 metres. R3331-55 +30.
- 5. Cousteaudinium aubryae. 675 metres. R3331-5 uns.
- 6. Cribroperidinium sp. 2170 metres. R3331-55 +30.
- 7. Cribroperidinium tenuitabulatume. 795 metres. R3331-9+30.
- 8. Cyclonephelium vannophorum. 1425 metres. R3331-30+30
- 9. Dapsilidinium pseudocolligerum. 2445 metres. R3331-64 +30
- 10. Deflandrea cf. eocenica. 735 metres. R3331-7 +30.
- 11. Deflandrea cf. wetzelii. 2055 metres. R3331-51 +30.
- 12. Diphyes brevispinum. 2170 metres. R3331-55 +30.
- 13. *Diphyes colligerum*. 2170 metres. R3331-55 +30.
- 14. Diphyes ficusoides. 2145 metres. R3331-54 +30.
- 15. *Diphyes* sp. 2145 metres. R3331-54 +30.
- 16. *Diphyes* sp. 2170 metres. R3331-55 +30.
- 17. "Dracodinium" ovale". 2145 metres. R3331-54 +30.
- 18. Eatonicysta sp. 2635 metres. R3331-70 +30.
- 19. *Enneadocysta* sp. 2170 metres. R3331-55 +30.
- 20. Ginginodinium flexidentatum. 2080 metres. R3331-52 +30

Roberval C-02

Plate 2



Dinocysts from the Roberval C-02 well. Scale bar represents 30 microns

- 1. Ginginodinium ornatum. 1245 metres. R3331-24 +30.
- 2. *Glaphyrocysta* cf. *ordinata*. 1450 metres. R3331-31+30.
- 3. *Glaphyrocysta intricata*. 2445 metres. R3331-64 +30.
- 4. *Glaphyrocysta ordinata*. 1125 metres. R3331-20 +30.
- 5. Glaphyrocysta pastielsii. 1055 metres. R3331-18 uns.
- 6. Glaphyrocysta cf. vicina. 1665 metres. R3331-38 +30.
- 7. Glaphyrocysta cf. vicina. 2025 metres. R3331-50.
- 8. Glaphyrocysta cf. vicina. 2025 metres. R3331-50.
- 9. *Glaphyrocysta* cf. *vicina*. 2445 metres. R3331-64 +30.
- 10. Glaphyrocysta sp. A sensu Williams & Brideaux, 1975. 1245 metres. R3331-24 +30.
- 11. Glaphyrocysta sp. B sensu Williams & Brideaux, 1975. 1185 metres. R3331-22 +30.
- 12. Glaphyrocysta sp. E sensu Williams & Brideaux, 1975. 825 metres. R3331-10 +30.
- 13. *Hafniasphaera* sp. 2115 metres. R3331-53 +30.
- 14. *Hemiplacophora semilunifera*. 2145 metres. R3331-54 +30.
- 15. Homotryblium oceanicum. 2025 metres. R3331-50..
- 16. *Homotryblium oceanicum*. 2170 metres. R3331-55 +30.
- 17. Homotryblium tenuispinosum. 2200 metres. R3331-56 +30.
- 18. Homotryblium tenuispinosum. 2115 metres. R3331-53 +30.
- 19. Horologinella sp. 1935 metres. R3331-47 +30.
- 20. Hystrichokolpoma granulaa. 2170 metres. R3331-55 +30

Roberval C-02

Plate 3



Dinocysts from the Roberval C-02 well. Scale bar represents 30 microns

- 1. *Hystrichokolpoma salacia*. 2080 metres. R3331-52 +30.
- 2. *Hystrichokolpoma truncata*. 735 metres. R3331-7 +30.
- 3. *Hystrichosphaeridium quadratum*. 2590 metres. R3331-69 +30.
- 4. Hystrichosphaeridium sp. 2115 metres. R3331-53 +30.
- 5. Hystrichosphaeridium tubiferum. 2710 metres. R3331-73 +30.
- 6. Hystrichosphaeropsis perforata. 2770 metres. R3331-75 uns.
- 7. *Impagidinium* cf. *victorianum*. 2710 metres. R3331-73 +30. Ventral view of ventral surface.
- 8. Impagidinium cf. victorianum. 2710 metres. R3331-73 +30. Optical section.
- 9. *Impagidinium* cf. victorianum. 2710 metres. R3331-73 +30. Ventral view of dorsal surface.
- 10. Isabelidinium cooksoniae. 2805 metres. R3331-76 +30.
- 11. Isabelidinium cretaceum. 2635 metres. R3331-70 +30.
- 12. Kenleyia. 2445 metres. R3331-64 +30.
- 13. *Kiokansium* cf. *polypes*. 2080 metres. R3331-52 +30.
- 14. Laciniadinium williamsii. 1485 metres. R3331-32 +30.
- 15. Lanternosphaeridium vectense. 1785 metres. R3331-42 +30.
- 16. Leberidocysta chlamydata. 2740 metres. R3331-74 +30
- 17. Lentinia serrata. 1185 metres. R3331-22 +30.
- 18. Lentinia serrata. 1425 metres. R3331-30+30
- 19. Lentinia wetzelii. 2170 metres. R3331-55 +30 R3331-55 +30
- 20. Lingulodinium cf. funginum. 2445 metres. R3331-64 +30

Roberval C-02

Plate 4



Dinocysts from the Roberval C-02 well. Scale bar represents 30 microns

- 1. Lingulodinium funginum. 1665 metres. R3331-38 +30,
- 2. *Lingulodinium* cf. *machaerophorum*. 2445 metres. R3331-64 +30.
- 3. Nematosphaeropsis sp. 1035 metres. R3331-17 +30.
- 4. *Oligosphaeridium dictyophorum*. 2500 metres. P3331-66 +30.
- 5. *Oligosphaeridium perforatum*. 1425 metres. R3331-30 +30.
- 6. Ovoidinium scabrosum. 2260 metres. R3331-58 uns.
- 7. Ovoidinium verrucosum. 675 metres. R3331-5 uns.
- 8. Ovoidinium verrucosum. 1935 metres. R3331-47 +30.
- 9. Palaeocystodinium sp. 645 metres. R3331-4C uns.
- 10. Palaeocystodinium sp. 1845 metres. R3331-44 +30.
- 11. Palaeocystodinium sp. 705 metres. R3331-6 uns.
- 12. Palaeoperidinium pyrophorum. 855 metres. R3331-11 +30.
- 13. Petalodinium condylos. 2170 metres. R3331-55 +30.
- 14. Petalodinium condylos. 2200 metres. R3331-56 +30.
- 15. Phelodinium sp. 2525 metres. R3331-67 +30
- 16. Phthanoperidinium alectrolophum. 1520 metres. R3331-33 +30.
- 17. Phthanoperidinium coreoides. 735 metres. R3331-7 +30
- 18. Phthanoperidinium multispinum. 1755 metres. R3331-41+30.
- 19. Piladinium edwardsii. 2145 metres. R3331-54 +30.
- 20. *Pseudoceratium* sp. 2500 metres. P3331-66 +30

Roberval C-02

Plate 5



Dinocysts from the Roberval C-02 well. Scale bar represents 30 microns

- 1. Reticulatosphaera actinocoronata. 645 metres. R3331-4 uns.
- 2. Scalenodinium scalenum. 2445 metres. R3331-64 +30.
- 3. *Schematophora speciosa*. 935 metres. R3331-47 +30. Ventral view of ventral surface.
- 4. *Schematophora speciosa*. 1935 metres. R3331-47 +30. Ventral view of dorsal surface.
- 5. Spinidinium echinoideum. 645 metres. R3331-4C +30.
- 6. *Spiniferites* cf. *scabrosus*. 735 metres. R3331-7 +30.
- 7. Spiniferella cornuta. 2525 metres. R3331-67 uns.
- 8. Spiniferites "digitus". 2145 metres. R3331-54 +30.
- 9. Spiniferites ovatus. 2200 metres. R3331-56 +30.
- 10. Spiniferites scabrosus. 2740 ,metres. R3331-74 +30.
- 11. Spiniferites sp. 2475 metres. R3331-65 +30.
- 12. Svalbardella sp. 2260 metres. R3331-58 uns.
- 13. Tenua cf. hystrix. 2805 metres. R3331-76 +30.
- 14. Tenua cf. hystrix. 2820 metres. R3331-77 +30.
- 15. Trithyrodinium conservatum. 1185 metres. R3331-22 +30.
- 16. Trithyrodinium conservatum. 1390 metres. R3331-29 +30.
- 17. Trithyrodinium conservatum. 1665 metres. R3331-38 +30.
- 18. Trithyrodinium conservatum. 1665 metres. R3331-38 +30.
- 19. Trithyrodinium evittii. 2590 metres. R3331-69 +30.
- 20. Wetzeliella articulata. 1725 metres. R3331-40 +30.

Roberval C-02

Plate 6



Palynomorphs (dinocysts, acritarchs and other algae, and miospores) from the Roberval C-02 well. Scale bar represents 30 microns

- 1. Wetzeliella "similis". 2080 metres. R3331-52 +30. Dinocyst.
- 2. Fromea sp. 2805 metres. R3331-76 +30. Acritarch.
- 3. Micrhystridium bigotii. 2260 metres. R3331-58 uns. Acritarch.
- 4. Micrhystridium stellatum. 2415 metres. R3331-63 uns. Acritarch.
- 5. Pediastrum. 1055 metres. R3331-18 uns. Algal.
- 6. *Pterospermella* sp. 2500 metres. P3331-66 +30. Algal.
- 7. Pterospermella sp. 555 metres. R3331-1 unsA. Algal.
- 8. *Pterospermella* sp. 1390 metres. R3331-29 +30. Algal.
- 9. Tetraporina sp. B sensu Fensome et al. in press. 2025 metres. R3331-29 +30. Algal.
- 10. Tetraporina sp. B sensu Fensome et al. in press. 2170 metres. R3331-55 uns. Algal.
- 11. Tetraporina sp.: A sensu Fensome et al. in press. 2260 metres. R3331-58 uns. Algal.
- 12. Veryhachium sp. 2385 metres. R3331-62 uns. Acritach.
- 13. "Acaryapollenites ". sp. 2415 metres. R3331-63 uns. Miospore.
- 14. Aquilapollenites sp. 2080 metres. R3331-52 +30. Miospore.
- 15. Aquilapollenites sp. 2560 metres. R3331-68 +30. Miospore.
- 16. Araleacioipollenites sp. 1520 metres. R3331-33k uns. Miospore.
- 17. Baculatisporites sp. 765 metres. R3331-8 +30. Miospore.
- 18. Bombacacidites sp. 2055 metres. Miospore.
- 19. Carpinus sp. 2355 metres. R3331-61 uns. Miospore.
- 20. Cicatricosisporites ornatus. 2080 metres. R3331-52 +30. Miospore.

Roberval C-02

Plate 7



Miospores from the Roberval C-02 (figs. 1-19) well and one dinocyst from the Roberval K-92 (fig.20) well. Scale bar represents 30 microns

- 1 *Cicatricososporites eocenicus*. 1905 metres. R3331-46 +30.
- 2 *Corsinispollenites oculusnoctis*. 735 metres. R3331-7 +30.
- 3 Extratriporopollenites sp. 1520 metres. R3331-33k uns.
- 4 Juglanspollenites sp. 975 metres. R3331-15 +30.
- 5 *Klukisporites pseuoreticulites*. 555 metres. R3309-62 +30A.
- 6 Momipites ventifluminus. 2355 metres. R3331-61 uns.
- 7 Osmundacidites wellmannii. 1055 metres. R3331-18 uns.
- 8 Porocolpopollenites sp. 2385 metres. R3331-62 uns.
- 9 Porocolpopollenites sp. 2355 metres. R3331-61 uns.
- 10 Pterocaryapollenites sp. 885 metres. R3331-12 uns.
- 11 Quercoidites sp. 795 metres. R3331-9 un.
- 12 Retitricolpites virgeus. 1125 metres. R3331-20 uns.
- 13 Nyssapollenites sp. 2055 metres. R3331-51 +30.
- 14 Symplocoipollenites vestibulus.
- 15 Tricolporopollenites sp. 795 metres. R3331-9 un.
- 16 Nyssapollenites? sp. 585 metres. R3331-2-uns.
- 17 Syncolporites sp. 2770 metres. R3331-75 uns.
- 18 Retitriporites sp. 2230 metres. R3331-57 uns.
- 19 Zlivisporites sp. 2055 metres. R3331-51 uns.
- 20 Lanternosphaeridium radiatum. 2270-2280 metres. P17700-01 (2270cu).

Roberval C-02/K-92

Plate 8



Dinocysts from the Roberval K-92 well. Scale bar represents 30 microns

- 1. Airieana verrucosa. 2540-2550 metres. P17709-01 (2540).
- 2. *Alisocysta reticulata*. 2510-2520 metres. P177078-01 (2510). Oblique antapical view, clearly showing the 1"" plate.
- 3. Alisocysta reticulata. 2510-2520 metres. P177078-01 (2510). Optical section.
- 4. *Alisocysta reticulata*. 2510-2520 metres. P177078-01 (2510). Oblique apical view.
- 5. Aptea polymorpha. 3160 metres. P2008177-01.
- 6. Areoligera gippingensis. 2510-2520 metres. P177078-01 (2510).
- 7. Canningia reticulata. Conventional core at 3014.75 metres. K-92 3014.75+
- 8. Canningia reticulata. 1730-1740 metres. P17682-01 1730cu).
- 9. Cerodinium diebelii. 3160 metres. P2008177-01.
- 10. Cerodinium diebelii. 2950 metres. P2008171-01.
- 11. Cerodinium kangliense. 360-370 metres. P17726-01.
- 12. Cerodinium speciosum. 2480-2490 metres. P17707-01 (2480).
- 13. Chiropteridium gilbertii. 1910-1920 metres. P17688 (1910cu).
- 14. Chytroeisphaeridia hydra. 3120-3140. metres. P17728-01.
- 15. Circulodinium paucispinum. 3090-3100. P17727-0-1.
- 16. Cleistosphaeridium sp. Conventional core at 3014.75 metres. K-92 3014.75+.
- 17. Cleistosphaeridium palmatum. 2270-2280 metres. P17700-01.
- 18. Cleistosphaeridium palmatum. 2300-2310 metres. P17701-01.
- 19. Cometodinium sp. Conventional core at 3014.75 metres. K-92 3014.75+.
- 20. Coronifera oceanica. Conventional core at 3014.75 metres. K-92 3014.75+.

Roberval K-92

Plate 9



Dinocysts from the Roberval K-92 well. Scale bar represents 30 microns

- 1 Deflandrea phosphoritica var spinulosa. 2510-2520 metres. P177078-01 (2510).
- 2 Deflandrea oebisfeldensis. 2450-2460 metres. P17706-0 (2450).
- 3 Airieana? sp. 2690-2700 metres. P17714-01 (2690).
- 4 Diphyes brevispinum. 2450-2460 metres. P17706-0 (2450).
- 5 *Distatodinium* sp. 2330-2340 metres. P17702 (2330).
- 6 Downiesphaeridium aciculare. 2570-2580 metres. P17710-01(2570).
- 7 Elytrocysta druggii. Conventional core. 3016.75 metres. R3309-56C.
- 8 Enneadocysta sp. 2450-2460 metres. P17706-0 (2450)
- 9 Eocladopyxis sp. 2480-2490 metres. P17707-01.
- 10 Eocladopyxis sp. 2090-2100 metres, P17694-01.
- 11 Epelidinium glabrum. 2330-2340 metres. P17702 (2330).
- 12 Exochosphaeridium sp. Conventional core. 3016.75 metres. K-92 3016.75+.
- 13 Fibrocysta sp. 2390-2400 metres. P17704-01.
- 14 Glaphyrocysta vicina. 2210-2220 metres. P17698-01.
- 15 *Glaphyrocysta* sp. A sensu Williams & Brideaux, 1975. 2240-2250 metres. P17699-01.
- 16 Glaphyrocysta sp. D sensu Williams & Brideaux, 1975. 1910-1920 metres. P17688 (1910cu)
- 17 Glaphyrocysta vicina. 2210-2220 metres. P17698-01 (2210cu).
- 18 Homotryblium tenuispinosum. 2330-2340 metres. P17702 (2330).
- 19 Hystrichokolpoma globulus. 2300-2310 metres. P17701-01.
- 20 Hystrichosphaeridium "dictyophorum". 23k30-2340 metres. P17702 (2330).

Roberval K-92

Plate 10



Dinocysts from the Roberval K-92 well. Scale bar represents 30 microns

- 1. Hystrichosphaeridium "dictyophorum". 2890 metres. P2008169-1
- 2. Hystrichosphaeridium "dictyophorum". 2950 metres. P2008171-01.
- 3. Hystrichosphaeridium "dictyophorum". 3160 metres. P2008177. Dorsal surface.
- 4. Hystrichosphaeridium "dictyophorum". 3160 metres. P2008177. Ventral surface.
- 5. *Hystrichosphaeridium tubiferum*. 2730-2740 metres. P17715-01 (2730). Ventral surface.
- 6. *Hystrichosphaeridium tubiferum*. 2730-2740 metres. P17715-01 (2730). Dorsal surface.
- 7. Impagidinium cf. victorianum. 3040 metres. P2008174-01.
- 8. *Impagidinium* sp. 2450-2460 metres. P17706-0 (2450). Right lateral view of right lateral surface.
- 9. *Impagidinium* sp. 2450-2460 metres. P17706-0 (2450). Right lateral view of left lateral surface.
- 10. *Impagidinium* sp. 3016.75 metres. K-92 3016.75+. Dorsal view of dorsal surface. Conventional core
- 11. *Impagidinium* sp. 2270-2280 metres. P17700-01 (2270cu). Ventral view of ventral surface.
- 12. Impagidinium sp. 2270-2280 metres. P17700-01 (2270cu). Optical section.
- 13. *Impagidinium* sp. 2270-2280 metres. P17700-01 (2270cu). Ventral view of dorsal surface.
- 14. Isabelidinium cooksoniae. 3016.75 metres. K-92 3016.75+. Conventional core.
- 15. Isabelidinium cretaceum. 3060-3070 metres. P17726-01.
- 16. Hystrichosphaeropsis perforata. 2980 metres. P2008172-01.
- 17. Hystrichostrogylon sp. 2450-2460 metres. P17706-0.
- 18. Lingulodinium funginum. 2450-2460 metres. P17706-0.
- 19. Manumiella seelandica. 3016.75 metres. K-92 3016.75+.
- 20. Piladinium columnum. 2240-2250 metres. P17699-01.

Roberval K-92

Plate 11



Dinocysts from the Roberval K-92 well. Scale bar represents 30 microns

- 1. Palaeocystodinium sp. 2240-2250 metres. P17699-01.
- 2. Palaeoperidinium pyrophorum. 3070 metres. P2008175-01.
- 3. Palynodinium grallator. 2840-2850 metres. P17719-01.
- 4. *Petalodinium condylos*. 2420-2430 metres. P17705-01.
- 5. Petalodinium condylos. 2240-2250 metres. P17699-01.
- 6. Petalodinium condylos. 2540-2550 metres. P17709-01
- 7. Phelodinium kozlowskii. 3120-3140 metres. P17728-01.
- 8. Phthanoperidinium levi murum. 1910 metres. P17688-01
- 9. Piladinium columnum. 2270 metres. P17700-01. Dorsal view of dorsal surface.
- 10. Piladinium columnum. 2270 metres. P17700-01. Dorsal view of ventral surface.
- 11. Pseudoceratium sp. 3070 metres. P2008175-01.
- 12. Sophismatia tenuivirgula. 1970-1980 metres. P17690-01.
- 13. Spiniferella cornuta. 2980 metres. P2008172-01.
- 14. Spiniferites cf. ramosus. 2510 metres. P177078-01.
- 15. Spiniferites scabrosus. 3010 metres. P2008173-01.
- 16. Spongodinium delitiense. 3210-3220 metres. P17731-01.
- 17. Spongodinium delitiense. 3040 metres. P2008174-01.
- 18. Systematophora ancyrea. 2180 metres. P17697-01.
- 19. Tenua cf. hystrix. 3016.75 metres, conventional core. K-92 3016.75+.
- 20. Thalassiphora patula. 2600-2610 metres. P17711-01.

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Plate 12



Dinocysts from the Roberval K-92 well. Scale bar represents 30 microns

- 1 Trinovantedinium flexidentatum. 2270-2280 metres. P17700-01.
- 2 Trithyrodinium evittii. 2810-2820 metres. P17718-01.
- 3 Baculatisporites sp. 1790-1800 metres. P17684.
- 4 Baculatisporites sp. 2150-2160 metres. P17696-01.
- 5 Cicatricosisporites ornatus. 2570-2580 metres. P17710-01.
- 6 Cicatricosisporites sp. 2880-2890 metres. P17720-01. Distal view.
- 7 Cicatricosisporites sp. 2880-2890 metres. P17720-01, Proximal view.
- 8 *Cingutriletes* sp. 2130-2140 metres. P17692-01.
- 9 Rugutriletes sp. 3016.75 metres. K-92 3016.75+. Conventional core.
- 10 *Triquetrites* sp. 1635 metres. R3331-37 +30.
- 11 Triquetrites sp. 1970-1980 metres. P17690-01.
- 12 Triquetrites sp. 2030-2040 metres. P17692-01.
- 13 Triquetrites sp. 1730-1740 metres. P17682-01.
- 14 Tasmanites sp. 2090-2100 metres. P17694-01.

Roberval K-92

Plate 13

